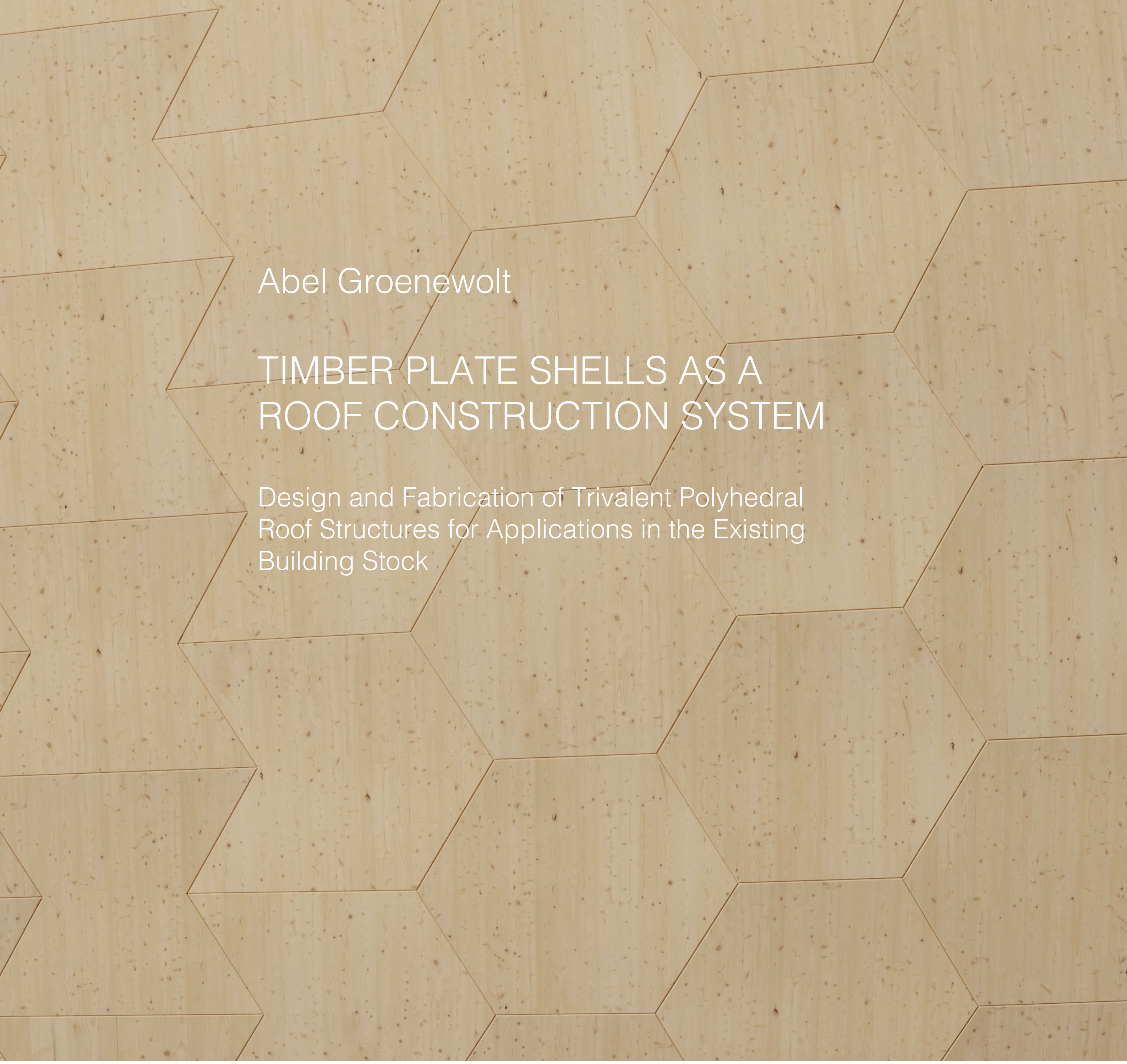

Abel Groenewolt

TIMBER PLATE SHELLS AS A ROOF CONSTRUCTION SYSTEM

Design and Fabrication of Trivalent Polyhedral Roof Structures for Applications in the Existing Building Stock

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Foreword

The dissertation of Abel Groenewolt investigates timber plate shells based on planar panels made of wood-based materials and explores their potential for resource-efficient lightweight construction and their possible application for building in existing building stock. The work builds on the research on timber plate shells carried out by the Institute for Computational Design and Construction (ICD) and the Institute of Building Structures and Structural Design (ITKE) at the University of Stuttgart and develops it further in the following areas: On the one hand, approaches for identifying and overcoming obstacles in architectural design and practical implementation of segmented shell roofs are developed and these are systematically processed in such a way that they can serve further dissemination and application in building practice. This is done with a special focus on vertical urban densification by adding storeys to existing buildings. Likewise, the dissertation makes a methodological contribution to the associated computational design approaches for trivalent polyhedral roof structures made of wooden panels.

Professor Achim Menges, AA Dipl.(Hons.)

Vorwort

Die Dissertation von Abel Groenewolt befasst sich mit Dachsegmentbauweisen basierend auf Platten aus Holzwerkstoffen und untersucht deren Potential für ressourcenschonende Leichtbaukonstruktionen und deren mögliche Anwendung für das Bauen im Bestand. Die Arbeit baut dabei auf den Forschungen zu Holzsegmentbauweisen des Instituts für Computerbasiertes Entwerfen und Baufertigung (ICD) und des Instituts für Tragkonstruktionen und Konstruktives Entwerfen (ITKE) an der Universität Stuttgart auf und entwickelt diese in den folgenden Bereichen weiter: Zum einen werden Ansätze zur Erkennung und Überwindung von Hindernissen in der architektonischen Planung und baupraktischen Umsetzung von Holzsegmentbauweisen für Dachkonstruktionen erarbeitet und diese so systematisch aufgearbeitet, dass sie einer weiteren Verbreitung und Anwendung in der Baupraxis dienen können. Dies erfolgt mit einem besonderen Schwerpunkt auf der vertikalen, urbanen Nachverdichtung durch die Aufstockung von Bestandsgebäuden. Ebenso leistet die Dissertation einen methodischen Beitrag zu den dazugehörigen, digitalen Entwurfs- und Planungsansätzen für trivalente polyedrische Dachstrukturen aus Holzplatten.

Professor Achim Menges, AA Dipl.(Hons.)

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A dissertation approved
by the Faculty of Architecture and Urban Planning of the
University of Stuttgart
for the conferral of the title of
Doktor-Ingenieur (Dr.-Ing.)

Submitted by
Abel Groenewolt
from Delfzijl

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Institute for Computational Design and Construction of the
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2023

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Von der Fakultät 1: Architektur und Stadtplanung der
Universität Stuttgart
zur Erlangung der Würde
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I thank my parents, my brothers, and all other family members for being who they are and for all shared experiences. Finally, I thank Pia for everything.

Abel Groenewolt

Contents

List of Abbreviations

BUGA Bundesgartenschau (federal German horticulture show)

CAGM Curvature-Adjusted Gauss Map segmentation

CLT Cross Laminated Timber

EPDM Ethylene Propylene Diene Monomer rubber (synthetic roofing material)

FEM Finite Element Method

HVAC Heating, Ventilation and Air Conditioning

ICD Institute for Computational Design and Construction, University of Stuttgart

ITKE Institute of Building Structures and Structural Design, University of Stuttgart

LCA Life Cycle Analysis

LVL Laminated Veneer Lumber

MDF Medium Density Fibreboard

OSB Oriented Strand Board

PUR	Polyurethane
TPI	Tangent Plane Intersection
UV	Coordinate system within a surface
VTPI	Variational Tangent Plane Intersection

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Abstract

This dissertation investigates the applicability of timber plate shells as a construction system for roof structures of buildings, departing from an architectural perspective and focusing on vertical densification projects.

As a light-weight timber construction system, timber plate shells do not just expand the architectural vocabulary, they can also contribute to a more sustainable way of building. However, timber plate shells have only been used in very few constructed examples, of which most are pavilions or demonstrator buildings. Therefore, the aim of the dissertation is firstly to identify and resolve potential impediments to the design and construction of timber plate shells, and secondly to collect and disseminate information and insights that may contribute to a broader application of timber plate shells in the construction sector.

After the motivation, aim, scope and methods are discussed in Chapter 1, Chapter 2 focuses on the context of this investigation, which is threefold: building in an urban context, timber construction methods, and plate shell research. Chapter 2 also contains a short overview of built plate shells.

In Chapter 3, various plate and joint types are discussed. Two plate types with distinct joint types are selected for further investigation: solid cross laminated timber plates connected with crossing screws, and hollow laminated veneer lumber components connected with finger joints and bolts.

These two plate types are assessed on a wide range of criteria in Chapter 4, including structural properties, weight, fabrication methods, material efficiency, environmental impact, air and moisture tightness, sound, thermal insulation, integration of air ducts, and costs. Both plate types turn out to be viable options for the construction of roof structures in vertical densification projects: hollow components for extremely lightweight structures, and solid plates for lightweight structures with higher fire resistance requirements. The weight benefits are most pronounced at longer spans.

Strategies that deal with various architectural design considerations are discussed in Chapter 5, such as connecting plate shells to existing structures, integrating ventilation channels, and bringing in daylight. Spatial typologies are also explored in this chapter.

Constraints and approaches for the design of plate shells and the connection between global design and segmentation patterns are discussed in Chapter 6. Chapter 7 contains contributions to geometric design methods, including interactive agent-based design.

Chapter 8 presents the conclusion: while the practical application of plate shells depends on the willingness of timber contractors to build in a currently unconventional way and on the willingness and ability of architects to use design methods that are novel and challenging, timber plate shells have all the qualities necessary to play a significant role in the construction sector as a lightweight, sustainable and economical roof construction system that is particularly suitable for vertical densification projects.

Zusammenfassung

Diese Dissertation untersucht die Anwendbarkeit von Holzplattenschalen als Konstruktionssystem für Dachkonstruktionen von Gebäuden, aus der Sicht der Architektur und insbesondere auf Aufstockungsprojekte.

Als leichtes Holzbausystem erweitern Holzplattenschalen nicht nur das architektonische Vokabular, sie können auch zu einer nachhaltigeren Bauweise beitragen. Bislang wurden jedoch nur sehr wenige segmentierte Holzplattenkonstruktionen realisiert, bei denen es sich meist um Pavillons oder Demonstrationsgebäude handelt. Ziel der Dissertation ist es zum einen, potenzielle Hindernisse für den Entwurf und die Konstruktion von Holzplattenkonstruktionen zu ermitteln und zu beseitigen, und zum anderen, Informationen und Erkenntnisse zu sammeln und zu verbreiten, die zu einer breiteren Anwendung von Holzplattenschalen im Bausektor beitragen können.

Nachdem in Kapitel 1 die Motivation, das Ziel, der Umfang und die Methoden erörtert wurden, konzentriert sich Kapitel 2 auf den dreifachen Kontext dieser Untersuchung: städtische Verdichtung, Holzbauverfahren und Plattenschalenforschung. Kapitel 2 enthält auch einen kurzen Überblick über gebaute Plattenschalen.

In Kapitel 3 werden verschiedene Platten- und Fugentypen diskutiert. Zwei Plattentypen mit unterschiedlichen Verbindungsarten werden für die weitere Untersuchung ausgewählt: massive Brettsperrholzplatten mit Schraubverbindungen, und hohle Furnierschichtholzkomponenten, die mit Keilzinkenverbindungen und Bolzen verbunden sind.

Diese beiden Plattentypen werden in Kapitel 4 anhand zahlreiche Kriterien bewertet, darunter strukturelle Eigenschaften, Gewicht, Herstellungsmethoden, Materialeffizienz, Umweltauswirkungen, Luft- und Feuchtigkeitsdichtheit, Schall, Wärmedämmung, Integration von Luftkanälen und Kosten. Beide Plattentypen erweisen sich als geeignete Lösungen für den Bau von Dachkonstruktionen bei Aufstockungsprojekten: hohle Bauteile für extrem leichte Konstruktionen und massive Brettsperrholzplatten für leichte Konstruktionen mit höherem Feuerwiderstand. Die Gewichtsvorteile sind bei größeren Spannweiten am stärksten ausgeprägt.

In Kapitel 5 werden Strategien für verschiedene architektonische Überlegungen besprochen, wie zum Beispiel die Verbindung von Plattenstrukturen mit bestehenden Strukturen, die Integration von Lüftungskanälen und der Einlass von Tageslicht. Auch räumliche Typologien werden in diesem Kapitel untersucht.

In Kapitel 6 werden Randbedingungen und Ansätze für den Entwurf von Holzplattenschalen und die Verbindung zwischen globalem Entwurf und Segmentierungsmustern diskutiert. Kapitel 7 enthält Beiträge zu geometrischen Entwurfsmethoden, einschließlich des interaktiven agentenbasierten Entwurfs.

In Kapitel 8 wird die Schlussfolgerung gezogen, dass die praktische Anwendung von Plattentragwerken sowohl von der Bereitschaft der Holzbauunternehmen abhängt, auf derzeit unkonventionelle Weise zu bauen, alsauch von der Bereitschaft und Fähigkeit der Architekten, neuartige und herausfordernde Entwurfsmethoden anzuwenden, dass aber Plattentragwerke aus Holz alle erforderlichen Qualitäten besitzen, um als leichtes, nachhaltiges und wirtschaftliches Dachkonstruktionssystem eine bedeutende Rolle im Bausektor zu spielen und besonders für Aufstockungsprojekte geeignet sind.

1
Introduction

1.1 Motivation

In light of the continuous growth of the global population, higher and higher levels of urbanization, and mounting pressure on land, the topic of urban densification is increasingly important for society in general and urban planning and architecture in particular. One way of realizing additional building volume in urban locations is vertical densification: the addition of one or more floor levels on top of existing buildings. To maximize the range of buildings that can be extended this way, lightweight building systems that can adapt to a range of geometric and structural conditions are needed.

Shell structures form an exceptionally lightweight structural typology. In addition to being extremely structurally efficient, such structures offer unique spatial possibilities. However, shell structures tend to be difficult to construct and the predominantly used material (reinforced concrete) is relatively heavy and has a large environmental impact. Additionally, the formwork needed to construct concrete shells results in additional construction waste that is often disposed of after a single use.

From the perspective of sustainable construction, wood is an excellent material as it is renewable and acts as carbon storage, thus counteracting global warming. Its low weight-to-strength ratio is advantageous in vertical densification projects, due to limits on the bearing capacity of the foundation or other parts of the existing structure. Various engineered timber plate materials that are suitable for structural applications are available on the market, including plywood, cross laminated timber (CLT) and laminated veneer lumber (LVL). However, wood is not particularly suitable for creating the continuous surfaces needed to create double-curved shell structures.

Shell structures can be geometrically approximated by planar segments. The result is a segmented shell that can be constructed out of timber plates. This structural typology combines the benefits of lightweight construction with the environmental benefits of wood and the spatial quality of shells, and allows for prefabrication, resulting in short on-site construction times. A further advantage is that the structure itself forms an enclosure to the space and can potentially form a finished interior surface, thus reducing the required number of layers in the construction buildup. Downsides are the geometric intricacy of such structures and the difficulty of producing many geometrically unique elements. Therefore, early examples of segmented shells mostly use shapes that feature a limited number of plate shapes, such as semi-regular polyhedra.

As demonstrated by the Forstpavillon in Schwäbisch Gmünd (completed in 2014), computational design and fabrication methods can be employed to realize less regularly shaped structures without incurring excessive costs. The project also convincingly shows the spatial quality that can be achieved by this system. The link between visual appearance, construction principles and structural logic may appeal to architects and engineers alike.

While the construction of this experimental building has yielded valuable insights, a whole array of new questions opens up, including (but not limited to) what spatial conditions can be created, what spans can be realized and which applications timber plate shells can provide economical solutions for, as well as what approaches are most suitable to design plate shells.

1.2 Aim

With the ulterior goal of contributing to a wider application of timber plate shells in the construction sector, the aim of this dissertation is threefold: Firstly, to evaluate the application potential of timber plate shells within the construction sector, in particular for vertical extensions of existing buildings. Secondly, to collect, evaluate and disseminate information about the architectural design of timber plate shells. And thirdly, to contribute to the development of computational design methods for plate shells.

1.3 Scope

The core of this dissertation consists of five chapters, which can be categorized into three main topics.

The first topic (chapters 3 and 4) consists of selecting and evaluating timber plate and joint types for applications in vertical densification. To this purpose, properties such as fabrication costs, environmental impact, air tightness, sound insulation, moisture tightness and fireproofing are evaluated. In-depth investigations in the field of structural engineering are outside of the scope of this dissertation, but a limited analysis is carried out to compare the weight of timber plate shells to more common timber roof structures.

The second topic (Chapter 5) explores and analyses architectural and spatial considerations of plate shells, including structural considerations (such as the effect of segmentation patterns on deformations), spatial typologies, joint details, daylight and integration of ducts and cables. While many of these topics are relevant to any timber plate shell design, they are evaluated in relation to the application of roof structures for vertical densification.

The third topic consists of the analysis and development of geometric design methods for plate shells. After comparing trivalent, tetravalent and hexavalent plate shells and examining the relationship between surface curvature and segmentation patterns, Chapter 6 discusses and evaluates various design methods for trivalent polyhedra. Chapter 7 introduces a novel segmentation method for anticlastic surfaces and a number of design methods for trivalent polyhedra and compares these methods with the methods discussed in Chapter 6.

1.4 Approach and methods

This study uses an exploratory approach and is based on a combination of various research methods. As is typical of any evaluation in the discipline of architecture, the evaluation of the application potential of timber plate shells for vertical densification projects depends on a large range of factors and builds on a variety of sources.

This dissertation approaches the design and fabrication of plate shells in the urban context systematically. Instead of drawing conclusions from a series of case studies, a more general investigation is pursued. Nevertheless, references to particular projects are sometimes made, in particular the BUGA Wood Pavilion. Drawings and photographs of this project are presented in Appendix A.

For background research into timber construction, primary and secondary sources in various forms have been consulted, ranging from scientific articles to product information provided by manufacturers. On the topic of urban densification, the main sources are data sources and reports authored or commissioned by governmental bodies and project-specific publications. The current and future development of the building stock is the backdrop of the research presented in this dissertation, but no claims to novel contributions on this subject are made.

For the topic of light-weight timber construction, primary sources (mostly product information provided by timber manufacturers) and secondary sources have been used.

For topics related to geometry and design approaches, conference and journal articles have been studied. Many of the presented computational methods were re-implemented to get better insight into their practical use. Informal interviews were carried out with various people who have been involved with the design of plate shells, in order to identify which topics merit discussing and investigating.

For the development of specific timber plate types and joint types, no claims of completeness are made. Instead, the aim is to show a range of solutions that are suitable to a variety of application scenarios. Specific properties of these plate and joint types are then analyzed using methods most appropriate for each property. Similarly, where spatial and geometric scenarios are presented, the shown examples are intended to show possibilities rather than aiming to cover all possible configurations.

While some trends may occur globally, the construction sector is highly localized. Wherever building code or local conditions are discussed, the geographical focus is on Europe, with some sections specifically discussing the German context.

In the field of architecture, there is no single method to compare buildings and decide which one is objectively better. Consequently, one cannot and should not expect absolute statements about one construction system being objectively better or worse than another system. However, by providing a systematic overview firstly of relevant properties of various types of plate shells and secondly of computational design approaches, this dissertation aspires to provide insights that are of use to architects who consider designing timber plate shells.

2
Context and current state

This chapter discusses three topics that form the context of this dissertation: building in an urban context, timber construction, and polyhedral plate shell research.

2.1 Building in an urban context

This section discusses the relevance of building in an urban context, as well as characteristics of vertical extension projects, to establish an overview of conditions relevant to the design of timber plate shells.

2.1.1 Relevance of vertical densification and urban infill

Due to ongoing global population growth and trends of urbanization [133], the question of how to increase the amount of housing in cities is currently very relevant. In the German context, cities are expected to keep growing [33] and in 2018, the federal government has formulated the aim of creating 1.5 million new dwellings within four years [137].

Local differences in demographics, economic conditions, planning policy and environmental policy can lead to strong local differences in housing demand. As Tichelmann points out, in large parts of Germany, the share of dwellings that is vacant is so large that there is little reason to increase the number of dwellings. However, even when only looking at areas where there is currently a sufficiently high demand, the number of apartments that could be realized through vertical densification is more than one million [129]. For reference, the total number of dwellings in Germany is currently around 42 million [119].

In addition to diminishing housing shortages, vertical densification can contribute substantially to sustainability goals: vertical densification helps lower the pressure on land and can lead to energy savings [129]. Furthermore, from an urban planning perspective, vertical densification can lead to a larger variety of dwelling types or even to a larger variety in functions within a building.

2.1.2 Relevant properties of construction methods for vertical densification

This section discusses various factors that (depending on the specific project and applicable building code) are relevant for vertical densification projects.

2.1.2.1 Geometric adaptability

Vertical extensions need to relate to the spatial, functional and structural conditions of existing buildings. The extent to which a construction method is able to do this largely defines the range of projects for which such a method is suitable.

2.1.2.2 Weight

Vertical extensions introduce new live loads as well as the self-weight of the structure. To avoid invasive and costly adaptations to the foundations or load-bearing structure of the existing building, the sum of introduced loads should not exceed the available unused structural capacity of the building. Tichelmann [129] provides an estimation of the structural capacity for vertical extensions of buildings built between 1950 and 1989 in Germany, showing that the majority of buildings from this period have the structural potential for at least one additional floor level.

2.1.2.3 Fire safety

Several fire safety factors need to be considered. First of all, the vertical extension needs to be properly connected to escape routes and floors and walls should provide sufficient resistance between fire compartments. Additionally, just as in new construction, façades and roofs may need to be constructed such that fire is contained for a certain amount of time, to prevent fire from spreading towards neighbouring and nearby buildings. Depending on the applicable building code, the addition of an extra floor may also affect the required fire safety measures of the existing building. As Tichelmann points out, many existing buildings in Germany that are higher than 7 meters already fulfil the F90 requirement [129], which means that adding a floor is unlikely to result in having to upgrade the existing structure to higher fire resistance requirements.

2.1.2.4 Integration of installations

Vertical extensions are often used as part of a larger project to improve the energy efficiency of a building. Existing vertical channels such as ventilation ducts may need to be extended, and new channels may need to be added (for example, for heat exchangers). Electric cables, water piping, ventilation channels and sprinkler systems that serve the newly added volume may also need to be integrated. The ability of a construction system to accommodate the integration of such installations is thus a relevant criterion.

2.1.2.5 Site logistics

In densely built urban settings, access to a building site may be limited in multiple ways: there may be only limited space to erect a construction site, access by heavy vehicles may be limited (in time, in size, in weight, or related to environmental properties of the propulsion system), and there may be limits to noise production. On the construction system level, properties such as assembly speed, element size, and element weight are thus significant criteria.

2.1.3 Challenges posed by building code

Apart from technical considerations regarding the construction of vertical extensions to existing buildings, various additional requirements that affect the existing building or its surroundings may need to be met according to building code. For the German situation, Baba et al. [10] mention various potentially challenging requirements, including:

- Additional parking spaces may need to be created.
- The floor area ratio may exceed the limit defined in the zoning plan.
- Building close to neighbouring buildings may require the permission of neighbours.
- By heightening the building, stricter norms may apply to the building as a whole (for example fire resistance, sound insulation, or the need to have an elevator).

While these challenges are very relevant, they equally apply to any construction system and are therefore not further discussed in this dissertation.

2.1.4 Typical spans

The maximum distance that needs to be spanned in vertical densification projects depends on the dimensions of the existing building. The median building depth (from the front façade to the back façade) in multi-story housing projects in urban centres listed in the book Floor Plan Manual Housing [111] (which covers a large number of floor plans of housing projects, mainly in Germany) is 14 meters, with only a few examples having a depth of over 20 meters.

For office buildings, the typical façade-to-façade dimension in Germany ranges from 12 to 14 meters, according to Van Meel [134], with a trend towards larger building depths. Looking at buildings in Stuttgart, larger depths do occur for some buildings, such as the old main station hall (around 24 m) and the architecture faculty at the University of Stuttgart (around 25 m), but spans between 15 and 20 m are more typical for buildings such as offices, university buildings, and hospitals.

Thus, if a structural system can span 15 meters, it will be able to span from façade to façade in the vast majority of residential buildings, whereas a span of 20 meters is enough to span from façade to façade in the majority of commercial buildings.

2.2 Timber construction

This section provides an overview of timber construction systems for floors and roofs, plate-shaped engineered timber products, and jointing methods.

2.2.1 Lightweight timber construction systems

Various construction systems are available in contemporary timber construction, ranging from on-site construction using beams and planks to largely prefabricated room units.

When choosing a construction system, there is a trade-off between on the one hand construction height, and on the other hand material use and weight: by increasing the construction height, material can be used more effectively, and thus less material is required. This trade-off occurs both for the global geometry (demonstrated by the low weight of a shell structure compared to a flat roof) and for the build-up of timber elements or components:

construction systems for roofs range from solid slabs of wood to extremely lightweight hollow slabs.

For lightweight timber floors, vibrations typically are the determining structural factor. As there are no vibration requirements for roofs, the decisive structural factors for dimensioning of a timber roof are deflection and stresses. Therefore roof structures often have a lower weight than floor structures, even when the same loads would need to be carried.

Typically, floor and roof construction systems focus on a single spanning direction; this allows arranging the fibre direction of the wood in the direction that results in the highest structural performance.

To identify applications that are covered by commonly available timber construction systems and applications that might benefit from the development of additional systems, various construction systems are compared in Fig. 2.1, based on product information provided by manufacturers [76; 84; 85; 122; 131; 138]. The span ranges shown in this figure indicate economical spans; technically, each system can cover larger spans when dimensions are increased.

The spans in Fig. 2.1 show that most timber roof construction systems are typically used for spans shorter than around 10 m. However, the Kerto-Ripa system and the Kielsteg system can be applied to spans of well over 20 m, which means these systems can span the typical distances discussed in Section 2.1.4. The only system in this figure that spans in two directions is CLT, but for larger spans this material is rather heavy, which is an important consideration when adding floors to existing buildings.

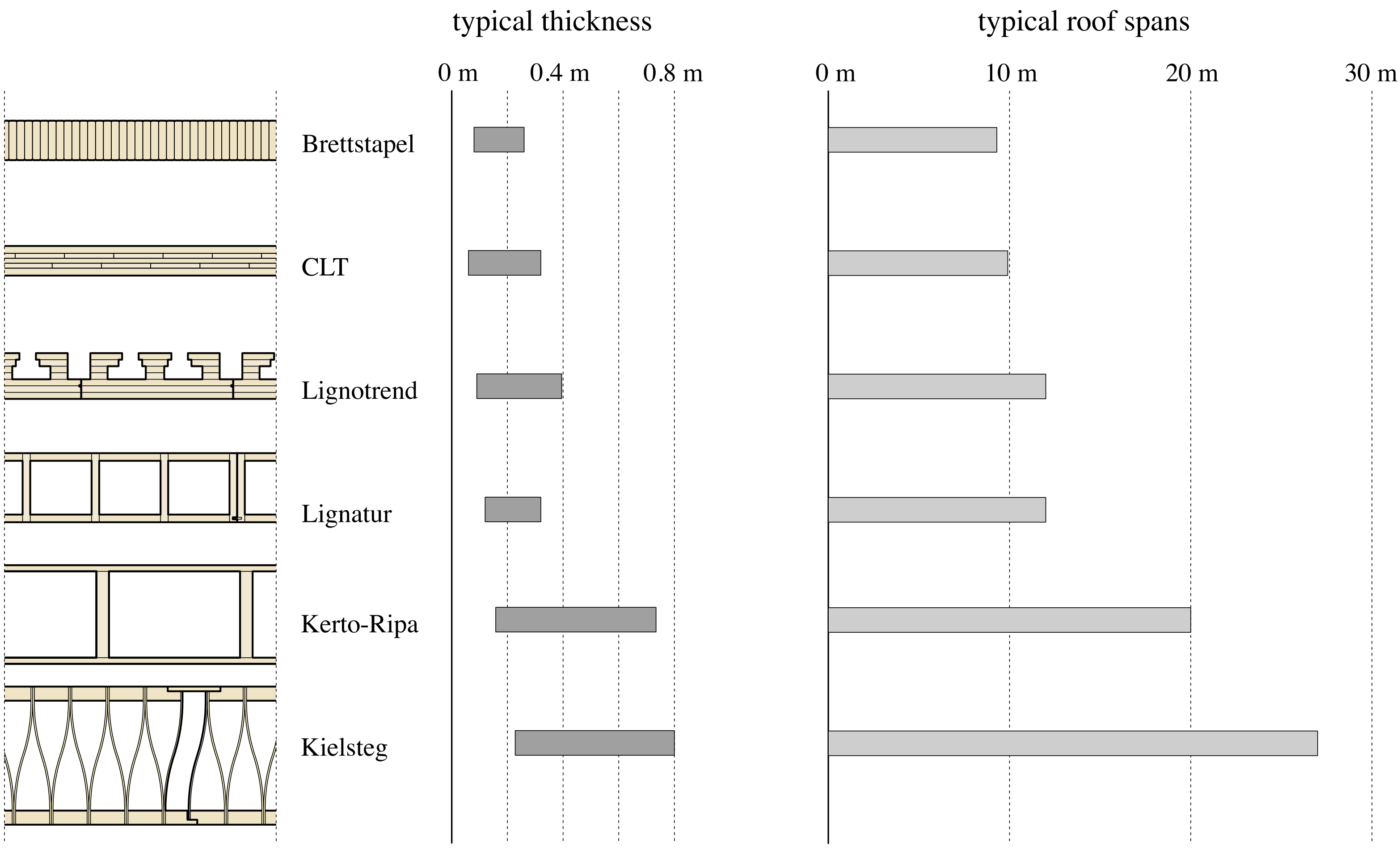

Figure 2.1: Comparison of typical roof spans for various timber construction systems.

2.2.2 Timber plate materials

This section gives an overview of various types of engineered timber plates that are produced commercially. With the exceptions of laminated strand lumber (LSL) and oriented strand board (OSB), all of these products consist of layers of wood, with some of the layers oriented perpendicularly to the other layers. Typically, the fibre directions within these plates are chosen such that the bending stiffness of the plates is higher in one direction than in the other. All listed materials except beech LVL and birch CLT are made of coniferous wood.

For the design of timber plate shells, commercially available dimensions are an important property. Apart from transport limitations, maximum dimensions depend on the fabrication process and may thus vary from manufacturer to manufacturer. Properties of timber plate materials from various manufacturers are shown in Table 2.1.

Product	**Thickness** mm	**Max. width** mm	**Max. length** mm	**Layer thickness** mm	**Density** kg/m³
CLT (KLH)	60 – 500	2 950	16 500	20 – 45	500
CLT (Hasslacher)	60 – 400	3 200	20 000	19 – 45	450 – 500 (coniferous) 600 – 620 (birch)
Three-ply (Dold)	13 – 60	2 500	6 000	4 – 46	480
Five-ply (Dold)	35 – 80	2 500	6 000	8 – 24	480
LVL (Kerto Q, Metsä)	21 – 75	2 500	25 000	3	480 – 510
LVL, beech (Baubuche)	20 – 40	1 820	18 000	3	730 – 800
Birch plywood (Metsä)	4 – 50	2 020	4 110	1.4	680
LSL (TimberStrand)	22 – 102	1 219	4 877		660
OSB	6 – 40	2 620	5 000		600 – 650

Table 2.1: Overview of engineered timber plates, based on product information by producers [41; 57; 58; 59; 70; 92; 93; 118] and Herzog [61]

The thickness of the timber layers within a plate is relevant for the joint design, particularly for screwed connections: depending on their fibre orientation, some layers should not be taken into consideration when determining the strength or stiffness of a connection. When using plates with thin layers, screws will cross many layers, making alignment of the screw direction with the fibre orientation less of a concern.

The structural performance of wood from deciduous trees is generally higher than wood from coniferous trees. This is reflected in the favourable structural properties of timber plate materials such as Baubuche and birch CLT, which can lead to thinner structures. Various other properties (such as ease of machining, char speed, and visual appearance) also largely depend on the wood species.

From the engineered timber plates listed in Table 2.1, the products with the largest dimensions are relatively new: LVL was developed in the 1970s, but was initially mostly used for beams [72]; plates with a width of 2.5 m have only been available since the early 2000s [73]. CLT was developed towards the end of the 20th century, with the first national technical approvals only coming into effect in the late 1990s [148].

2.2.3 Large-span timber structures

This section discusses examples of roof construction systems for large-span timber structures, in order to provide a frame of reference. The examples are categorized following four of the categories used by Engel [44]: Form-active Structure Systems, Vector-active Structure Systems, Bulk-active Structure Systems and Surface-active Structure Systems. Built examples of plate shells are not included in this section, as these are discussed in Section 2.4.

2.2.3.1 Form-active structure systems

2.2.3.1.1 Arched glulam girders

Glulam girders have been developed in the 19^{th} and early 20^{th} centuries [21; 105]. The Reichseisenbahnhalle for the 1910 world fair in Brussels is an early example of a structure in which parallel girders span 43 meters [105]. Arched glulam girders are used for large-span constructions to this day: for example, a number of hangars constructed at EuroAirport Basel-Mulhouse in 2008 and 2010 span around 90 m [65].

2.2.3.1.2 Hanging structures

The Solemar Dürrheim [141] features a roof that has a membrane-like shape and hangs from columns. The main timber elements are curved and are arranged along the main stress lines; secondary timber elements are placed perpendicularly to these elements, resulting in a grid-like configuration. Form-finding was used in the design process to arrive at a structurally efficient shape.

2.2.3.2 Vector-active structure systems

2.2.3.2.1 Trusses

Instead of solid glulam arches, trusses can be used, resulting in lower material use and lower weight, but requiring more connections and a larger height of the structure. An iconic example is the Hamar Olympic Hall in Norway, constructed for the 1994 Winter Olympics [1].

Various utilitarian structures such as warehouses and industrial halls have been constructed using timber trusses in the past decades, including by the German company LIGNA systems. According to this company, glulam girders can be economically used for spans up to 25 m, whereas timber trusses are a more economical choice for larger spans [83].

2.2.3.2.2 Space frames

The US navy constructed a series of blimp hangars during the second world war, some of which are still standing (such as the ones in Tustin and in Tillamook [23]). These hangars are constructed using a series of interconnected trusses, forming a structure similar to a space frame. This construction type is very susceptible to fire, but the realized spans of 90 m were unprecedented at the time, and the interior volume of the remaining hangars is still among the largest of any timber structure in the world.

An example of a true space frame (spanning in two directions) is the gymnasium in Oguni, Japan, spanning 63.5 by 47 m [28].

2.2.3.2.3 Grid shells

A particularly lightweight construction type is the grid shell, as demonstrated by the Multihalle in Mannheim [25], designed by Frei Otto and completed in 1975. Using a four-layer lattice of 50 mm x 50 mm laths that is constructed flat and then pushed into shape, this shell spans 60 m and is a prime example of a form-found structure.

2.2.3.2.4 Triangulated domes

Of all timber structures, the largest spans are achieved by dome structures with a triangulated structure of glulam beams, including venues such as the Tacoma Dome (spanning over 160 m) [60] and Superior Dome (span 163 m) [31], as well as storage halls such as the Brindisi coal storage (143 m) [31] and the Saldome salt storage domes (93 m and 120 m) [66]. When the global shape of such designs is a truncated sphere, all primary beams will have the same radius, allowing relatively efficient fabrication. When a repeating triangulation pattern is used, the number of different metal connectors can be limited, which is critical to minimizing the cost of this construction system.

2.2.3.2.5 Zollinger system

The Zollinger system (developed in the early 20th century) consists of many relatively short elements that form a diamond grid, in which each of the elements starts and ends near the midpoints of neighbouring elements. Typically, the system has been used to construct roofs that are curved in a single direction, with a constant radius. This construction system has been used for residential projects as well as for larger buildings, including the Neubiberg hangar (with a span of around 26 m, constructed in 1934) and the even larger central area of the St. Louis Arena in the late 1920s [116]. In 2003, the Zollinger system was used to construct a hall with a span of 65 m in Rostock [110].

2.2.3.3 Bulk-active structure systems

2.2.3.3.1 Straight glulam girders

Even when not being shaped to optimize force flow, straight glulam girders (with constant or variable height) can be used to span distances of up to 70 m [64], allowing applications for various industrial and commercial spaces as well as sports facilities.

2.2.3.3.2 Slabs

Typical spans of flat roofs constructed out of solid or hollow timber components can be found in Fig. 2.1.

2.2.3.4 Surface-active structure systems

2.2.3.4.1 Folded structures

Structures made out of LVL or CLT in shapes resembling origami have been applied in various projects over the past years, including the chapel of St.-Loup, Switzerland. Like plate shells, folded structures combine structural functions with enclosing space. However, instead of closely approximating a smooth surface, the folds are used to create structural height, in order to create higher bending stiffness [121].

2.3 State of the art of polyhedral plate shell research

This section discusses research on topics related to polyhedral plate shells in the context of architecture, with a focus on trivalent structures. While polyhedra have been studied in the field of geometry for millennia [45] and domes have been built for millennia as well [30], a successful connection between these two domains was only made in the 20th century.

2.3.1 From meridian segmentation to geodesic domes

In historical examples, if domes were constructed from multiple segments, these segments were typically curved and followed meridian curves. [95]. The idea to construct domes by approximating spheres with a triangular grid based on the subdivision of platonic solids (later referred to as geodesic domes) was first used to construct an experimental dome for the Zeiss company in Jena by the engineer Bauersfeld in the 1920s. Compared to structures following meridian curves, such structures are much more material efficient as they act as a shell, with only minimal bending moments occurring [40]. Furthermore, subdividing a sphere in a geodesic pattern has the benefit of requiring only very few different element sizes.

2.3.2 Pavlov's spherical plate shells

In Russia in the 1970s, G.N. Pavlov designed various spherical plate shells, using geometric duality and various triangular subdivision methods that he developed [96; 97]. One structure made of aluminium plates spanning 20 m was constructed as early as 1976; Pavlov states that domes like this and similar ones with spans of

12 and 16 m were produced industrially [95]. Apart from investigating the segmentation of spheres, Pavlov also explored designs that combine multiple spherical shells, including a linear design consisting of spheres featuring a rotated meridian segmentation that are truncated by two parallel planes and the ground plane (see Fig. 2.2).

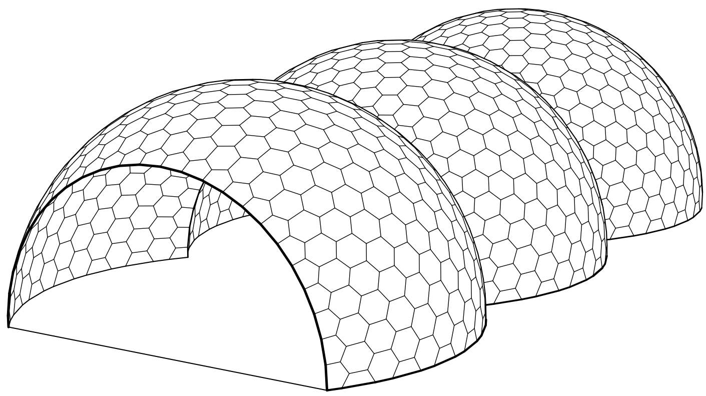

Figure 2.2: Linear arrangement of spherical shells (after Pavlov [96]).

2.3.3 Ture Wester and structural duality

Ture Wester carried out investigations into the use of plate shells (which he refers to as *plate structures*) in architecture in Denmark [142; 146], apparently independently from Pavlov. Wester's publications cover a range of topics, including (but not limited to) structural duality, the use of polar reciprocation (explained below) as a design tool, and observations on plate shells features in the shell of a sea urchin.

In geometry, polar reciprocation is a reversible transformation that turns a shape into a related shape that is referred to as its dual. In the case of polyhedra, the faces of the original correspond to the vertices of the dual, such that the distance from the vertex to a predefined pole point P is equal to the inverse of the distance from P to the plane of the corresponding face in the dual. Geometrically speaking, both shapes are polyhedra, but one can interpret one shape as a triangulated lattice structure (consisting of bars only, without faces) and the other as a plate shell with hinged joints (see Fig. 2.3). A remarkable property of the duals created by polar reciprocation is that if one structure is a structurally rigid lattice, its dual is a structurally rigid plate shell [143; 147], and the shear forces occurring in the joints of a plate shell can be calculated using the normal forces in a lattice structure [143]. This property can be employed to simplify and speed up structural calculations of forces and deformations that occur in plate shells [16; 77; 143; 146].

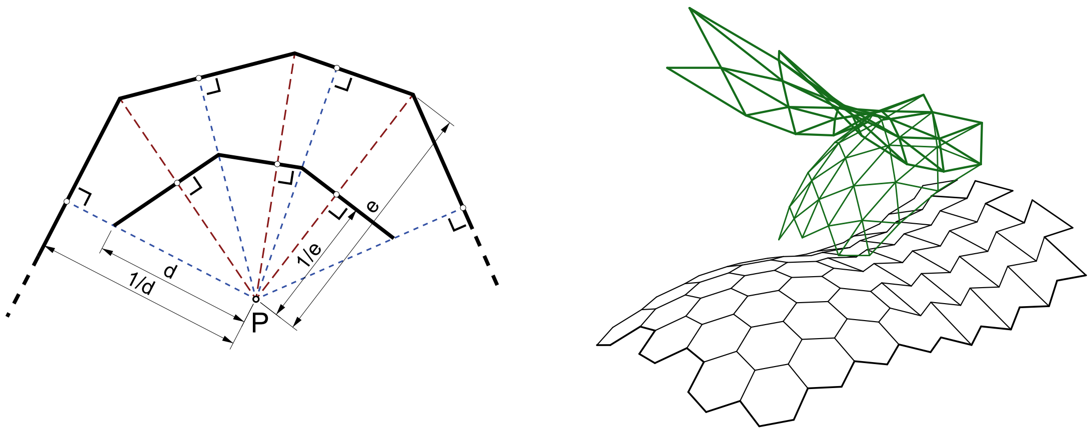

Figure 2.3: A pair of polylines that can be turned into each other using polar reciprocation (left) and a trivalent polyhedral structure that is the dual of a lattice structure (right).

Wester observes that openings in a plate do not compromise structural stability as long as the plate remains sufficiently strong and stiff, as well as rigid in its plane. In a structure designed by Wester and T. Ebert, this possibility is taken to its extreme: the plates are mostly open and are formed by timber edge members of

68×68 mm, stabilized with 19 mm plywood knees in the corners (see Fig. 2.4) [145].

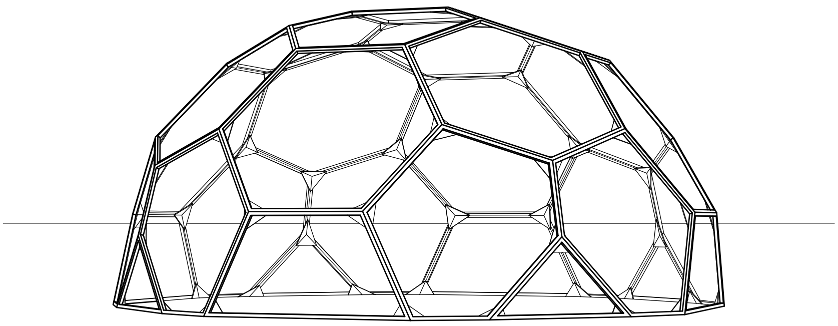

Figure 2.4: Plate shells spanning 12 m, designed by Wester and Ebert (after [142] and [145]).

2.3.4 Significance of computation

Both Wester and Pavlov discuss the vital role of computer software in the design and realization of plate shells. Pavlov notes that the highly labour-intensive task of calculating coordinates for spherical grids can be carried out more effectively using computers [95] and even includes source code in one of his publications [95].

Wester developed a program called CADual that can construct dual shapes out of given input shapes, and can analyze their structural efficiency [143; 145]. Using this program, geometry can be generated and studied much more rapidly than would be possible when manually constructing dual geometry. However, details of the program's exact functionality and user interface have unfortunately not been published. Most polyhedral shapes that Wester shows (presumably generated with the CADual program) are variations on – or modifications of – regular segmentation of spheres.

2.3.5 Analysis, export and import

Any 3D modelling software can generate data regarding geometric properties such as the surface area, edge length, and volume of three-dimensional objects. Modelling software with a programming interface allows the creation of custom scripts that export relevant data in file formats used by fabrication machinery (including but not limited to industrial robots) or analysis software (for example the FEM software Sofistik).

Whether this direct output is beneficial depends on the complexity of the project and the software tools used; for simple fabrication processes, the required information could also be exported as a simple geometric model. For complex fabrication processes, direct export of machine code can lead to substantial labour savings, as files do not need to be processed between the moment they are exported by the designer and the moment the fabrication process is executed. However, this requires the person responsible for the data export to have detailed knowledge of the used fabrication processes, which cannot be assumed to always be the case.

For the BUGA Wood Pavilion [7], life cycle analysis (LCA) and life cycle costing data were integrated into the computational model, so that the impact of design choices on these criteria can be evaluated efficiently. In the model, the material thicknesses of all building parts can be defined individually, and all screw and bolt positions are defined. This information was used for LCA as well as structural analysis [75].

2.3.6 Structural properties of joints in polyhedral plate shells

Polyhedral plate shells have the benefit that forces can be transferred from plate to plate using predominantly shear and compression. Therefore, when the geometry is structurally rigid (which normally is the case for trivalent plate shells), no bending stiffness is needed to reach stability [143], and joints between plates only need to transfer shear forces, out-of-plane shear forces, tension and compression. However, bending stiffness can still strongly contribute to the stiffness of plate shells, in particular when shear stiffness or out-of-plane shear stiffness is low [19].

Research by Li shows that the orientation of joints has a large impact on the resulting forces [80], which suggests that there is significant variation in structural performance between different segmentation designs that approximate the same global geometry. Potentially, joint patterns could be adjusted to concentrate forces on the available support points, or to distribute the forces evenly.

As timber plate shells may consist of a large number of plates, many small deformations in the joints can lead to a large total deformation [81]. Furthermore, combinations of initial deformations in different directions (along the edge, perpendicular to the edge and out of plane) can lead to global deformations that are larger than the global deformation that would result from initial deformations in each individual direction [19]. When combining various connection types (such as finger joints and screws), tolerances need to be carefully considered, as otherwise one of the connection types might only become active after significant deformation has already taken place [81].

2.3.7 Materialization

This section discusses various materials that have been used for the construction of plate shells built over the past decades.

2.3.7.1 Metal

Pavlov designed segmented shell structures in various materials. One solution he shows is using planar sheets of aluminium, with the edges bent upwards so that neighbouring plates can be connected (see Fig. 2.5). The plates are then filled with thermally insulating material and covered with a waterproofing layer [95].

A more recent example of a metal plate shell is the Spaceplates system by Romme, Sørvin and Bagger [103]. The Solar Egg in Kiruna is constructed out of metal plates as well [86].

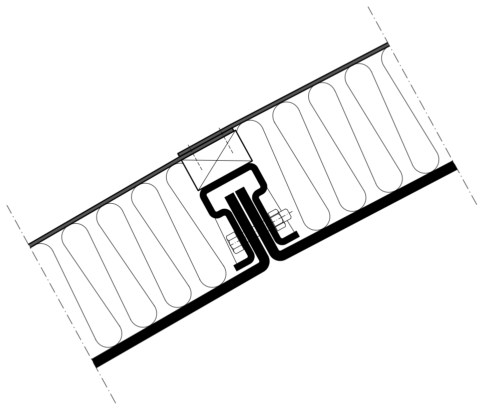

Figure 2.5: Aluminium plate connection detail, after Pavlov [95]

2.3.7.2 Fibreglass plastic

Pavlov describes the use of 5 mm thin fibreglass-reinforced plastic sheets to construct a dome spanning 15 m in Kirov. The joints are not sealed; instead, the plates overlap to achieve waterproofing [95; 97].

2.3.7.3 Wood

Wester shows a realized plate shell made out of wood frames [145], presumably fixed with metal fasteners. Almegaard presents a prototype made out of 19 mm plywood, connected with 4 mm thick aluminium strips that are bent to match the angle between the plates [4]. The Forstpavillon in Schwäbisch Gmünd (developed by the ICD and ITKE at the University of Stuttgart) is made from beech LVL plates, connected using finger joints in combination with crossing screws [81]. CLT has been used in a project by SPINN Arkitekter [8] as well as a project by Robeller and Viezens [102].

2.3.7.4 Glass

Ture Wester discussed the idea of covering wood frames with glass in such a way that the glass and wood work together structurally, and also suggested that a structure made purely out of glass could be realized [145]. Anne Bagger investigated plate shells made of laminated glass and discusses various joint details, including glued connections and friction connections. A design with glued-in aluminium strips is stated to be the most favourable joint type [12].

2.3.7.5 Ceramics

Wester contributed to a relatively small project consisting of ceramic tiles held together with mortar [145].

2.3.7.6 Acrylic, polypropylene, and polycarbonate

Whereas later versions of the Spaceplates system (see Section 2.3.7.1)) are created out of metal, a prototype has been constructed out of acrylic sheet plates, bent at the edges so they can be bolted together [103].

Multiple small transparent or translucent segmented shells exist, using hexagonal and pentagonal plates. The PolyShell project is a small polypropylene shell designed by the Danish firm Søren Jensen. In this project, edges are folded twice and connected with plastic rivets, forming hollow elements. Rivets are also used for connections between elements [15].

Other small shells have been constructed out of polycarbonate, including VikingDome's Aura Dome [136].

2.3.7.7 Polystyrene

While not technically a plate shell, the Hyperbody Protospace 4.0 at TU Delft shows that expanded polystyrene foam with wooden edge inlays can be used to construct segmented shell structures, although the pavilion itself only carries self-weight [135].

2.3.7.8 Stone

Even though it is not a polyhedral plate shell itself, the Armadillo vault by the Block Research Group [20] demonstrates that unique stone elements can be efficiently produced using digital design and fabrication methods, which suggests that stone could be used for plate shells as well.

2.3.8 Plate shell design methods

Various ways to design plate shells have been developed over the past decades, ranging from mathematically constructed approximated spheres to interactive agent-based segmentation of irregular base surfaces. There are large differences between these methods regarding the kind of geometric input that they start from, the kind of designs they are suitable for, and the design freedom they provide. An evaluation of the methods can be found in Section 6.5.

2.3.8.1 Mathematically constructed arrangements

As shown by Pavlov, there are various ways to create regular spherical plate shells, including subdividing Schwarz triangles (resulting in the plate shell equivalent of geodesic domes) or by using the intersections of meridians and rings on a sphere [96]. While computers were used to calculate coordinates, the required computation power was small enough to be already practical in the 1970s. However, the design freedom is limited to the use of spheres and spheroids.

2.3.8.2 Polar reciprocation

The use of geometric duals generated by polar reciprocation to generate plate shells is another method that can be carried out with relatively limited computational power, as no surface evaluation is needed. Instead, segment planes are defined by the vector from an input point to the pole.

Ture Wester shows a particularly effective application of a variation of this method in the Pentagonia sculpture [146]. The geometry of this sculpture can be generated by creating a triangle grid that starts from a subdivided pentagon, constructing planes at each point on the triangle grid using the vector from the pole to the point as the normal direction, then intersecting the resulting planes using the original triangle grid as connectivity graph (see Fig. 2.6). This example shows that the link between input geometry and the resulting polyhedral shape may not initially be intuitive, but a usable result can be created with very little input geometry and comparatively little computation.

In addition to generating polyhedral geometry, Wester also demonstrates a way of using polar reciprocation to modify plate shell designs by applying polar reciprocation in relation to a certain pole, then defining another pole for the reverse operation [146].

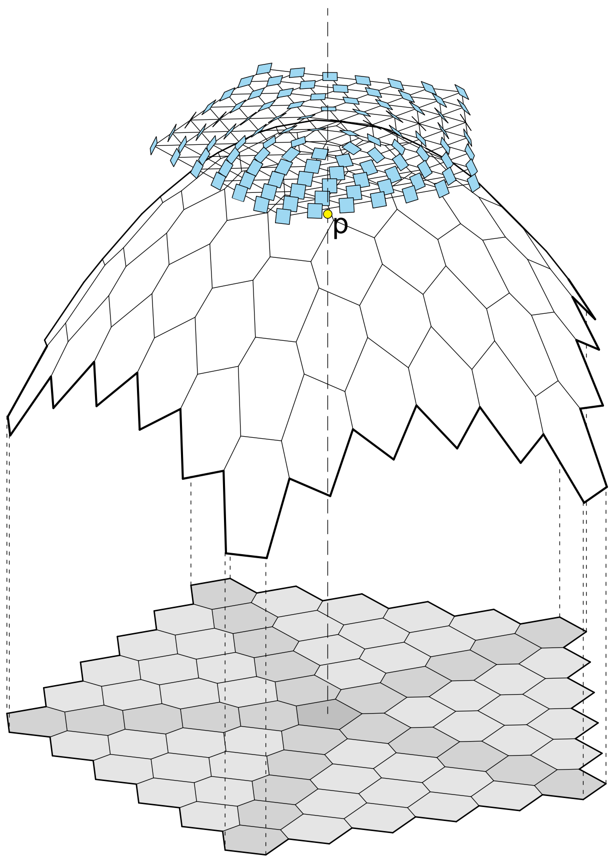

Figure 2.6: Construction of Wester's Patagonia sculpture, using a 2D triangle grid and a pole (p) as input. The projection of the structure on the horizontal plane is shown at the bottom.

2.3.8.3 Reciprocal form diagrams

In the 19th century, Maxwell showed that force diagrams (such as are used in graphic statics) and two-dimensional projections of a polyhedron are geometrically linked: when the force diagram of a two-dimensional form diagram shows that the form diagram is in equilibrium, then the form diagram is identical to a two-dimensional projection of a polyhedron [89]. Hartz et al. [56] illustrate how this property can be used to design polyhedral shapes: by first drawing a two-dimensional net that is not in equilibrium, then finding equilibrium using the force density method [107] and finally reconstructing a polyhedral shape using linear equations.

2.3.8.4 Tangent plane intersection

Whereas Wester mathematically constructs segments by intersection planes, resulting in a polyhedron that seems to approximate a surface, Troche shows an approach that starts with a surface, on which positions are selected for the generation of tangent planes that are then intersected to create a polyhedron [130]. This Tangent Plane Intersection (TPI) method has the advantage that the input geometry and the resulting polyhedron are similar in shape.

Naturally, the curvature of the input surface strongly influences the resulting output; this topic is investigated in-depth in Section 6.2. However, as discussed by Troche, picking points where tangent planes are to be generated is a critical step as well. Finally, after generating the tangent planes, the neighbouring tangent planes need to be identified. The difficulty of this process strongly depends on the curvature conditions and tangent plane positions and is discussed in the next section.

2.3.8.5 Intersection methods

When creating segmentations by intersecting tangent planes, the step of defining the connectivity between plates can be carried out in various ways: connectivity information can be generated based on geometric features (such as proximity) after having defined planes, it can be generated during the intersection process (intersecting planes one by one), or tangent planes and connectivity can be created together in a grid-like pattern (optionally adjusted to local curvature). A visual representation of plane connectivity can be created by drawing lines between plane origins (or points representing these plane origins, for example in UV space instead of Cartesian space) of segments that share an edge; such a graph will be referred to as a *connectivity graph*.

Troche discusses using Delaunay triangulations to define adjacency but notes that invalid intersections (self-intersection and interpenetration) may occur (see Fig. 2.7), for which a consecutive reparation step needs to be carried out [130]. While the reparation step shown by Troche is relatively straightforward as it only involves a single edge swap, other situations may involve multiple interrelated connectivity errors; to resolve such errors, a much more sophisticated method would need to be developed. Troche mentions the particular difficulty of areas with highly anisotropic curvature.

Instead of using Delaunay diagrams using tangent plane origins, a Delaunay diagram can also be created from UV coordinates [88; 120]. This can be effective when the UV directions are aligned to the principal curvature direction, but invalid segments can occur even under such conditions.

Manahl et al. introduce another connectivity method that uses Delaunay triangulation, after first moving the origins of potentially adjacent planes by distances based on surface curvature (in such a way that local curvature becomes isotropic) and additionally using intersections with osculating paraboloids to compensate for local curvature variations. This method (as presented in [88]) only works for synclastic surfaces, but leads to valid segmentation results for a vastly larger range of sets of planes than using Delaunay triangulations in UV or Cartesian space.

Hansen describes an iterative intersection method for a subset of synclastic surfaces that produces robust results: from an initial bounding box, the tangent planes slice off part of the geometry one by one [54]. This incremental slicing method (also used in [52]) works very reliably when for any plane, all remaining plane origins are on the same side of the plane, as is often the case for synclastic surfaces.

Fig. 2.7 shows a comparison of tangent plane intersection methods for synclastic surfaces. The top row shows a surface featuring near-isotropic curvature; all methods lead to the correct result for the given set of tangent planes. The middle row shows a surface for which Cartesian and UV-based Delaunay connectivity graphs lead to some invalid intersections (which can easily be resolved, as discussed by Troche [130]), while the method by Manahl et al. and the slicing method each lead to the correct result. The bottom row shows an example of TPI with a UV-based connectivity graph leading to a better result than the TPI solution based on a Cartesian Delaunay connectivity graph. The examples show that the validity of a solution depends on the combination of base surface geometry, plane placement, and the intersection method.

For anticlastic surfaces, Hansen [54] discusses a method that first creates strip-like geometry from the tangent planes at points on curvature lines, then uses this geometry to cut away parts from an initial volume.

When tangent plane locations are defined in a controlled way on a grid that is adjusted to surface curvature (for example by using curves that follow principal curvature), this grid itself can be used as a connectivity graph. Such ways to define tangent plane locations are discussed in the next section.

2.3.8.6 Structured tangent plane placement

The placement of tangent planes is an important step in the TPI process, as the validity of segmentation patterns based on a base

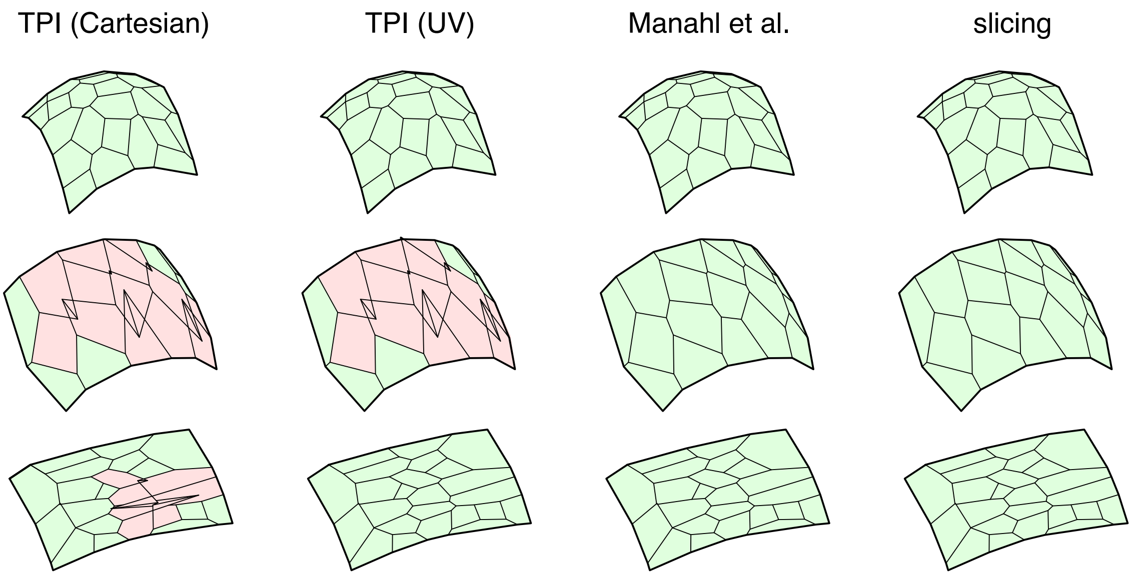

Figure 2.7: Comparison of segmentations generated using plate intersection methods based on Delaunay triangulation in Cartesian space, Delaunay triangulation in UV space, Manahl's method and incremental slicing.

surface depends on the combination of the base surface, tangent plane placement, and the plane intersection method.

Troche describes a method in which tangent plane positions are created row by row, following curvature lines, with variable spacing along the curvature lines [130]. The idea of using curvature lines has also been proposed by Almegaard [5], who demonstrates the use of a grid based on asymptotic lines for plane placement. Wang et al. [139] present a method that is also based on curvature lines, but uses the Dupin indicatrix (which is related to curvature anisotropy) to define spacing, resulting in very fair looking segments, although Li et al. [82] discuss some limitations of this method near umbilical regions and near parabolic lines.

Li et al. [82] present a method that generates a suitable conjugate curve network from a principal direction field. They also introduce an elegant method to limit changes in plate size near umbilical regions by introducing three pentagons and moving these away from the umbilical point, as well as a method to modify the segmentation in order to create more regular transitions around parabolic lines.

Pluta et al. [99] present a method that is conceptually similar to Li's method. The method constructs a triangulation based on a design surface (either a NURBS surface or a mesh), generates non-planar polygons based on this triangulation (predominantly hexagons) and then planarizes the polygonal segments. The spacing and orientation of the triangulation are based on principal curvature directions. The method works well at principal curvature direction transitions and based on the presented examples, it appears to allow a larger variety of input shapes than Li's method.

2.3.8.7 Agent-based tangent plane placement

Baharlou and Menges [14] propose an agent-based method for the placement of tangent planes that is conceptually similar to Reynold's flocking system [101]. In Baharlou's implementation, each agent moves on a surface and interacts with other agents according to rules set by the designer. Among others, such rules can be aimed at meeting fabrication criteria (such as minimum or maximum angles between segments) or material constraints (in particular stock material dimensions) [14].

This idea has been used in various projects developed at the University of Stuttgart, including the Forstpavillon in Schwäbisch Gmünd [74; 115] and the BUGA Wood Pavilion in Heilbronn [7].

2.3.8.8 Plane offset and rotation

In addition to the placement of tangent planes, rotation or offset can be used to control segmentation. Rotation is used by Baharlou

[14], whereas examples of segmentations using offset planes (see Fig. 2.8) are shown by Bagger [12].

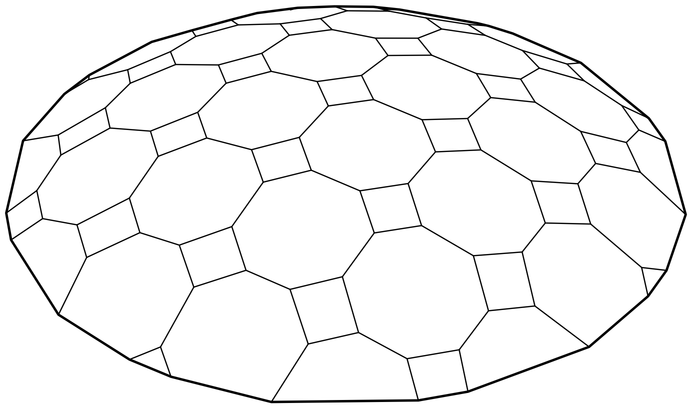

Figure 2.8: A segmentation pattern in which the four-sided plates have been moved in their normal direction (after Bagger [12]).

Zimmer et al. use degrees of freedom in position and rotation in an optimization framework using a variational formulation of TPI, which they coin VTPI. This method can be used to improve a plate shell on any geometric metric; Zimmer uses the examples of normal smoothness and position in relation to vertex neighbours [151].

2.3.8.9 Point clustering

Cohen-Steiner, Alliez and Desbrun introduce a method in which many points (generated on a mesh or a surface, but presumably a point cloud from a 3d scan would also work) are clustered using a clustering algorithm, after which each cluster is approximated by a triangle or a non-planar polygon [29]. Cutler and Whiting developed a method in which the polygons are guaranteed to be planar, by fitting planes through the clusters and then intersecting these planes. However, the way this method defines connectivity is not robust, so some manual adjustment of the geometry is often needed [32]. Even though the amount of control a designer has over the output is limited, the method's potential as a design tool has been demonstrated by Ramboll's TRADA pavilion [55].

2.3.8.10 Planarization of non-planar segmentations

The process of planarizing segments in an initial shape containing non-planar segments is an active field of research in computer graphics. Simple geometric methods exist (such as iteratively approximating the planes of all segments and moving points towards the intersection points of these approximated planes), but solutions in which the resulting segments are closer to their original shape have been developed using non-linear solvers [22; 100; 151]. The Kangaroo solver [98] is also capable of planarizing initially non-planar segments. Examples of the output of several planarization methods are shown in Fig. 2.9.

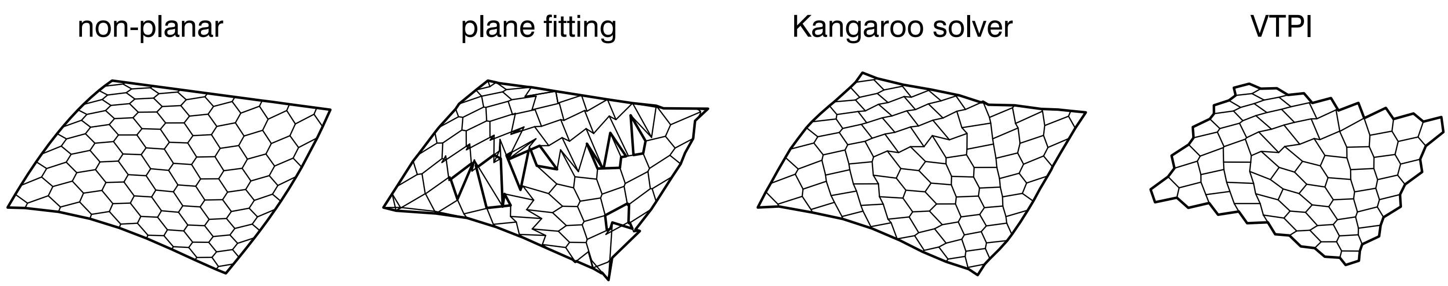

Figure 2.9: Comparison of planarization methods of a non-planar segmentation (left): using iterative movement of points to fitted planes (middle left), using the Kangaroo solver with planarity constraints (middle right), and using variational tangent plane intersection (right).

2.4 Examples of built plate shells

This section provides an overview of built examples of plate shells. The aim is not to present a complete catalogue, but rather to indicate what kind of plate shells have been constructed over the

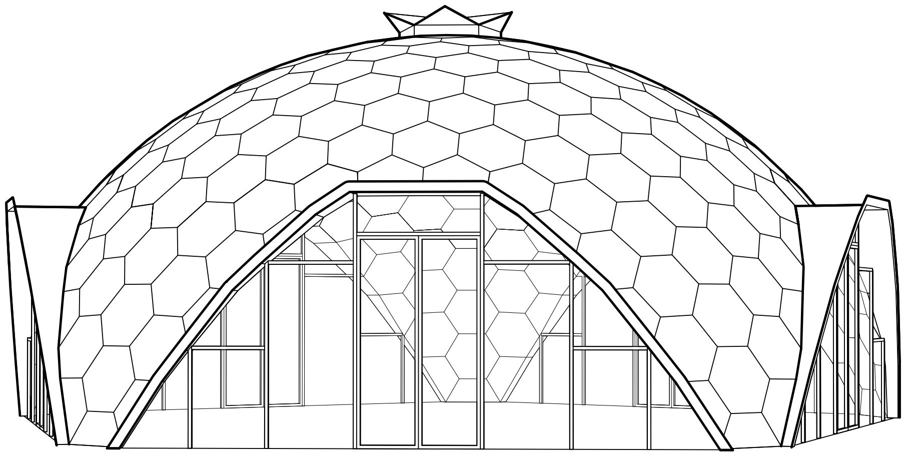

Figure 2.10: A plate shell designed by Pavlov, constructed from steel plates.

past decades. A differentiation is made between open pavilions and experimental structures, small-scale enclosed structures, and buildings.

2.4.1 Geodesic domes

Many early examples of built plate shells can be considered geodesic domes in the loose definition of the term: they feature a strong geometric regularity and approximate a sphere. This includes various structures designed by Pavlov in the 1970s, such as café Sever in Gorky, café Olimpiya in Krasnodar (see Fig. 2.10) and multiple shells in Baku [95; 126], and Wester's 1981 Y-dome [142; 144].

From 1992 onwards, the Easy Domes company has been creating building kits for geodesic timber domes (or more precisely truncated icosahedra), which can be bolted together on-site. As of 2019, eight realized projects are listed on the company website [43]. Another company constructing timber buildings in a truncated icosahedron shape is Hexadomos in Chile [62]. In 2009, Marc Newsom constructed a truncated icosahedron from Kerto

LVL as a small exhibition pavilion [128]. In 2011, Shinsaku Munemoto & Associates constructed another project in the shape of a truncated icosahedron, functioning as an assembly house. Whereas Easy Domes reinforces the plates with bars placed in an orthogonal arrangement in addition to the bars reinforcing the edges (which are covered afterwards), the project by Munemoto features a more intricate stiffening bar arrangement that remains visible [9]. Grid.bg constructed a steel geodesic dome in 2018 [51].

Some domes that are built to protect radar installations (also called radomes) are constructed as plate shells, including examples in Teufelsberg and Titterstone Clee Hill.

The Spaceplates prototype (2011) and the Spaceplates structure in Bristol (2012) feature plates that are radially arranged on spheroids [103].

The Aura Dome by Viking Dome is a commercially available transparent geodesic dome that can be ordered in diameters ranging from 3.6 to 8 meters [136].

2.4.2 Pavilions, small buildings, and experimental structures

Several small projects are non-spherical yet feature plates that are regularly shaped when projected on a horizontal plane. For instance, the projections of Madsen, Rudjord and Wester's ceramic Pentagonia sculpture's plates form just three different shapes [146]. Projected in the same way, Almegaard's plywood pavilion consists of plates that form perfect hexagons on the ground plane [4].

The 2010s saw a surge of projects with irregular geometry: projects that are not spherical, contain many different plate shapes, and do not show regular patterns when projected on a plane. This includes the Kobra am Campus project in Graz [149], the shell constructed as part of the RobArch 2012 workshop by ICD Stuttgart ([13], pp. 139–141), the Ramboll Trada Pavilion (2012) [55], Søren Jensen's Polyshell (2015) [15], Studio RAP's Skilledin Office (2015) [125], the SFB timber shell by ICD and ITKE (2017) [114], the Solar Egg in Kiruna by Bigert & Bergström (2017, made out of steel) [86], the X-Fix Timberdome in Kaiserslautern (2018) [102], and the BUGA Wood Pavilion (2019) [7]. In all of these projects, digital design tools and digitally controlled fabrication played a vital role.

Figure 2.11: The Forstpavillon in Schwäbisch Gmünd. Image source: ICD/ITKE, University of Stuttgart

2.4.3 Buildings

Only very few plate shells exist that are actual buildings (which in this context is defined as enclosing space, having thermal insulation and being watertight) but don't use geodesic geometry. Steve Baer's own home and his proposed Zome system may be the first examples [11].

Of the buildings built using computational tools and digitally controlled fabrication, the earliest and largest so far is the Forstpavillon, Schwäbisch Gmünd (2014) (Fig. 2.11) [74], constructed out of beech LVL. The Hammerfest Cabins by SPINN architects with Format engineers (2018/2019) are a more recent example, made of CLT [8].

3

Plate and joint types

This chapter discusses various ways to construct and connect timber plates. Based on relevant criteria for vertical densification projects (such as weight, structural height and on-site assembly speed and complexity), two plate types with distinct joint types will be selected for further evaluation on a range of criteria in Chapter 4.

3.1 Plate types

Timber plates can either be constructed out of a single slab of material or built as components consisting of multiple parts. In the latter case, material can be placed where it is needed most: because of the importance of force transfer through the edges, it makes sense to reinforce these. The material in the middle of the plate is less important structurally: while forces can be transmitted most efficiently when a plate does not contain openings in the plate, structurally stable structures can be created even when plates feature large openings (Fig. 2.4) [146]. Additionally, as long

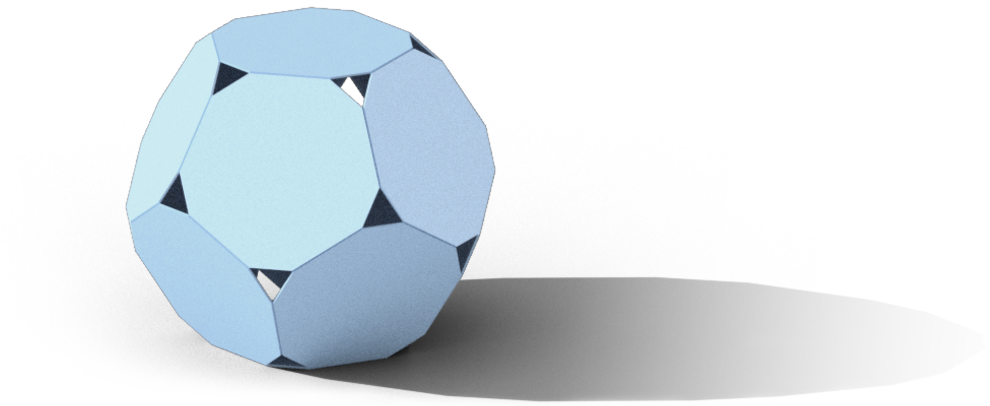

Figure 3.1: A structurally stable dodecahedron-shaped plate shell with open corners (after Wester [146]).

as a plate's edges are connected, corners are also not critically important for structural stability (Fig. 3.1) [146].

3.1.1 Solid plates

The most simple timber plate type consists of a single layer of material (Fig 3.2, left). Solid beech plywood plates have been used in the Forstpavillon in Schwäbisch Gmünd [74], but other timber plate materials could be used as well, for example LVL, oriented strand board (OSB), medium density fibreboard (MDF) or CLT (see Table 2.1).

3.1.2 Edge-reinforced plates

Increasing the thickness of a plate's edges increases the stiffness of a plate and provides more space for joint connections (Fig. 3.2, center). As structural properties of joints are an important criterion for material dimensioning, increasing the edge thickness by gluing wooden slats to the edges of a plate allows the use of thinner material for the plate itself, leading to lower weight.

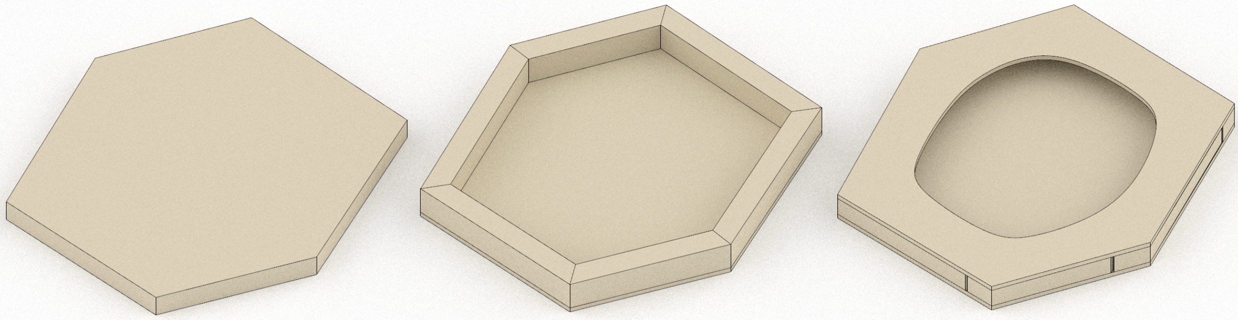

Figure 3.2: Example of a solid plate (left), an edge reinforced plate (middle), and a hollow component (right). The plates are pictured with the bottom side up.

3.1.3 Hollow components

By gluing wooden edge bars on a plate and gluing a second plate on top, hollow components can be created (Fig. 3.2, right). For the BUGA Wood Pavilion, such hollow components were used [7]. Compared to edge-reinforced plates, this solution has the structural benefit that forces in edge elements can be transferred more efficiently, and bending moments can be counteracted by the combination of the top and bottom plates. By creating one or more openings in one of the plates, the edge elements can be accessed from the inside of the component, allowing components to be connected on-site.

3.2 Joint design

Joints between plates need to fulfil multiple criteria, such as stiffness in various directions (compression, tension, in-plane shear, out-of-plane shear, and bending), limited initial deformation, air and moisture tightness, manufacturing speed and complexity, assembly speed and complexity, potential for disassembly, environ-

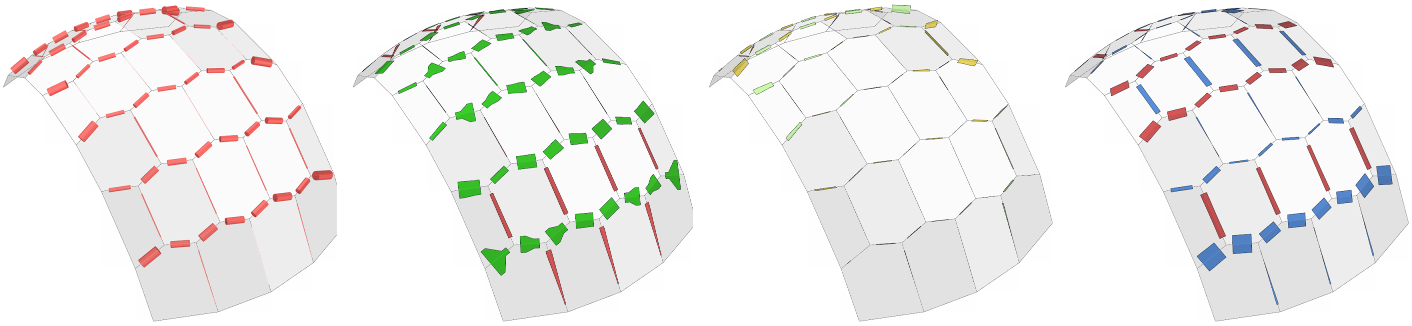

Figure 3.3: Visualization of joint forces of a plate shell under vertical load, showing that the strength and kind of force vary from area to area on a plate shell. From left to right: shear forces, tensile and compression forces, out-of-plane shear forces, and bending moments.

mental impact, cost and aesthetics. As the structural conditions at various joints in a plate shell can vary significantly (see Fig. 3.3) and creating joints is a time and cost-intensive operation, it may be economical to adapt joints to local conditions.

3.2.1 Force directions

The dominant forces to be transferred between plates in a pure plate shell are shear forces in the direction of the joint. However, in practice normal forces and out-of-plane shear forces occur as well. Furthermore, introducing bending stiffness around an edge's axis can significantly limit deformations [19]. So in total, at each joint, there are three translation directions and one rotation direction to take into account.

3.2.2 Assembly directions

Given the structural requirement to limit translations in three orthogonal directions and the necessity to have at least one free insertion direction for assembly, it is necessary to lock at least one direction after a plate has been put into place. This can be done

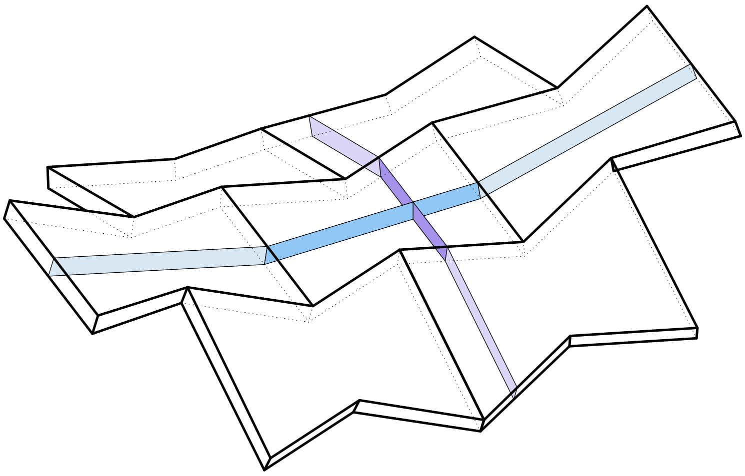

Figure 3.4: Sections through an anticlastic plate shell. Due to the joints tilting in different directions for the two sections, a plate in an anticlastic plate shell cannot be inserted when all its neighbours are already in place, unless the joint orientation of some joints is adjusted.

using connectors such as screws, bolts or plugs. In principle, it should also be possible to geometrically lock the insertion direction using neighbouring plates that are placed afterwards, but this would require intricate geometry and a predefined assembly order.

When using finger joints in synclastic plate shells, plates can be inserted in any order, provided that no parts of the joint geometry overlap (such as is the case in lap joints) and no external objects block the insertion direction. On anticlastic surfaces, this is not even the case when using butt joints, as the tilt direction of joints varies between the principal curvature directions (Fig. 3.4). Therefore, on anticlastic surfaces, the assembly order needs to be carefully considered. Similar conditions occur where two synclastic shells come together in a kink.

Possible assembly directions can be visualized as a visibility map [27], which is the area of a sphere that indicates from which directions a part can be inserted into an assembly. On a unit sphere,

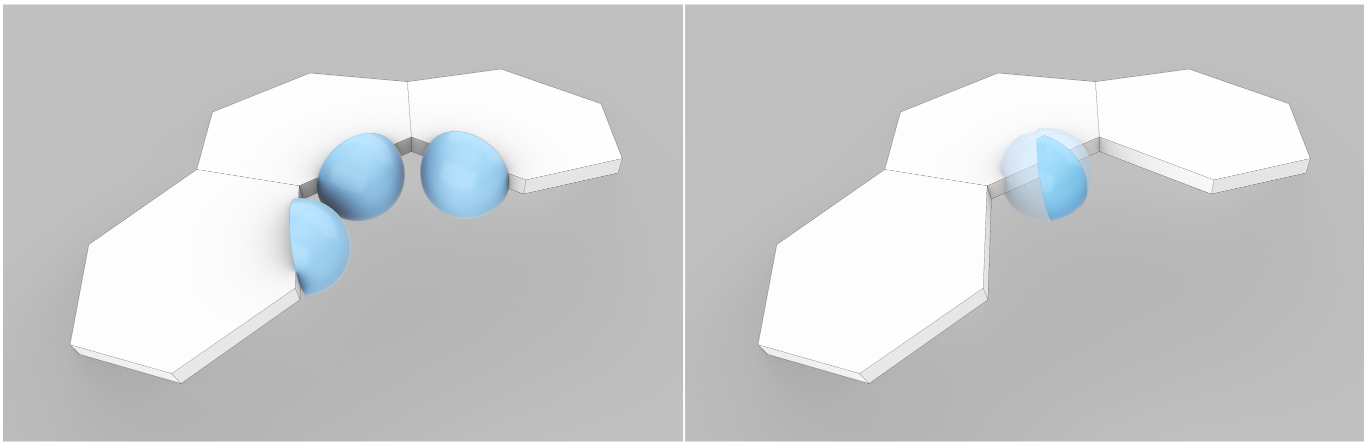

Figure 3.5: Possible insertion directions for a plate, visualized using sphere segments: for each butt joint, a plate can be inserted from any of the directions visualized by the sphere segments (left). The resulting potential assembly directions are marked by the area where all three segments overlap (right).

the normals of joint surfaces of plates that have already been placed can be used to define hemispheres that indicate insertion directions that are not blocked. The area of the sphere shared by all hemispheres (if any) shows the possible assembly directions (Fig. 3.5).

Geometric joint features such as finger joints strongly limit the range of possible assembly directions: all surfaces of the joint geometry should be taken into account when assessing possible assembly directions. Whether the combination of the global geometry and the finger joint design leads to a solution that can be assembled can be assessed using the visualization method described above, as illustrated in Fig. 3.6 (left).

In anticlastic regions or at kinks between surfaces, it can happen that finger joints make assembly geometrically impossible, regardless of the assembly order. This situation can be resolved by rotating some of the joint planes. Fig. 3.6 (right) shows an example of such a solution, in which finger joints are rotated a couple of degrees within the edge plane. Logically, such joint

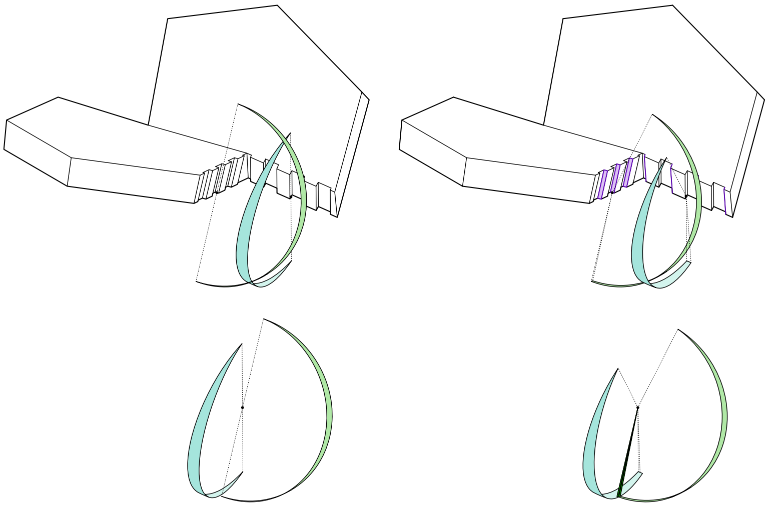

Figure 3.6: Possible insertion angles for two edges with finger joints, visualized per joint (top) and combined on a unit sphere (bottom). As the sphere segments do not overlap, it is impossible to place a plate here with unmodified joint geometry (left). This situation can be resolved by rotating the marked surfaces (right).

geometry adjustments can only be made after an assembly order has been established.

On anticlastic surfaces, the use of tightly fitting finger joints is practically impossible without modifications to finger joint geometry, as the main joint surfaces of three neighbouring plates preclude insertion from above or below, and the finger joints prevent insertion of the plate within the plate plane. For the Forstpavillon project, the structure was designed with gaps of 1 mm between the plates, which made assembly possible, but at the cost of decreased joint stiffness [81].

3.2.3 Precision and tolerances

Joint fabrication precision impacts not only the ease of assembly, but also structural performance (see Section 4.2) and fire resistance (see Section 4.8).

Apart from absolute tolerances in plate geometry, final joint tolerances also depend on the on-site assembly process, particularly on whether the connection mechanism pulls the plates together. This is the case when using bolts or partially threaded screws, but not when using fully threaded screws. Therefore, before inserting fully threaded screws, plates either need to be held tightly together using some external means or need to be connected using other connectors first, for example, partially threaded screws. In the latter case, screw connectors such as KNAPP T-Joint [71] could be used to prevent the screw head from being pulled into the material.

3.3 Joint types

This section describes a range of joint connection methods. In an actual joint, multiple methods may need to be combined. The list is not intended to be exhaustive, but covers all principles used in the projects discussed in Section 2.4.

3.3.1 Geometric connections: finger joints and dovetail joints

Finger joints are geometric joints with high in-plane shear stiffness, but negligible stiffness in other directions. Straight finger joints strongly limit possible assembly directions, but this can be ameliorated by using a slightly tapered shape instead (shown in Fig. 3.7, left).

A related joint is the dovetail joint (Fig. 3.7, right), which in addition to in-plane shear stiffness also provides tension and compression stiffness, as well as some bending stiffness. The exact geometry for this type of joint can only be generated after defining an assembly order, because planes on the joint need to be tilted to create a valid insertion direction (see Section 3.2.2).

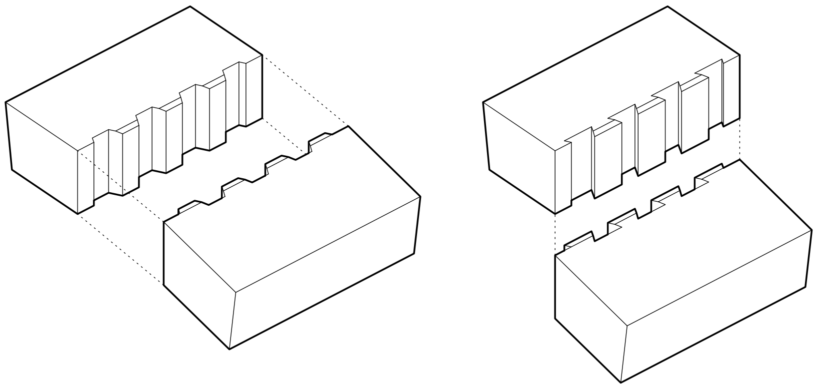

Figure 3.7: A finger joint (left) and a dovetail joint (right).

For geometric connections, high fabrication precision is required to ensure a tight fit, which is a prerequisite for high structural performance (see Section 4.2). For the BUGA Wood Pavilion, calibrating the robotic milling setup resulted in a milling accuracy of 0.3 mm [90].

Creating geometric connections requires considerable milling time, proportional to the amount of material that needs to be removed to create the connection. Dovetail joints require particularly long milling times due to their depth and geometry. For finger joints, two milling strategies are illustrated in Fig. 3.8: side milling with a cylindrical milling bit (oriented perpendicularly to the plate surface) and end milling with a slightly tapered milling bit (pointing towards the joint). The former method results in rounded corners with a radius equal to or larger than the milling bit radius, whereas the latter method results in sharp corners.

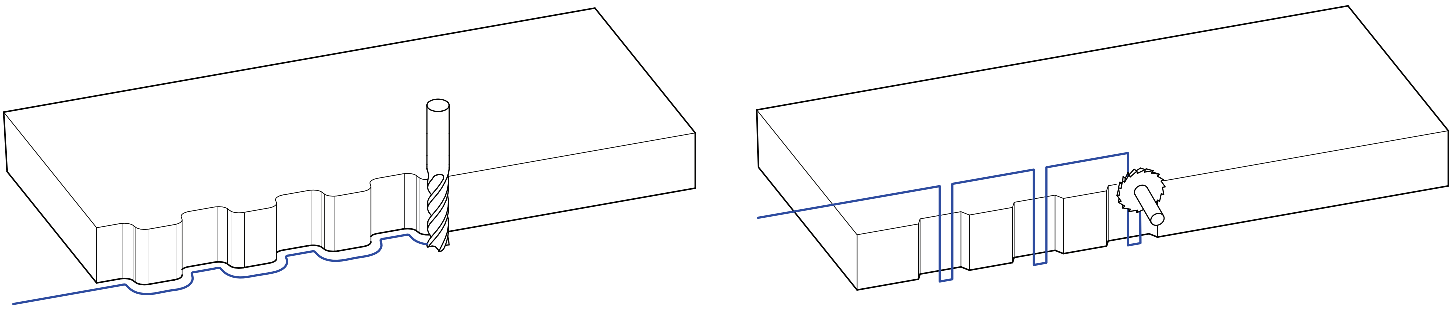

Figure 3.8: Finger joint milling strategies: side milling with a cylindrical milling bit (left) and end milling with a tapered milling bit (right).

3.3.2 Bolts

Bolted connections can resist tensile forces and in combination with the compression stiffness of the plate material itself, bending stiffness can also be achieved. Furthermore, when there is a tight fit between the bolts and the holes they are placed in, shear stiffness and out-of-plane shear stiffness can be realized. Thus, when the plates themselves take compression forces, stiffness in all necessary directions is achieved. In addition to the benefit of being able to resist forces in multiple directions, bolts have the advantage of being removable and can thus be used in structures that are to be disassembled and rebuilt.

For plates constructed out of ductile material (such as steel plates), edges details that can be bolted together (see Fig. 2.5) can easily be created [95; 103]. In the case of timber plates, hollow components can be connected when openings are present in one of the surfaces and when there is enough distance between the plates to reach the edges, but solid plates would require pockets to insert and reach bolts and nuts. Such pockets would need to be quite long in order to allow for inserting and accessing bolts. Therefore, it is more practical to use crossing screws instead of bolts to connect solid plates.

A tight fit for bolts is necessary to obtain high structural performance: DIN EN 1995-1-1:2010-12 states that holes should be at most 1 mm larger than bolts [35], but tighter fits are preferable as they lead to smaller deformations. In situations where a tight fit of bolts cannot be guaranteed, toothed washers or split rings could be used to provide shear stiffness, given that care is taken that these elements do not prevent a joint from closing tightly. Alternatively, holes could be pre-drilled in one plate, while the hole on the neighbouring plate is drilled on-site, using the pre-drilled hole as a guide.

Washers are necessary due to the limited compression strength of wood. If possible, shallow pockets should be milled for these washers, to compensate for the angle between neighbouring plates. If this is not possible, adjustable washers could be inserted between the washer and the bolt or nut, as illustrated in Fig. 3.9. Additionally, tapered washers may be needed if the plate angle exceeds the maximum angle of adjustable washers. Tapered washers are available in a few specific angles, so relying on only tapered washers by themselves seems impractical, as it would constrain the plate angles that can be used in a design.

3.3.3 Fully threaded crossing screws

Fully threaded screws can be used to provide stiffness in all required stiffness directions. Screws are a common connector in timber construction and can be inserted in softwood and softwood products (such as LVL or CLT) with common power tools. To prevent screws from slipping away, pockets could be milled or drilled in the plate first, either in the prefabrication stage or on-site. If added during prefabrication, the pockets can also act as indicators of the required screw positions.

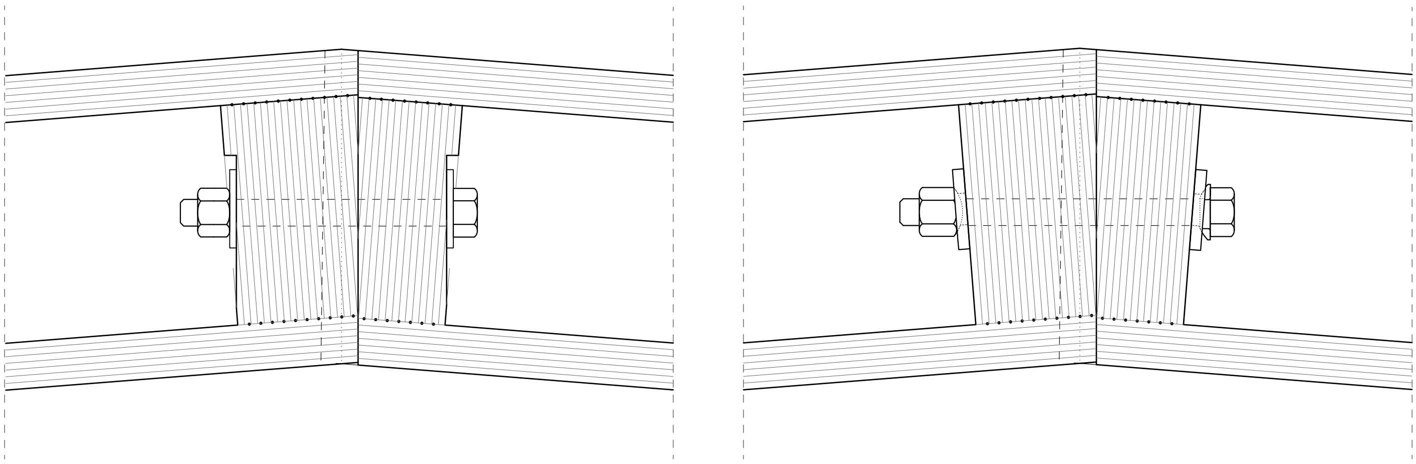

Figure 3.9: Bolt connection using milled pockets (left) or adjustable washers (right).

The joint stiffnesses that can be achieved with screws depend on several factors, including the length and diameter of the screws, and the fabrication and assembly tolerances: with low tolerances, there is no risk of local buckling, and bending stiffness will result from the combination of material contact and the screws. But when there are gaps between plates, bending stiffness is compromised [81]. For thick plates, screws could be inserted at multiple levels, so that there is a lever arm that can help achieve bending stiffness even when tolerances are large (Fig. 3.10).

Screws can be inserted from above or from below. Inserting the screws from above has the advantage that the insertion process is more ergonomic and that in case of a fire, screws are not directly exposed. Inserting the screws from below has the advantage that the top of the plates does not need to be accessible for assembly, which would allow including additional layers of material (such as thermal insulation material) in the prefabrication process.

The angle at which screws are inserted affects the joint stiffness, as shown by the stiffness formulas given by Li [81]. Compared to the arrangement where crossing screws are placed in the plane perpendicular to the edge direction at an approximately 45° angle with the plate surface, orienting the screws at a smaller angle lowers out-of-plane shear stiffness, but increases tensile stiffness and bending stiffness. As the latter two properties tend to more strongly affect the stiffness of a plate shell [19], lower insertion angles are preferable. Lower insertion angles also allow for longer screws, which increases all stiffness values except in-plane shear stiffness (which remains equal).

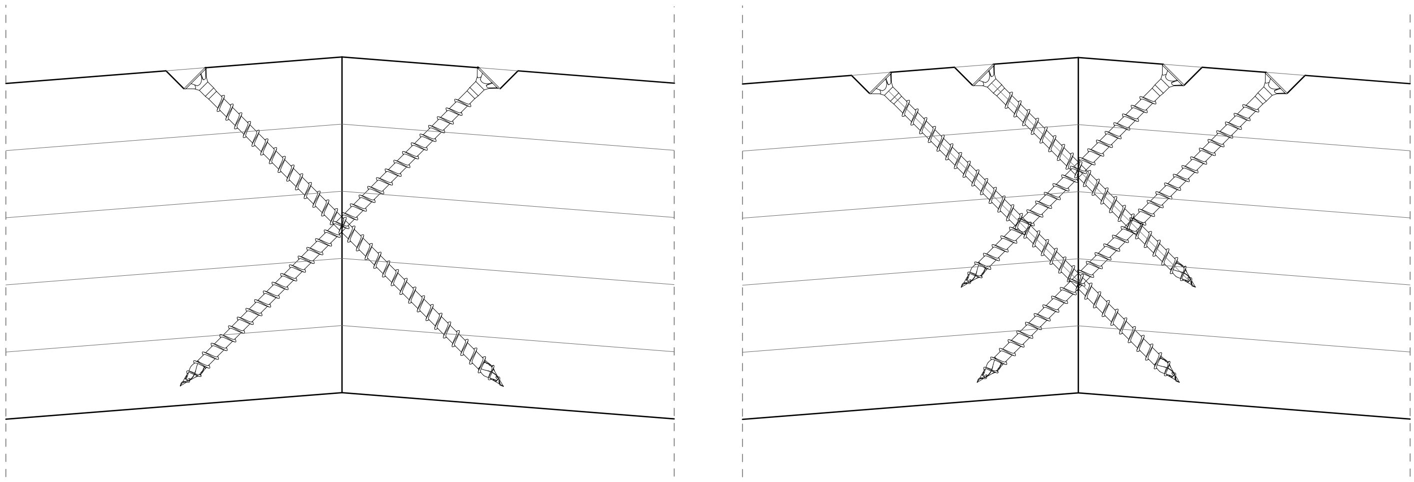

Figure 3.10: Screw connection with all screws passing through a single line (left) and in a double-layer arrangement (right).

3.3.4 Plugs

Butterfly-shaped wooden plugs function similarly to dovetail joints, but without constraining assembly directions and assembly order. They can provide in-plane shear stiffness, tension and compression stiffness as well as bending stiffness. High fabrication accuracy is required when friction is used to keep the plugs in place.

A hardwood plywood dovetail plug consisting of two halves (split in a slanted orientation) is available on the market under the name of X-Fix [109]. These plugs can be used to connect ordinary CLT slabs but have also been used in an experimental plate shell [102]. Glue or nails may be needed to secure the plugs, to guarantee that they stay in place in the long term and/or to fulfil building code requirements.

3.3.5 Dowels and biscuits

Dowels or biscuits can provide in-plane and/or out-of-plane shear stiffness; they can be useful in combination with connectors inserted in the out-of-plane direction, such as plugs. These connections strongly limit the range of potential assembly directions.

3.3.6 Glue

Glue is commonly used to connect timber parts in engineered timber products, such as glulam beams or CLT. To guarantee the structural performance of a glue joint, an environment in which temperature and humidity are controlled is required. High precision is required as well; for example, DIN EN 15425 lists a maximum glue thickness of 0.3 mm for general-purpose timber gluing applications using PUR [37]. These conditions generally cannot be guaranteed on a construction site, therefore gluing is mainly used in prefabrication processes.

Logistic challenges can be posed by a limited open time (the maximum time between applying glue and starting a clamping process) and by a minimum curing time, during which a component may need to be pressed. As open time and curing time are generally linked (glue with a longer open time also needs to cure longer), there is a trade-off between reserving enough time to put components together and limiting curing time.

The Kobra pavilion [149] uses glued tapered cleats to connect plates. Compared to gluing the butt joint directly, this has the benefit of having a larger gluing area. Additionally, inserting the cleats can help align plates.

3.3.7 Metal plates and hinges

Almegaard [4] uses 2.5 mm thick aluminium strips that are screwed on plywood plates; this connection provides stiffness in all required directions, although bending stiffness is much stronger in one direction (the direction in which material contact between the plates can occur) than in the other direction, where the bending stiffness equals that of the aluminium strip itself. The strips are bent to match joint angles and are perforated to accommodate the screws, two rows on each side. As Almegaard's design is symmetrical along six planes as well as rotationally (3-fold), only a small number of different strip types needed to be created [4].

Wester used kitchen hinges in one of his pavilions [142]. As bending stiffness is not required for stability, this is an elegant solution to the problem of having to connect plates at a large number of different angles. This solution was used in Ramboll's Trada pavilion as well [55].

3.3.8 Fibrous joints

Garufi et al. introduce the use of carbon fibre-reinforced polymer tows, connecting timber plates using a three-dimensional tying pattern. The tows are cured using an electric current, a process that could potentially be applied on-site [47].

3.3.9 Textile joints

Leitner proposes and analyses a joint type consisting of fabric that is glued into thin timber plates [79]. These joints act like hinges (with no significant bending stiffness until contact between chamfered edges of plates is reached, and then only in one direction), and thus multiple connected plates can be constructed out of a flat sheet and then folded into their final form. The plates can be seen as a sandwich construction, consisting of two timber plates with fabric glued in the middle. While multiple plates can be prefabricated into assemblies that fold together, multiple such assemblies are needed to create larger constructions. Therefore, some metal fasteners would still need to be added on-site [79].

The proposed erection system makes the most sense when the final structure can be folded into a shape that is easy to transport. Leitner shows such a structure: a hall spanning 7.20 m using a modular folded roof that can be constructed out of Kerto plates of 1.8 x 10.8 m, with a thickness of 33 mm. In this application, the plates can be transported efficiently. However, in geometrically less regular structures consisting of large plates, the number of plates that can be combined in a single foldable assembly would be small.

3.3.10 Overlapping plates

Most joints presented so far are variations on the butt joint. However, overlapping joints can also be used when using plates that are thin enough to be bendable.

An early example of overlapping joints can be found in Buckminster Fuller's plywood dome, for which he filed a patent in 1957. In this system, plywood plates are arranged on a spherical surface such that the corners of a plate always overlap other plates; the corners are bent to make them locally coplanar with the plates they overlap. The plates are also bent in the middle. The resulting shell is not continuous; some openings remain. Buckminster Fuller mentions that plates could be connected either by gluing or with fasteners “of any conventional type” [46].

Pavlov uses overlapping hexagons in some of his projects and also shows overlapping circular plates [96]. An advantage of this joint type is that one can use identically shaped plates while varying the connection positions between plates to increase the range of possible designs.

3.4 Selection of plate and joint types for further investigation

As investigating all possible joint and plate types in detail is beyond the scope of this dissertation, plate and joint types that are most likely to be suitable to actual applications for vertical densification are selected. As the criteria for the most suitable solution are project specific, two scenarios are chosen: The first scenario aims for low complexity, to find a solution that can readily be employed in the construction sector at relatively low costs. The second scenario aims for minimum weight, to be able to use timber plate shells for applications where existing structures can only carry very little additional weight. These plate and joint types have also been described in Krieg et al. [75].

3.4.1 Low complexity and low costs: solid plates connected with crossing screws

The main criterion for plates with low complexity and low cost is minimal fabrication complexity. Solid timber plates are the least complex plate type, as apart from formatting the joints, no other fabrication steps need to be carried out. Due to their simple geometry, butt joints are the fastest and easiest to prefabricate.

Suitable materials for solid plates include CLT, LVL and plywood. These are all available in either softwood or hardwood, but softwood is easier to machine and thus preferable for the low complexity scenario. Both CLT and LVL are available in large sizes and various thicknesses. As CLT is cheaper than LVL, it will be used for this scenario, but LVL could also be used if desired.

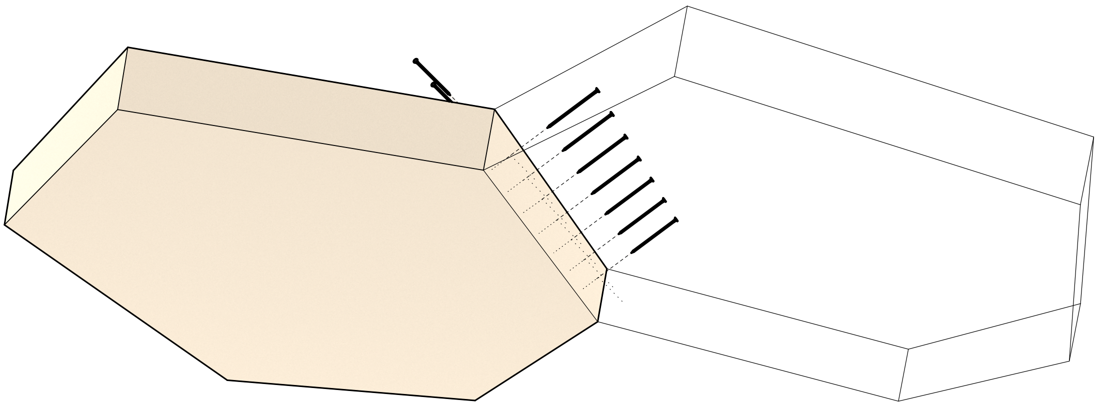

Figure 3.11: Plate and connection type with minimal complexity: solid plates with crossing screws.

To connect the plates, connection types that are already common in the timber construction industry add the least complexity to the construction process. Therefore, fully threaded screws are selected to connect the plates in this scenario (Fig. 3.10, left). The resulting system is shown in Fig. 3.11.

3.4.2 Minimal weight: hollow components connected with finger joints and bolts

For the minimum weight scenario, the main criterion is the self-weight of the plates. Hollow plates are significantly lighter than solid plates for a given span [19] and as their top and bottom surface work together structurally, hollow plates can also be expected to be more structurally efficient than plates with reinforced edges.

Therefore, this plate type is selected for the minimum weight option.

The material for the top and bottom plates needs to be suitable for structural applications and needs to be available in the structurally required thickness, which can be expected to be a couple of centimeters [19]. Examples of such materials are plywood and LVL. LVL is available in larger dimensions, which leads to fewer size constraints and potentially lower material use (due to the use of larger plates, higher nesting efficiency, or both) and is therefore preferable. The edge elements can also be constructed out of LVL.

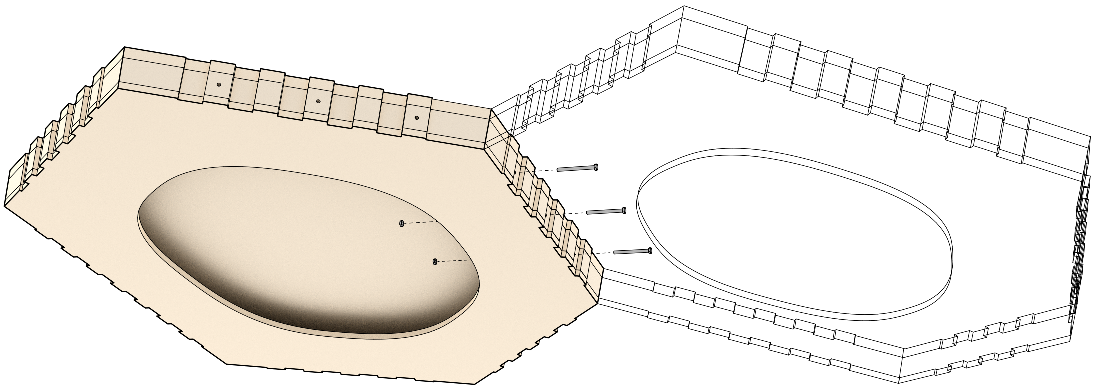

Figure 3.12: Plate and connection type with minimal weight: hollow components with finger joints and bolts.

Because of their high shear stiffness, finger joints are used for the edges (Fig. 3.9). Additional fasteners are needed for tensile forces and out-of-plane forces; either screws or bolts could be used. Bolts were used in the BUGA Wood Pavilion project [7] and will also be used for the minimum weight scenario (Fig. 3.12).

3.5 Conclusion

This chapter discussed various ways to fabricate and connect timber plates. Three plate types are shown: solid plates, thin plates with reinforced edges, and hollow components consisting of two thin plates that are connected at the edges. Solid plates feature the least complexity, whereas hollow components have the highest structural performance per unit of weight.

Many joint connection methods have been discussed, including geometric connections, bolts and screws, plugs, dowels and biscuits, glue, metal plates, hinges, fibrous materials, and textile joints. To fulfil all structural requirements of a joint, multiple connection methods may need to be combined. In anticlastic areas or at kinks in the global geometry, the assembly order and insertion directions need to be assessed, for example, using a visibility map. Certain designs are impossible to assemble, particularly when using geometric joints such as finger joints. In some cases, this can be resolved by adjusting the orientation of the joint plane or the finger joint geometry.

As the choice of plate types and joint types depends on specific project requirements, suitable plate and joint types for two application scenarios have been chosen: one scenario aiming for low complexity and low costs, and one scenario aiming for minimum weight.

The selected low complexity and low cost scenario consists of solid CLT plates connected with screws. The selected low weight scenario consists of hollow components constructed from LVL, connected with finger joints and metal fasteners. These two systems will be analyzed in detail in the next chapter.

4

Assessment of timber plate shell properties in the context of vertical densification

This chapter describes and evaluates technical properties of timber plate shells in the context of building construction in general and vertical densification in particular. As described in Section 3.4, the two investigated systems are solid CLT plates connected with crossing screws (aiming for low complexity and low costs) and hollow LVL components connected with finger joints and bolts (aiming for minimum weight).

4.1 Construction weight of timber plate shells

As new spaces on top of existing buildings introduce loads that were not originally anticipated in an existing structural system, the weight of new construction can be critical to the viability of a vertical densification project. Therefore, this section compares the weight of the proposed plate systems to other timber construction systems at various spans.

4.1.1 Weight comparison between CLT plate shells and other timber roof structures

All construction systems in this comparison cover a rectangular area, of which only the short sides are supported. Vertical loads of self-weight plus 1 kN/m² are used; no horizontal loads are applied. Deflections are calculated using the program Sofistik using settings as indicated in Appendix B. Stress limits are not taken into consideration. Material dimensions are set such that deflections are at most 1/300 of the span.

For the mass comparisons, a density of 480 kg/m³ is used for CLT, and a density of 680 kg/m³ is used for plywood. The mass of metal fasteners is included in the comparison.

The plate shell geometry used for the comparison is illustrated in Fig. 4.1. The rise of the plate shells is 53 cm, 231 cm and 379 cm for spans of 6, 12, and 25 m, respectively. Structural behaviour will differ for different plate shell geometries. Various structurally relevant factors are discussed separately in Section 5.3. A minimum thickness of 60 mm is used for the plate shells, because this is the smallest commonly available thickness for CLT.

For plate shells, support conditions have a very large effect on deflection: when all supports are hinged, deflection is much smaller than when roller supports are used on one of the sides. For a span of 6 m, FEM calculations show a difference in deflection of around 12 times and for spans of 25 m, FEM calculations show differences in deflection of a factor of more than 100. As some other construction systems are much less sensitive to these support conditions, comparisons are shown with two different support conditions: firstly, using hinged supports on one side and roller supports on the other, and secondly, using hinged supports on both sides.

4.1.1.1 6 m span

As shown in Fig. 4.1, for a span of 6 m, a structure consisting of wooden beams with a layer of plywood on top is lighter than a CLT slab or a CLT plate shell. When support conditions can be considered hinged supports, a CLT plate shell is about 50% lighter than a CLT slab, but a CLT plate shell is heavier than a CLT slab when such support conditions are not available.

4.1.1.2 12 m span

At a span of 12 m, timber plate shells are lighter than CLT slabs. When hinged supports are available at all lines of support, timber plate shells are also lighter than the Kielsteg system [69], which is a very efficient system for constructing timber roof structures. An even lighter solution can be realized using glulam girders, at the expense of a larger construction height.

4.1.1.3 25 m span

At a span of 25 m, CLT slabs are no longer feasible. When hinged supports are used on all sides, plate shells use less than half the mass of the Kielsteg system. At this span, the weight of a timber plate shell is lower than that of a structure consisting of glulam girders, provided that hinged supports are present on both supported sides.

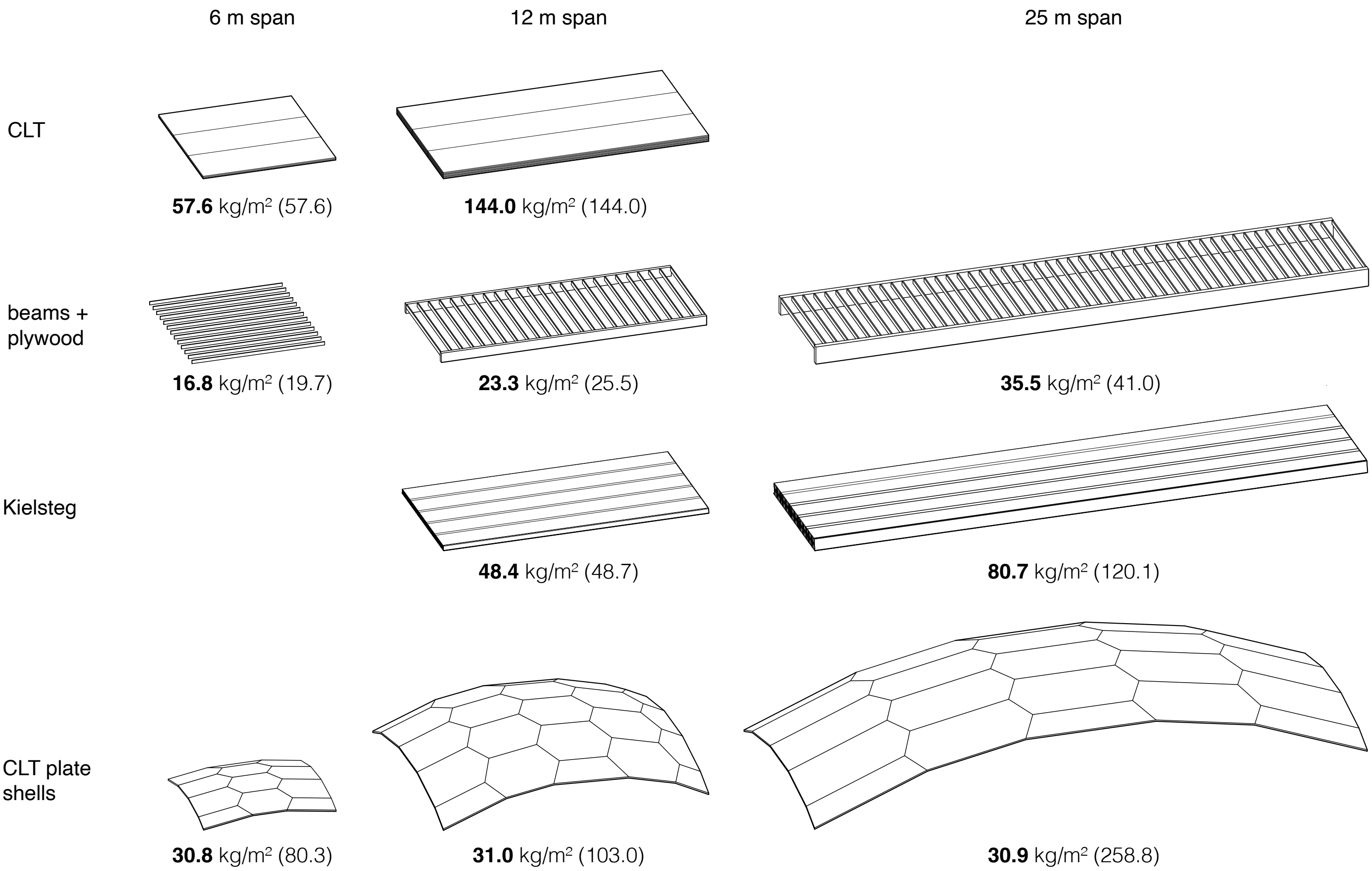

Figure 4.1: Construction mass per square meter of various timber construction systems at spans of 6, 12 and 25 m. The bold values represent structures supported by hinged supports on both short sides, the values between parentheses represent structures where roller supports are used on one of the sides.

4.1.2 Weight comparison between solid and hollow plates

A comparison between the self-weight of a solid CLT plate shell and a plate shell consisting of hollow components at a span of 25 m is made by Bechert et al. [19]. For the particular test case (in which the dimensions of the two systems are chosen such that the resulting deflections are similar), the weight of the structure using hollow components is just under 50% of the weight of the structure using solid plates.

4.2 Fabrication accuracy in relation to structural performance

Initial deformation of joints in a plate shell strongly influences the stiffness of a plate shell [81]. The influence of gaps resulting from fabrication inaccuracy is strongest when gaps in the compression direction and the shear direction are combined; compared to perfectly fitting joints, gaps of half a millimetre in the shear and normal directions may double global deformations and gaps of one mm in these directions may quadruple global deformations (see Fig. 4.2) [19].

Acceptable tolerances for timber products in Germany are defined in DIN 18203-3 [34]. For dimensions and openings in CLT, ranges of 2 to 5 mm are given, depending on element size. DIN EN 14080 (D) lists acceptable tolerances of +/- 2 mm for the width and length of CLT elements [36]. With well-calibrated carpentry machinery, contractors can work more accurately, but this needs to be specified and agreed upon explicitly.

Not all tolerances are equally critical. For example, the edge elements in hollow components do not need to touch at corners to transfer shear forces effectively, as the corners of plates are not

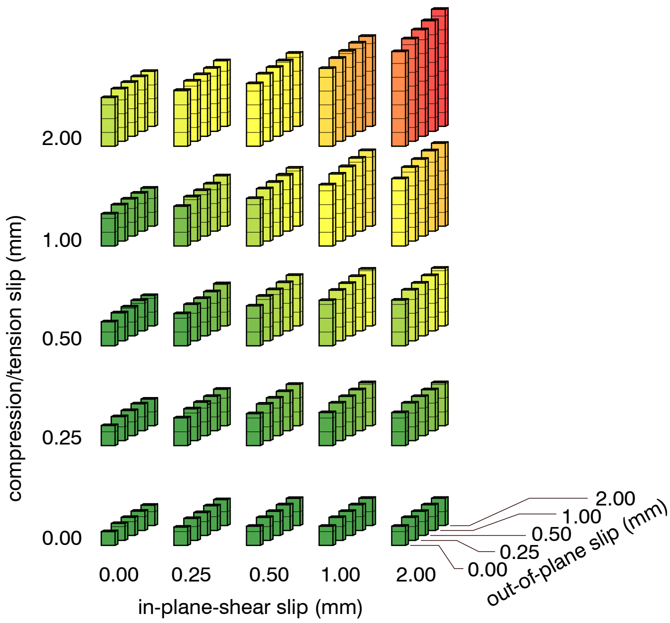

Figure 4.2: Relative global deflection of a plate shell for various amounts of initial deformation in three orthogonal joint directions, compared to a structure with no initial deformation (represented by a single cube, bottom left).

necessary for pure plate action [146]. Furthermore, deviations in the thickness of components are not of structural importance as these deviations do not cause initial deformation in the joints. In the BUGA Wood Pavilion, high tolerances were acceptable for the placement of edge elements during the production of the hollow components, as the final geometry was only created after milling the finger joint geometry.

4.3 On-site assembly

The two plate types introduced in Section 3.4 have very different properties when it comes to assembly. Due to the finger joint geometry, the hollow components can only be inserted from specific directions and stay in place even before being fixed with bolts. The solid CLT plates with flat joints can be more freely inserted, but need to be temporarily fixed before being screwed together, for example using partially threaded screws (see Section 3.2.3). Hollow components can be placed quickly, as there are few connections per edge: for the BUGA Wood Pavilion, about 40 components (around 64 m^2) were assembled on-site per day by a single team of two people [7]. When using bolted connections, plate shells with hollow components can be disassembled and reassembled.

For synclastic shells with butt joints or finger joints, any assembly order can be used as each plate can be placed in the direction perpendicular to its surface, whereas for anticlastic surfaces or at kinks between surfaces, a predefined order may need to be used. Due to the joint geometry, the assembly order is critical for plates with finger joints or other geometrically intricate joints in anticlastic areas (see Section 3.2.2).

Falsework could be used to indicate and verify the target geometry, but when the plates are fabricated and placed with enough precision, plate shells can also be assembled without falsework, as demonstrated by the BUGA Wood Pavilion in Heilbronn [7].

4.4 Prefabrication complexity and prefabrication time

The fabrication complexity of the solid and hollow plate types differs strongly. This section describes possible fabrication processes for both types.

4.4.1 Prefabrication of CLT plates

The solid CLT plate type discussed in Section 3.4.1 features planar joints, which for convex plates can be cut with an angled saw blade in a single process step. Concave angles within a plate cannot be cut with a saw blade in an equally fast process without partially

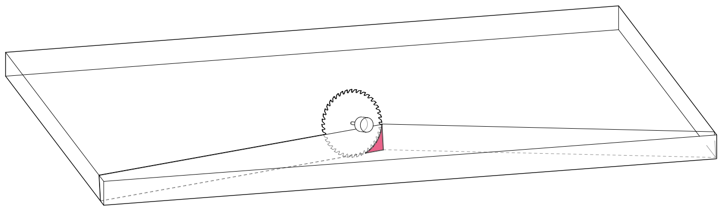

Figure 4.3: Joint area in a concave corner that cannot be reached with a saw blade without either sawing into the butterfly-shaped plate or sawing off excess material in multiple steps.

cutting through the work piece, as the axis of the saw blade could not be moved down without running into the blank material (Fig. 4.3). In order to prevent cutting into the work piece, the saw blade could be used to remove most of the material in multiple steps, after which the convex corner can be approached from the side. The final shaping of concave corners can also be executed in a consecutive milling step, for example, using a large jointing cutter.

As an alternative to cutting plates with a saw blade in multiple milling steps, a 5-axis water jet could be used. In addition to being able to cut concave angles without extra steps, water jets can achieve very high precision. However, this type of machine is not commonly used in the timber construction industry.

Cylindrical pockets should be milled in the top surface if partially threaded screws are used to connect plates before inserting the fully threaded screws (see Section 3.2.3), although this production step could also take place on-site. Optionally, a shadow gap or bevel could be milled into plate edges visible from the enclosed space (see Section 5.8), and inner surface treatment (for example, with oil or varnish) can be included in the prefabrication stage.

Apart from the surface treatment, all of these steps could be executed in a few minutes by a portal woodworking machine that is suitable for formatting CLT (for example, a Hundegger PBA [53]). As CLT is used more and more, such machines can be expected to become increasingly common in the timber construction sector.

4.4.2 Prefabrication of hollow components

The proposed hollow components are much more complex to prefabricate than solid plates. First, all parts need to be roughly formatted, then the parts need to be glued and assembled, and then pressed while the glue is curing. Finally, edges and bolt holes need to be sawed, milled and/or drilled.

Formatting of the top and bottom plates can be done using 3-axis milling. The edge parts should ideally not only be cut at the required angle, but angled pockets should be milled at each bolt location on the sides that will be on the inside of the component, as this side is difficult to access after the components are glued together.

Gluing and assembly of the parts can be carried out manually, although robotic assembly is also possible [90]. The components should be pressed after gluing.

Sawing and milling joints, drilling bolt holes, and milling an access opening could be carried out by a portal woodworking machine, after fixing the component at such a height that the sides are accessible by milling and drilling tools, for example, using a supporting console with an appropriately sized vacuum table. Due to the larger number of operations and the longer tool paths, the final formatting will take significantly longer than formatting the CLT plates, but it should still be possible to carry out this step within a few minutes, provided that sufficiently large milling tools are used on a machine with automatic tool changing.

In addition to the rough formatting and the milling taking more time than the cutting of solid CLT plates, various additional steps add to the fabrication time of hollow components, including handling of elements, gluing, clamping or pressing while the glue cures, and preparation of the milling process (placing a rough component on a vacuum table and measuring its exact location and orientation).

4.4.3 Morphospace

The range of plate shapes and dimensions that can be fabricated and used depends on limits imposed by available stock material dimensions, the fabrication processes of plates, transport limitations, and on-site assembly processes.

For solid plates, the saw blade diameter limits the maximum plate thickness and the plate angle. Concave angles smaller than 90° cannot be cleanly cut with a jointing cutter (and as with all concave angles, also not with a saw blade; see Section 4.4.1). Dimensional limits are posed by the available width of CLT: CLT is available in widths up to the height of one story (for example, Hasslacher lists dimensions up to 3.20 m, and Stora Enso lists 2.95 m). Transport considerations can also pose practical limits.

For hollow components, the bolt connections cause constraints: components need to have a minimum thickness to be able to access the bolts during on-site assembly and angles between plates should be small enough to make it possible to insert a bolt (see Fig. 4.4). Plate dimensions are limited by available LVL dimensions. For Kerto, the maximum length poses no practical constraints but the width is limited to 2.5 m [92].

4.5 Material efficiency

When cutting a regular hexagon out of a rectangular plate, 25% of the material is cut off; for a pentagon, the cut-off waste is 31%.

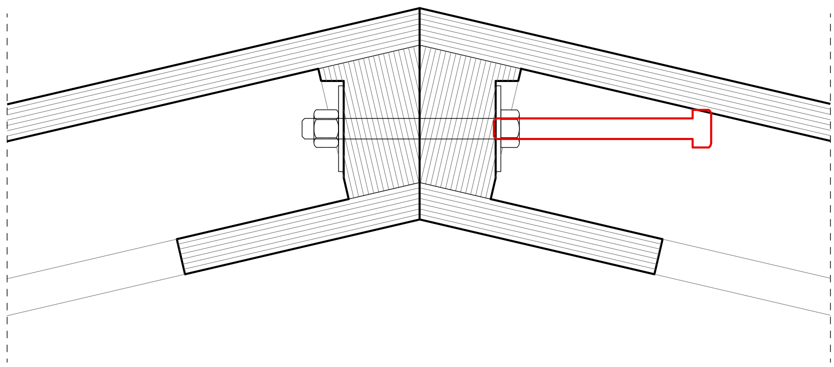

Figure 4.4: Insertion of a bolt to connect two hollow components: the space needed to insert the bolt (marked in red) limits the maximum angle between neighbouring plates.

When the stock material is not available at the exact required dimensions and when leaving some material around the edges, cutting losses can even exceed 40%. As it is uneconomical to use plate sizes that are much less wide than the available stock material, and as there are thus at most a few plates that are cut from a single slab of material, the material efficiency that can be gained by efficient nesting is limited.

While the cutting waste for plates can be rather large, the cutting waste of edge elements of hollow components is small, because the width of these elements is constant, and because the slanted ends of multiple elements can be nested efficiently. For the plate shape shown in Fig. 4.5, cut-off waste for a solid plate is at least 27%, while cut-off loss (including milling) for the edges is just 3%. If hollow components would be made without openings, cut-off waste in this example could be as low as 20% (using plate thicknesses of 2 cm and edge height and width of 10 cm), but with the illustrated opening, cut-off waste is at least 33%, which as a percentage is higher than the cut-off waste of a solid plate. However, in absolute terms, cut-off waste for a solid plate with a

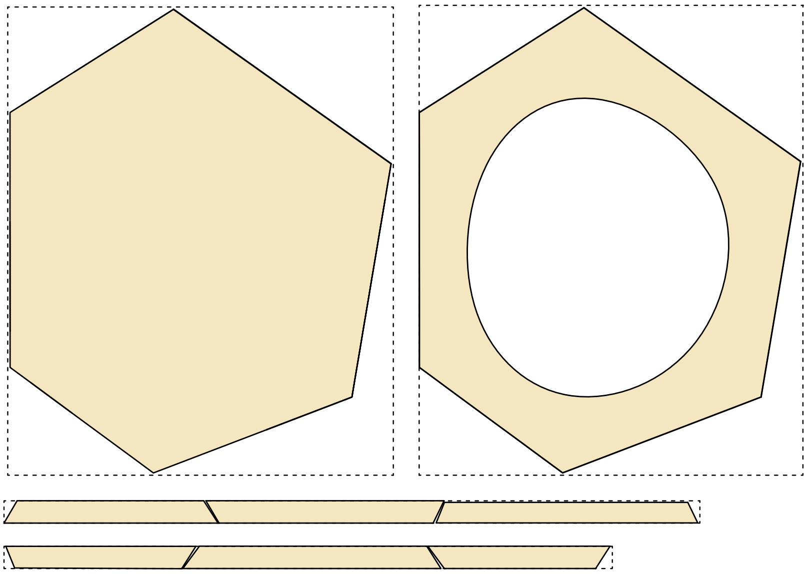

Figure 4.5: Visualization of material efficiency of plates and edge elements: by cutting multiple edge elements out of a single timber element, material waste is minimized. Due to their less rectangular shape and the small number of plates per sheet of timber material, nesting for plates is not as efficient.

thickness of 14 cm is 48% larger than cut-off waste for a hollow component in this example.

Adjusting plate shapes can lead to considerable material efficiency gains: giving a hexagon a more elongated shape while retaining all corner angles leads to less cut-off waste, and making the short sides less sharp reduces cut-off even further. This is illustrated in Fig. 4.6.

Using such elongated plates in a design leads to a barrel-like plate shell. Compared to a similar structure constructed out of near-regular hexagons with the same width, significant material savings can be achieved. Fig. 4.7 (left) shows such a design; its cut-off waste percentage of 12% compares very favourably to the 25% cut-off of a regular hexagon. In addition to reducing material waste, the number of plates and the total edge length of this

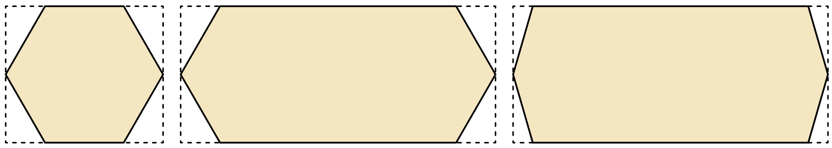

Figure 4.6: Cut-off waste of a hexagon, an elongated hexagon and an elongated hexagon with a larger angle between its short sides, with cut-off waste of 25%, 12.5% and 6.25% respectively. Bowtie-shaped plates lead to the same amount of cut-off waste when the same outer dimensions and angles are used.

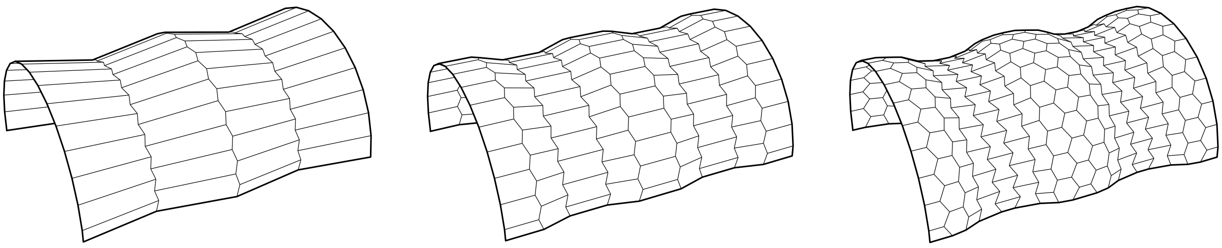

Figure 4.7: Plate shell designs constructed out of elongated plates, producing only 12%, 10% and 13% of cut-off waste respectively, thanks to plate shapes that can be efficiently nested.

design are much smaller than that of a design consisting of near-regular hexagons, leading to faster fabrication, fewer connectors, and faster assembly.

When plates are so small that multiple plates fit on a slab of material, the combination of shapes influences nesting efficiency and thus cut-off waste. The structures in Fig. 4.7 (center and right) show designs featuring a combination of near-regular hexagonal, chevron and bowtie shapes, which can be much more efficiently nested than plate shells featuring only hexagonal or only bowtie shapes: when fitting bounding rectangles individually for all plates of the shell illustrated on the right individually, the cut-off loss is 27%, but after nesting multiple plates on rectangular slabs, the resulting cut-off loss is reduced to 13% (Fig. 4.8, right). Note however that for solid plates, plates cannot be cut out of the mater-

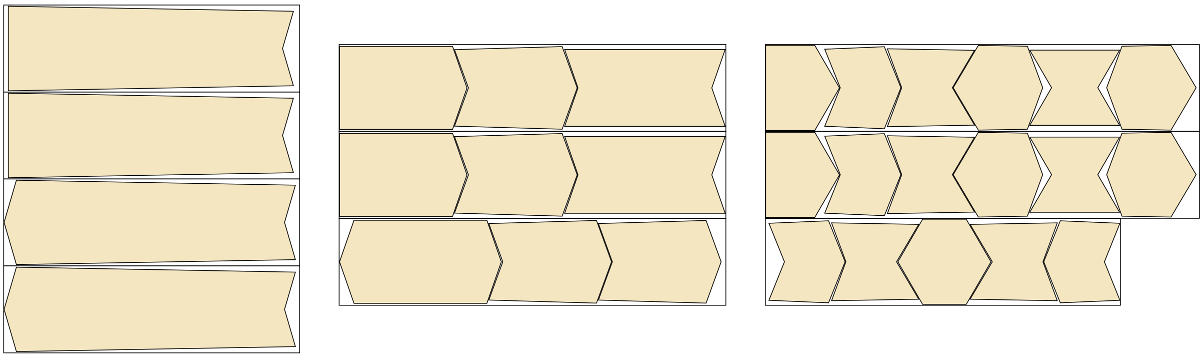

Figure 4.8: Nesting example of rows of plates from Fig. 4.7, resulting in cutting losses of 12%, 10% and 13% respectively.

ial using a circular saw blade when nested this way (see Section 4.4.1).

4.6 LCA comparison between timber plate systems

In order to compare the environmental impact of the two timber plate systems using life cycle analysis, the environmental impact of all used materials and processes needs to be established and combined. Data on environmental impact is not available for all processes and materials, so some estimates and approximations need to be used.

Even when exact environmental impact data for all processes and materials is known, factors such as transport distances for raw materials or energy use by machinery vary from supplier to supplier. Additionally, some effects can be calculated per cubic meter of material, while other effects depend on the total edge length of a plate, so the exact environmental impact depends on the design of a plate shell and is thus project specific. Despite these limitations, a single solid plate will be compared with a hollow component to develop an understanding of the relative environmental impact of the two plate systems.

Table 4.1 lists global warming values for relevant materials, using data from the Ökobaudat database [24]. Global warming data was not available for the impact of milling and sawing processes, so only the energy use of these processes is considered. By estimating the energy use of a spindle (in this case, 15 kW) and the milling or sawing speed (for example, 5 cm/s), the energy use can be converted to a value per tool path meter.

material	**units**	**CO_2 equivalent**	**source**
LVL	m^3	-468.6	Ökobaudat (2017)
CLT	m^3	-633.0	Ökobaudat (2017)
steel screws	kg	2.91	Ökobaudat (2014)
PUR glue, polyol free	kg	8.85	Ökobaudat (2013)
PUR glue, polyol free	m^2	1.77	converted (200 g/m^2)
milling/sawing	kWh	0.61	Ökobaudat (2015)
milling/sawing	m	0.051	Ökobaudat (15 kW, 5 cm/s)

Table 4.1: LCA global warming values (in equivalent kg of CO_2 emissions) for materials and processes.

When comparing the impact of a solid CLT plate (10 cm thick) to a hollow LVL component (top and bottom plate thickness 2 cm, total thickness 14 cm), the solid plate has a significantly better carbon footprint (Fig. 4.9). This is due to the larger amount of wood and therefore higher storage of CO_2, but the carbon footprint of solid plates is also lower than that of hollow components when carbon storage effects are disregarded. For the comparison, a single plate of 5 m^2 with a total edge length of 8.5 m was used.

The plates themselves have a negative carbon footprint, but the non-orthogonal shape of plates can lead to material waste in the thermal insulation and the waterproofing layer. In case of

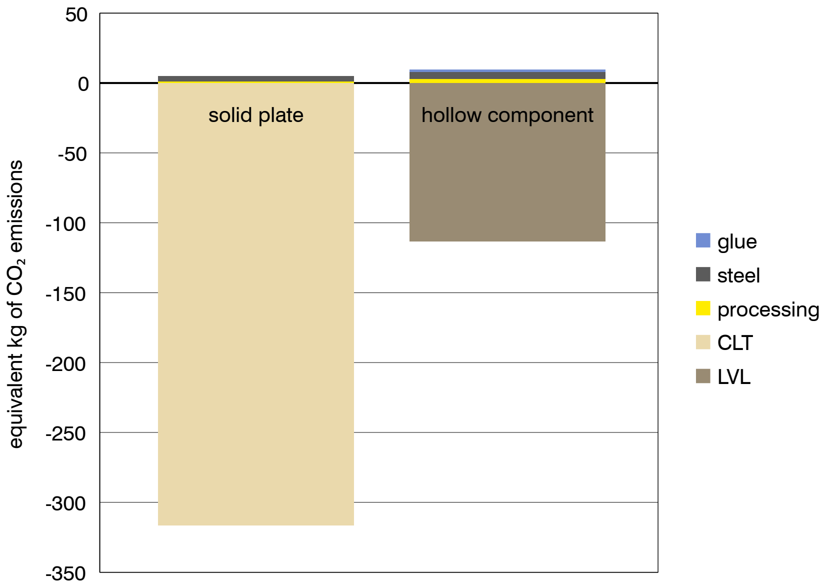

Figure 4.9: Global warming contribution of a CLT plate and a hollow component, in equivalent kg of CO_2 emissions. For both systems, the negative carbon footprint of the timber is much larger than the global warming contributions of the steel, the glue and the processing energy.

an estimated 15% cutting loss, this would result in an additional equivalent of 6.5 kg CO_2 for a layer of EPDM and 12.6 kg CO_2 for a 24 cm thick layer of mineral wool [24]. In this example, the impact of the cutting loss of thermal insulation and waterproofing is thus larger than the environmental impact of metal fasteners, gluing, and formatting combined, but an order of magnitude smaller than the positive contributions of carbon storage of a CLT plate.

4.7 Air and moisture tightness

Due to increasingly high thermal insulation and air tightness standards, humidity that ends up in the thermal insulation layer can no longer be assumed to be taken away by air moving through the construction. As wood and plywood are extremely airtight [150], LVL can be assumed to be very airtight as well. According to tests executed at TU Graz, CLT featuring side bonding and dovetailing in its layers has an air tightness that is practically infinite [132]. Both CLT and LVL also form a significant moisture barrier; Stora Enso lists a μ value of 20 to 50 for CLT [122], whereas Metsä Wood lists μ values ranging from 62 to 200 for Kerto (measured across the layers) [91]. As a result, moisture that ends up in the thermal insulation layer due to diffusion or condensation cannot easily escape. Therefore, it is important to carefully plan and execute the moisture barriers in the construction, including minimizing the amount of moisture that enters the thermal insulation layer by convection through joints [117].

Wood joints such as tongue and groove connections cannot provide the level of air tightness required by current standards [49; 150]. However, the air tightness of wood joints can be greatly improved by the use of a variety of materials, including natural materials such as wool or peat moss [3]. For CLT, Stora Enso lists solutions that can be placed in the joint (EPDM seal, sealing strips, or pre-compressed tape such as compriband) or on the joint (adhesive tape) [122].

For timber plates with flat joints, both seals in the joint and adhesive tape on top of the joint are viable options. The former solution would require routing a continuous slit in all joint surfaces. The point where the seal starts and ends would require special attention, and when placing plates on-site, there is a risk of displacing the seal. In contrast, tape on top of the joints does not require any adaptation of the joint geometry and can be applied after assembling the plates, making tape a more reliable and practical solution. Note that CLT manufacturer Stora Enso does not recommend adhesive tape for CLT construction because of potential difficulties in areas that are hard to reach, such as corners

[122]. However, as angles between plates in plate shells are typically shallow, this is not a concern in plate shells, except in designs that feature kinks.

For timber plates with finger joints, including seals in the joint is complicated. Therefore, adhesive tape would also be the most practical option for this joint type. Any parts of the finger joint that stick out above the surface need to be milled away in order to enable tape application.

4.8 Fire safety

Annex I of EU regulation 305/2011 lists various requirements regarding fire safety in buildings, relating to safeguarding load-bearing capacity, limiting the generation and spreading of fire and smoke, enabling safe evacuation and considering the safety of rescue teams [127]. Within Germany, each state has its own building code, largely based on a federal template called Musterbauordnung [18]. That document lists specific requirements for various materials and building parts, depending on the type of building at hand. Guidelines for calculating the strength and stability of timber structures under fire conditions are described in Section 1.2 of Eurocode 5 [35].

The first four sections of the requirements for roofs in the Musterbauordnung relate to resistance to incoming sparks and radiation, which relates to the roof covering and not the structure. Section 5 discusses the prevention of fire propagation through roof lights, solar installations, cornices, dormers, and other roof elements. Regarding the fire resistance of the roof structure, sections 6 and 7 are most relevant: Section 6 includes a fire resistance requirement of 30 minutes if the roof surface is adjacent to a roof surface of a neighbouring building. Section 7 describes the situation where a building volume is adjacent to a wall with openings (such as windows) and/or without fire resistance. In this case, within five meters of the wall, the newly constructed roof needs to fulfil the same fire resistance requirement as the floors in the spaces behind this wall. Depending on the building category of these spaces, this requirement is 30, 60, or 90 minutes. The Musterbauordnung does not contain a general minimum requirement for fire resistance. For example, for small free-standing buildings that keep a certain distance to the edge of a site, no fire-resistance requirement is given [18].

CLT has a predictable charring rate; Stora Enso lists 0.65 mm/minute for its outer layer and 1.3 mm/minute for the first 25 mm of each consecutive layer [123]. Fire resistance can be achieved by making sure sufficiently much material can be burned away before the structure collapses. When the required structural thickness of plate shells is governed by maximum deformation and not by failure of the structure, the amount of extra material required for fire safety may turn out to be smaller than initially expected; calculation examples that demonstrate this for CLT floor slabs are given by Schickhofer et al. [108]. The exact required thickness of the plates and the minimum cover of screws need to be defined using Eurocode 5 [35].

Joints between plates form a potential weakness in fire resistance. Annex E of Eurocode 5.1.2 indicates that for wooden cladding, lap joints or tongue-and-groove-like joints significantly decrease the fire-enclosing function, whereas any other joint (such as a butt joint) completely annuls this fire-enclosing function. However, tests executed by HolzForschung Austria on behalf of Stora Enso show that both butt joints covered with a wooden spline and lap joints can provide fire resistance as good as the CLT material itself just by inserting strips of compriband. According to these tests, the compriband does not even have to be located close to the exposed side of the joint [123]. Tests at TU Braunschweig show that a layer of compressed mineral wool is enough to make butt joints (without any spline) or lap joints smoke tight [67], although Kampmeier advises additionally using elastic sealant on both sides of the joint in case the fabrication or assembly is too inaccurate to guarantee consistent compression of the mineral wool [68]. Based on the combination of these results, a joint detail including compriband can be expected to be tight enough not to affect the fire resistance of a plate shell when executed accurately enough. However, this would need to be confirmed by physical tests. Furthermore, the effect of airtight adhesive tape applied on top of tight butt joints and finger joints needs to be established, as this would lead to the most simple joint detail.

Instead of (or in addition to) increasing plate thickness, the inside of CLT plates can be covered with fire-resistant gypsum board [123]. Joints between the gypsum boards can be filled with gypsum-based board filler. In plate shells, the boards would need to have shapes that match the plate shapes. To avoid additional complex and time-consuming preparation steps, gypsum boards could be fixed to the CLT material before plates are cut out.

Other common strategies that help reach better fire safety (such as the use of smoke detectors and sprinklers, limiting the amount of inflammable and combustible material in the space, limiting the size of fire compartments, limiting the number of occupants or creating additional fire exits) equally apply to plate shells.

For hollow plates, increasing fire resistance by using thicker material is not a viable option, as three surfaces and the inside of the edge elements can all be reached by fire. An inner layer of gypsum board could be added after the shell is assembled, covering the openings in the components. Alternatively, the openings could be placed in the top surface of the components instead of the bottom, so that the closed bottom plate can be given the necessary thickness for fire resistance. In either situation, the inside of the component could be filled with incombustible material (such as mineral wool) to mitigate the risk of fire occurring in places where it cannot be seen and reached [48].

4.9 Sound insulation

Minimum sound insulation requirements for buildings in Germany can be found in DIN 4109. The requirements for roofs depend on the noise level zone that the building is located in and on the function of the space. For living and sleeping spaces in apartments in zones with a noise level of up to 60 dB(A), the minimum airborne sound insulation requirement is 30 dB(A) [38].

For the airborne sound insulation of CLT floors, Stora Enso provides a formula that takes the mass of the floor (per square meter) as one of its parameters [124]. For a slab of 120 mm thick and assuming a density of 500 kg/m³, this formula gives a sound insulation value of 36.7 dB. When adding wood fibre-based thermal insulation, soft-board, and cladding to CLT roofs, DataHolz lists sound insulation values from 46 to 48 dB [63]. According to sections 7.1 and 7.2 of DIN 4109, these values are suitable for housing in areas with a noise level of up to 75 dB or offices in areas with a noise level of up to 80 dB. Noise levels this high mostly occur near main arteries and only affect a small fraction of buildings; for example in Stuttgart only 0.2% of inhabitants live in areas with a noise level higher than 75 dB(A) [78]. Thus, roofs constructed out of CLT can fulfil sound insulation requirements without special measures in the vast majority of situations.

Hollow components without insulation material inside have limited sound insulation capacity. As a reference, hollow Kerto-Ripa floors with 25 mm Kerto for the top surface and 37 mm Kerto for the bottom surface have a measured airborne sound insulation of just 31 dB [138]. Considering that the proposed hollow components would have openings to facilitate the assembly process, the actual sound insulation of hollow components is much lower. On the other hand, filling the cassettes with mineral wool and adding thermal insulation on top will considerably increase the sound insulation values. Assuming that this additional airborne sound insulation would amount to around 10 dB, insulation values of 40 dB could be reached. This is sufficient for housing in areas with a noise level of up to 70 dB, which, in the example of Stuttgart, covers 98% of situations [78].

4.10 Acoustics

This section discusses three topics that relate to acoustics: sound absorption, flutter echoes, and focusing.

4.10.1 Sound absorption

Sound absorption of wood is low, particularly for higher frequencies, of which less than 10% is absorbed [113]. This can result in strong reverberation, which is undesirable in spaces with high requirements for speech intelligibility or with high noise levels. When using sound-absorbing materials for walls or floors is not possible or desired, additional sound-absorbing material could be applied to the inner surface of plates. Hollow components can be partially or completely filled with a sound-absorbing material.

4.10.2 Flutter echoes

Flutter echoes are echoes caused by reflections between two parallel surfaces [113]. As at most a few plates in a plate shell are perfectly parallel to the floor, flutter echoes are unlikely to be a concern in plate shells.

4.10.3 Focusing

Focusing of sound through reflections against near-spherical ceilings may occur, although due to the faceted geometry of plate shells, this effect will be less strong than in smooth domes. Gade states that there is a risk of focusing when the radius of curvature of the ceiling is more than half the height between one's ears and the ceiling, although it may be less of an issue when the radius is larger than twice this distance, and the floor or furniture are sound absorbent [113]. When plate shell designs are a close approximation of a sphere, this issue can be checked geometrically (using a program or script) by generating omnidirectional rays from a source point, creating one or more reflections, and visually or computationally evaluating if a significant number of reflections converge at a single location.

4.11 Thermal insulation

To meet thermal insulation standards, additional thermal insulation material needs to be added regardless of the plate type. Given the particular shape of plate shells, fabrication and installation processes need to be carefully considered. Three possible strategies to add thermal insulation are discussed in this section.

4.11.1 Rigid and semi-rigid thermal insulation materials

Rigid or semi-rigid thermal insulation materials (for example, wood fibre-based boards or high-density rock wool boards) can be cut to shape using a 5-axis CNC machine. On-site, this material can be applied after the joints between plates have been made airtight. Once the thermal insulation layer has been added, roofing material (such as bitumen or EPDM) can be applied on top. Alternatively, the thermal insulation could be added to CLT slabs before cutting out the plates. This would, however, require a very large saw blade. In this scenario, the joints between CLT plates cannot be reached from the top, so tape cannot be applied as an air barrier. Instead, a solution that is included within the joint (for example a compriband strip) would need to be used.

4.11.2 Soft insulation materials

For plate shells with limited curvature, soft insulation materials that are delivered on rolls (such as certain types of mineral wool) could be applied between wooden battens. Due to their flexibility and compressibility, such materials can be used to traverse plates without miter formatting. However, installing the battens (ideally in two perpendicular layers) is a labour-intensive process, and an additional rigid layer (for example, plywood) would need to be added on top before roofing material can be applied. A benefit of this solution is that any additional surfaces (which may be added for aesthetic reasons) can also be attached to the battens.

4.11.3 Sprayed insulation materials

Sprayed insulation materials (such as cellulose) can be applied to any geometry. When using cellulose to insulate walls, excess material is sometimes scraped off to obtain a flat surface. A similar process could be used to retain the segmented appearance of the roof, provided the edge heights are marked (for example, by placing battens at the edges at the desired height before applying the sprayed material).

Sprayed polyurethane foam can also be used. While the environmental impact of polyurethane foam is unfavourable compared to other thermal insulation materials [42], polyurethane foam does have the technical advantage of being watertight, so that only a UV protective coating needs to be added to ensure waterproofing.

4.12 Roofing

This section discusses properties of various roofing materials in relation to their potential applicability for plate shells.

4.12.1 Roofing membranes

Roofing membranes (such as EPDM or bitumen) can be applied to roof surfaces at any angle, including flat roofs. Material can either be pre-cut to the size of individual plates (optionally with some overlap at the joints), or to larger surfaces that cover multiple plates. The latter approach (which has been used for the BUGA Wood Pavilion) is less labour-intensive and reduces the number of joints in the roofing membrane. This method can only be used when using material that can accommodate some stretching, such as EPDM.

4.12.2 Rigid plates

Plates made out of timber or metal placed on wooden laths can be used as the outer surface of a roof. This may be done for visual appearance or to provide mechanical protection and UV protection for the underlying roofing material. Such plates would need to be tailored to the plate shell geometry (resulting in formatting costs, added logistic complexity, and cut-off waste), but due to their limited thickness, edges would not need to be slanted, and thus three-axis formatting processes (such as milling, sawing, water jet cutting, or laser cutting) can be used. Water tightness is not provided by such plates and thus needs to be ensured by the layer below the plates.

4.12.3 Metal strips or profiles

Instead of following the exact segmented roof shape, a curved metal roof could be constructed, using zinc, steel, copper or aluminium. However, such roofs only provide an effective rain-tight roof for somewhat inclined surfaces: for example, NedZink lists a minimum inclination of 3° and recommends an inclination of at least 7° [94]. Therefore, for areas near the apex of a shell, a different solution would need to be used. Furthermore, a suitable substructure would need to be created, and the global design would need to consider the geometric constraints of strip-like roofing.

4.12.4 Roof tiles and shingles

Roof tiles and wooden shingles only provide sufficient rain protection at strongly inclined roof surfaces. Plate shells typically include areas with low roof slope angles, which precludes the application of these materials.

4.13 Integration of installations

This section discusses possibilities for the integration of various kinds of installations within the two selected plate types.

4.13.1 Cables

Electric cables can be integrated in solid CLT plates by routing channels into the upper surface of the plates, smoothly curving down into locally drilled or milled holes wherever electricity needs to be provided. Cables of the YMvK type could be inserted directly, with the benefit of small bending radii and relatively easy installation, or conduits could be placed in the routed channel. The latter option is preferable in case of cable breakage and may be required by building code in some countries.

If the main air barrier is located on top of the joints (using tape, see Section 4.7), the routed channels would also need to be covered. When the air barrier is formed by seals within the joint, covering the routed channels is not necessary, provided the entry and exit points are sealed off.

In hollow components, cables (such as XMvK or YMvK) can be easily led through the structure, particularly when holes in the edge elements are already created in the prefabrication stage. In case building code prescribes the use of conduits, these can also be led through the edges, although installation will be more complex. Routing conduits through the top plate of a hollow component should be avoided because this would strongly reduce structural performance and because leading conduits through a thin plate without compromising air tightness is challenging.

4.13.2 Piping

Rigid pipes (for example for sprinklers) could be installed in solid CLT plates similarly to cables: by routing channels from the top. However, a significant loss of construction height would occur, and considerable effort would need to be put into creating pipe geometry that matches the plate shell geometry.

In hollow components, sprinkler systems could not be routed in the top plate, as generally, the material would not be thick enough to accommodate this. Leading sprinkler systems through the hollow inside of the components is possible when openings are cut through the edges and pipe geometry is adjusted to the plate shell geometry.

4.13.3 Air ducts

In solid plates, integrating air ducts would compromise structural integrity, as large amounts of material would have to be removed. In hollow components, flexible ducts could be led through the hollow interior, provided that edge elements include openings to lead the ducts from plate to plate. The dimensions of ducts are naturally limited by the distance between the top and bottom plates of hollow components; depending on this distance and the required ventilation rate, it may or may not be possible to meet ventilation demands. Although rigid ducts produce less noise than flexible ducts, their application is impractical due to the many necessary joints that would need to be created at positions that are hard to reach.

Various ways to integrate air ducts in the global design of a plate shell are discussed in Section 5.6. Solutions that are independent of the structure can also be used, such as placing the air ducts freely in the space or integrating air ducts in the floor or in the walls.

4.14 Costs

As a relatively new construction system that has only been applied in a few projects (many of these involving collaborations between academia and the construction industry), there is currently insufficient data to establish a statistically significant body of cost data on timber plate shells. Furthermore, due to the risks of taking on a project that contractors are unfamiliar with, finding a contractor willing to construct a timber plate shell may prove difficult. A quoted price is likely to be higher than expected based on material and labour costs, as contractors naturally need to offset risks, and as investments may need to be made in the production facilities.

It is, however, possible to estimate material costs and the necessary machine and labour time. Tables 4.2 and 4.3 show such estimates for a solid CLT plate and for a hollow component. For each fabrication step, there are many uncertainties that depend on the conditions in a specific fabrication facility (such as the available machinery, the layout of the facility, the methods used to store and move material, the skill level of employees, and the level of automation). Therefore labour and machine time estimations should be considered a rough estimate.

solid plates	**unit cost**	**amount**	**cost (€)**
CLT (10 cm thick)	600 €/m³	0.59 m³	354.00
screws	0.25 €/piece	85 pieces	21.25
labour + machine time (prefabrication)	100 €/h	25 min.	41.67
on-site assembly	44 €/h	45 min.	33.00
			449.92

Table 4.2: Estimation of production costs for a 5 m² hexagonal CLT plate that is 10 cm thick.

Material costs in Tables 4.2 and 4.3 are estimates based on prices listed by various retailers and values given by Baukosteninformationszentrum Deutscher Architektenkammern [17]. The hourly labour costs for assembly are also based on this source. For the prefabrication stage, a combined hourly rate for a machine with an operator is assumed. These costs are set higher for the hol-

hollow components	**unit cost**	**amount**	**cost (€)**
LVL	750.00 €/m³	0.26 m³	208.13
glue	13.58 €/kg	0.166 kg	2.25
bolts, nuts, washers	2 €/connection	10 connections	20.00
labour/machining	150 €/h	90 min.	225.00
on-site assembly	44 €/h	30 min.	22.00
			477.38

Table 4.3: Estimation of production costs for a 5 m² hollow hexagonal component that is 14 cm thick.

low components because of their higher complexity. The material dimensions are based on a study by Bechert et al. [19].

For solid plates, the costs of the timber itself represent 78% of the total costs; for hollow components, this share is 44%. The material cost savings of hollow components are slightly lower than the additional machining and labour costs during prefabrication. Therefore the hollow component system is more expensive than the solid system in this comparison. However, the difference between the two cost estimates is only 6%, which is not significant given the limited accuracy of the estimates: for example, if the estimate for machining time for the prefabrication of hollow components would be decreased by 10 minutes, the cost difference would all but disappear.

4.14.1 Cost comparison with CLT slab

In the material use comparison in Section 4.1.1.2, a CLT slab needs to be 300 mm thick to span 12 m, whereas a timber plate shell of just 60 mm can span the same distance when using hinged supports. Based on the cost estimation shown above, a plate shell's production and construction costs are under €100 per square meter. Using a cost of €600/m³ for CLT, the cost for a square meter of the 300 mm CLT slab is €180. Thus in this example, the cost savings of using less material far exceed the additional fabrication costs. In situations where the structural support conditions are less suited to plate shells (such as when the supports are not fixed in the horizontal surface), the cost savings are smaller due to the additional material needed to create thicker plates.

A more exact cost comparison would need to be project-specific and should include the additional costs for the layers above the structure (thermal insulation, waterproofing, and optionally cladding) and the costs of joint seals, as well as additional design and planning costs. Given the cost savings from the low amount of necessary material compared to CLT slabs, timber plate shells can be expected to be cost-competitive with CLT slabs in projects where the existing structure provides structural support conditions that are suitable for plate shell or where such conditions can be created (see Section 5.3.1). The potential cost advantages of plate shells compared to other timber construction systems are largest for structures with longer spans because of higher material savings (see Section 4.1).

In addition to potential cost savings in the structure itself, there is significant economic potential due to the lower weight, which allows realizing projects where heavier systems would not be suitable at all. Furthermore, the spatial possibilities and architectural qualities that plate shells provide can add value to buildings, although this is hard to quantify.

4.15 Conclusion

In this chapter, properties of the plate and joint types selected in Chapter 3 were assessed.

With the exceptions of short spans (for which conventional timber construction methods are more material efficient) or structures that need to have a limited construction height, solid CLT timber plate shells are shown to be an exceptionally lightweight construction system, as long as the supports can resist thrust forces. Using hollow components instead of solid plates can result in further weight savings of over 50%.

Although plates in a timber plate shell are typically smaller than prefabricated floor slabs, on-site assembly is still relatively quick: a team of two people can assemble about 40 plates per day. As demonstrated by the BUGA Wood Pavilion project, this assembly can take place without falsework.

Regarding air tightness and moisture control, the two plate types perform equally well and solutions identical to those used for conventional timber construction (such as applying adhesive tape on joints) can be used.

Regarding fire safety, solid plates perform well as long as they are thick enough to not lose structural integrity after part of the wood has burned away. Hollow components can only be applied in situations where there are practically no requirements for containment of fire, unless the components are covered with fire-resistant material on the inside.

Thermal insulation is better for solid plates, but this can easily be mitigated by using slightly more thermal insulation material when using hollow components.

Regarding acoustics, sound-absorbing material can easily be integrated into hollow components, but not in solid plates. On the other hand, solid plates provide much better sound insulation, although hollow components can also provide sufficient sound proofing in the vast majority of cases when filled with insulation material and when including the contribution of the thermal insulation layer.

Electric cables and lighting can be integrated easily in hollow components; cables can be led through dedicated holes in the edges or through gaps at the corners of the components. In solid plates, cables could be integrated as well, but this would require the creation of grooves for this purpose, either in the prefabrication process or on-site. Small ventilation channels could theoretically be integrated into thick hollow components, but this is not practical due to the large number of necessary connections at non-standard angles. Strategies for the integration of HVAC systems will be explored further in Section 5.6.

Material cut-off losses will occur when producing non-rectangular plates out of rectangular stock material. For regular hexagons, the cut-off is at least 25% when cutting one hexagon out of a rectangular slab, but cut-off losses could even approach 50% in unfavourable cases. Substantial material savings can be achieved by taking cut-off losses into account in the design process: by using stretched plates and controlling curvature, cut-off losses can be kept under 10%. Hollow components produce less cut-off waste than solid plates in absolute terms, but not necessarily in relative terms.

The environmental impact of timber structures is generally very good, thanks to the effect of carbon storage; timber plate shells are no exception. Solid plates provide much larger carbon storage than hollow components but for both systems, the favourable effects of carbon storage are more than an order of magnitude larger than the impact caused by the use of metal fasteners and the energy use of formatting. While cutting losses of timber may not show additional environmental impact in life cycle analysis, cutting losses also occur for the waterproofing layer and (depending on the type of material used) the thermal insulation layer. However, the positive contributions of carbon storage outweigh the environmental impact of additional cutting losses in these other layers.

Compared to conventional prefabricated roofs, plate shells are more costly to produce due to a larger number of joints, resulting in higher formatting costs (particularly when using finger joints), more time needed for assembly and higher costs for fasteners. The high accuracy that is needed for good structural performance also contributes to higher formatting costs. In addition to the structure itself, thermal insulation, waterproofing, and cladding layers are also more complex to prefabricate and install. However, cost savings in materials can be substantial and may offset these additional costs. Hollow components have much higher fabrication costs than solid plates, but feature lower material costs. In comparison to concrete shell structures or other one-of-a-kind structures, timber plate shells are likely to be a cost-effective option as no formwork or custom-made joint elements (such as cast or milled metal joints) are required, but accurate cost comparisons can only be made by evaluating specific projects.

Overall, this chapter demonstrated that both plate shell types introduced in Chapter 3 are suitable for vertical extension projects. The system made out of CLT plates is easier to produce and has advantages in situations requiring fire resistance or high sound insulation. The system with hollow components is more complex to fabricate, but results in a much lighter structure.

5

Architectural design of plate shells

This chapter explores topics related to the architectural design of plate shells. While the focus is on vertical densification projects, some of the findings apply to timber plate shells generally or even to plate shells made of other materials.

The chapter starts with an overview of the choice of plate type, thermal insulation material, and waterproofing material, building upon findings from Chapter 4. After this, spatial typologies, structural support considerations, lighting, and HVAC integration are discussed. The last section of this chapter shows examples of plate shells for a series of spatial situations and discusses joint details and architectural quality.

5.1 Suitable applications

Plate shells are relatively difficult to design and fabricate, but timber plate shells are a suitable construction system for a number of applications due to their specific properties.

First of all, timber plate shells are particularly suitable for projects where weight is a major concern, as their weight can be significantly lower than that of other construction systems, particularly at larger spans (see Section 4.1), provided that thrust forces can be effectively resolved. Vertical extensions of existing buildings are an example of projects where weight is often a major concern, as the addition of extra floors is not typically anticipated in the design of the existing structure. Even when a majority of buildings have the structural potential to carry an additional floor (see Section 2.1.2.2), low self-weight of the roof structure has advantages: it can minimize the necessary interventions in the existing structure, it can make vertical extensions possible for buildings with a load-bearing capacity that is just too low to carry heavier roof structures, and it allows the use of functions with higher live loads.

Secondly, timber plate shells can be a good choice when structural efficiency leads to material savings that offset the costs of the fabrication complexity (see Section 4.14).

Thirdly, timber plate shells are suitable for projects where their specific appearance or spatial possibilities (discussed in Section 5.7) are desirable.

5.2 Buildup choice

The choices for a specific plate type (solid or hollow) and for additional layers (such as thermal insulation and waterproofing) can be made largely independently; therefore, these choices are discussed in two subsections.

5.2.1 Plate type choice

Various properties of two plate and joint types have been discussed in Chapter 4. To support the plate type choice for a particular project, the most relevant properties are summarized in Table 5.1. In this table, the plates are only compared to each other and not to other construction systems: for example, even though both plates act as carbon storage, this property is marked as positive for the solid plates and negative for the hollow components as the former type stores more carbon.

	solid plates	**hollow components**
low weight	-	+
fire resistance	+	-
simplicity	+	-
carbon storage	+	-
sound insulation	+	-
acoustics	-	+
costs	0	0
disassemblability	-	+
cable integration	-	+

Table 5.1: Relative strengths and weaknesses of solid plates and hollow components.

For vertical extension projects, fire resistance is often a concern, particularly in densely built areas. As solid plates feature better fire resistance and sound insulation while being simpler to construct and having a more positive environmental impact, this plate type is the best choice for most projects.

In case fire resistance is not a concern, hollow components should be used if the weight of the structure needs to be extremely low, when acoustics (but not sound insulation) are of particular interest, when the option to integrate cables and/or lighting is deemed important, or when the structure is likely to be disassembled and reassembled in the future.

5.2.2 Additional layers

On top of the timber plates, additional material is needed to ensure air tightness, moisture tightness, thermal insulation, and waterproofing. As discussed in Section 4.7, air and moisture tightness can be achieved by applying airtight tape on the joints on top of the plates. Thermal insulation material and a waterproofing membrane can then be added.

For the thermal insulation layer, systems that consist of a single layer and do not rely on additional elements for structural support are a good option, as such systems are geometrically the least complex. Examples of suitable systems are wood fibre insulation boards, mineral wool, and glass wool, each with a sufficient density to be walked upon without damage. When supports for an additional visual layer on top of the waterproofing layer are required, soft insulation materials in combination with wooden battens can be considered, as in that case, the wooden battens can also serve as support for the additional layer.

As a waterproofing material, materials that allow stretching have the benefit that larger areas (consisting of multiple plates) can be covered with a single sheet of material, which minimizes the number of joints and total joint length. This has both economical benefits and reduces the risk of leaking. An example of a suitable waterproofing layer material that allows some stretching is EPDM (see Section 4.12.1).

Further layers may be added for visual appearance; for example, both the Forstpavillon and the BUGA Wood Pavilion feature an additional timber layer raised by wooden battens. Such a layer also protects the waterproofing material from impact damage (for example, when accessing the roof by foot) and from UV radiation, although the joint areas are still exposed.

5.2.3 Formatting of the thermal insulation layer

To ensure that a thermal insulation layer consisting of rigid thermal insulation plates fits tightly at all plate edges, either these plates would need to be formatted at the correct angle for each edge, or the edges would need to be filled in with a more compressible material. This section discusses several ways to create a thermal insulation layer using various levels of prefabrication. Of these options, prefabricating the thermal insulation plates and installing them on site after the timber plates have been fixed seems to be the most practical solution.

5.2.3.1 On-site formatting

Formatting thermal insulation plates on site is a complicated procedure, as in addition to following the shape of the timber plates, the joint edges need to be cut at the correct angle at each edge. The process would be significantly simplified if the material would allow some compression, so that the edges can be cut straight or at a fixed angle, but this solution is at odds with the requirement that the material should be rigid enough to walk on.

A combination of using rigid material (cut at straight angles) to cover the central part of a timber plate and a more flexible material to cover the joints would simplify the formatting complexity, as the rigid insulation would not need to be cut at slanted angles. Any sprayable material (such as cellulose thermal insulation) or expanding foam that results in sufficient rigidity to support the waterproofing layer could be used to fill the joints.

5.2.3.2 Pre-formatting

A process in which thermal insulation plates are formatted in a prefabrication process and installed on site greatly simplifies the installation process, while at the same time ensuring a tight joint fit. The prefabrication process complexity is comparable to the formatting of polygonal CLT plates and should thus be feasible in timber plate shell projects.

5.2.3.3 Prefabrication

Including the application of a thermal insulation layer in the prefabrication process of timber plates would lead to less complex labour on the construction site but would make the top of the joints between the timber plates inaccessible. This precludes the use of tape for air proofing and also means that no mechanical fasteners (such as crossing screws) could be applied from above.

When adding thermal insulation material to the plates while excluding a narrow zone along the joint, air proofing tape can still be applied on-site, after which straight strips of thermal insulation material can be used to fill the gaps. As this approach does not resolve the accessibility limitations, it only works well when inserting crossing screws from below or when connecting hollow components with bolts.

5.3 Structural considerations for the design of timber plate shells

This section discusses structural properties of timber plate shells that are relevant from the perspective of architectural design. Establishing and evaluating the structural performance of joints (such as stiffness and bending stiffness) lies outside the scope of this dissertation.

To get a qualitative understanding of the structural impact of design choices, Finite Element Analysis is carried out. Only displacement under a single load case is considered; other load cases and stress are not investigated. Only relative results are shown, comparing design variations to a base case. Details about the calculation setup used to generate the figures can be found in Appendix B.

5.3.1 Support conditions and thrust

Shell structures are particularly effective when horizontal movement of support points is prevented. In the examples in Section 4.1, shells with supports constrained horizontally on both sides show deflections between 18 and 135 times smaller than shells for which supports are constrained horizontally on only one side. Therefore, the way an existing structure supports a plate shell should be a central consideration for any plate shell design.

In funicular shell structures, the magnitude of thrust forces (the horizontal forces acting on the supporting structure) depends on the direction in which the shell touches the ground and thus on the height of the shell, with shells with a higher rise causing lower thrust reactions. This effect also occurs in plate shells, as shown in Fig. 5.1.

Thrust forces can be cancelled out by structurally connecting the support points on all sides of a shell. For continuous domes, this can be done with a tension ring. For shell structures standing on an existing horizontal surface (such as a concrete floor), the forces could be led through this surface (after reinforcing the surface when necessary). In specific cases, beams or walls located right below but perpendicular to a shell support can also help resist the thrust forces. When plate shells do not rest on a floor but span from wall to wall, thrust forces may need to be resolved

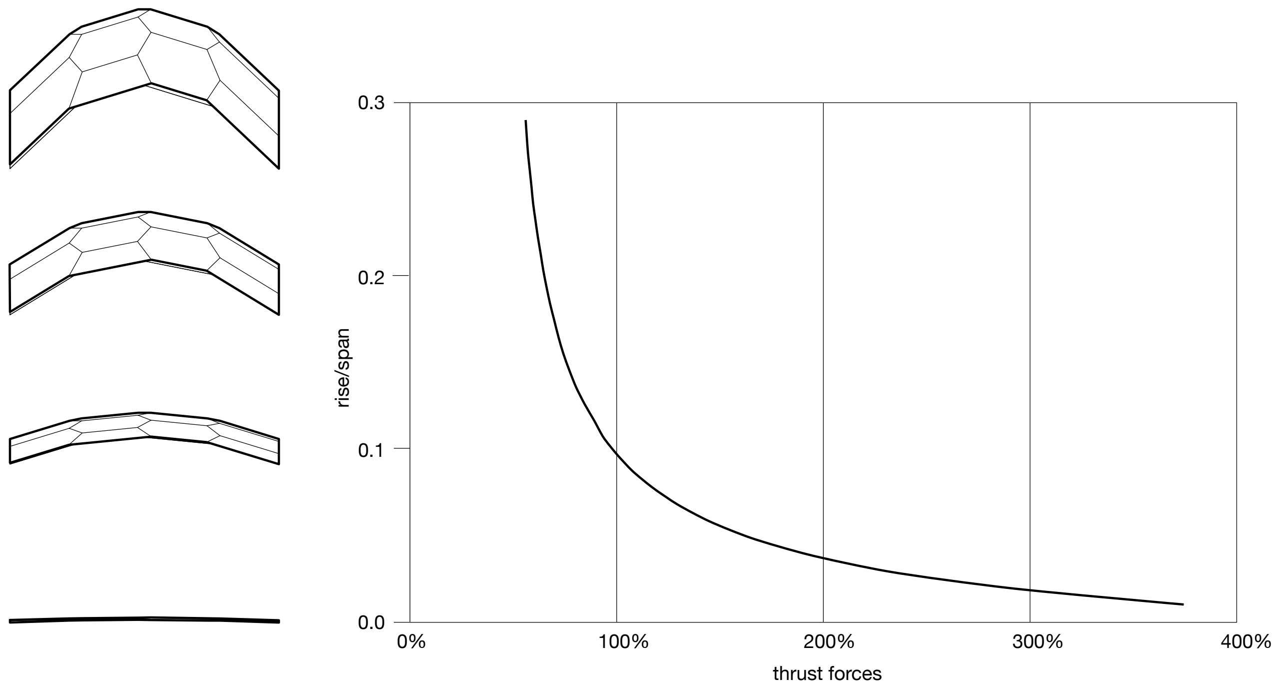

Figure 5.1: Thrust forces as a function of shell rise.

by introducing tension cables or rods at the level where the plate shell is supported (see Fig. 5.2). In symmetrical configurations, thrust forces cancel out where two shells come together.

5.3.2 Construction height in relation to structural performance

Shell structures with low rise-to-span ratios are less structurally efficient than those with higher rise-to-span ratios, as the same loads lead to higher forces; in two dimensions, this can easily be verified using graphic statics [106].

An example showing the effect of rise (achieved by scaling a plate shell vertically) in a plate shell spanning a space from wall to wall in an arch-like manner is shown in Fig. 5.3. As can be seen, nearly flat plate shells have only very limited stiffness, whereas

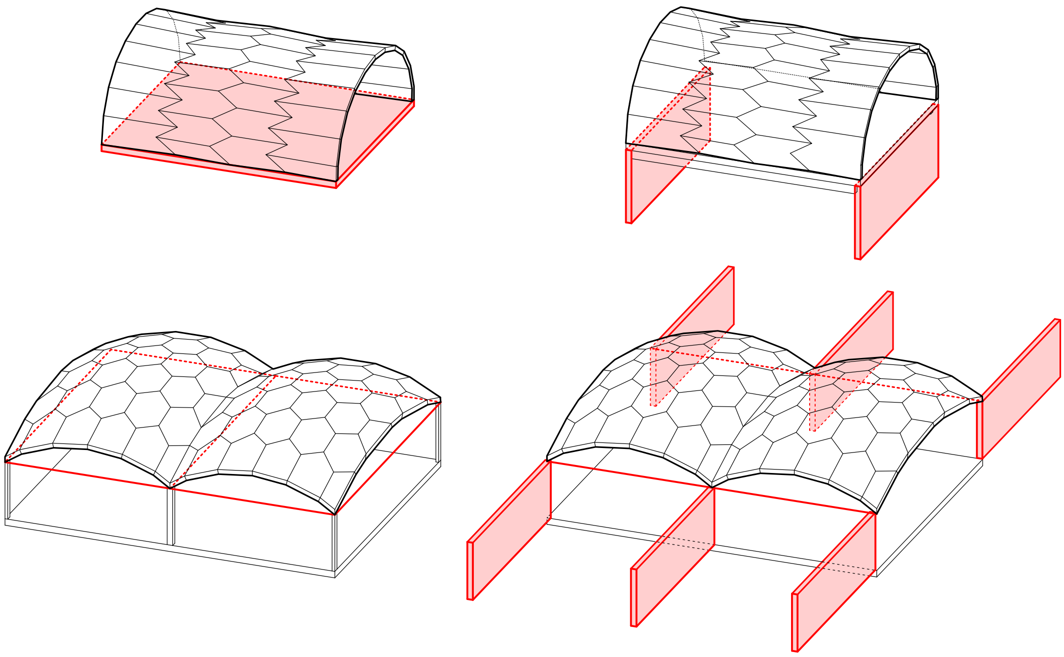

Figure 5.2: Strategies to counter thrust forces: connecting support points within the floor surface (top left), using walls below the supports (top right), connecting supports with tension rods or cables in the interior space (bottom left), and using walls adjacent to the space (bottom right).

increasing the height of the plate shell decreases deformation dramatically. Near-flat regions should therefore be avoided in plate shell designs.

As the structure shown in Fig. 5.3 is curved in two directions, it would be interesting to investigate the influence of varying the rise height in two orthogonal directions individually. However, such a comparison cannot be made as adjusting rise height in just one of the directions will change the segmentation pattern, which by itself also influences stiffness, as seen in the next section.

5.3.3 Structural properties of segmentation patterns

Segmentation patterns influence the force flow through a structure and the distribution of reactions on supports: depending on the

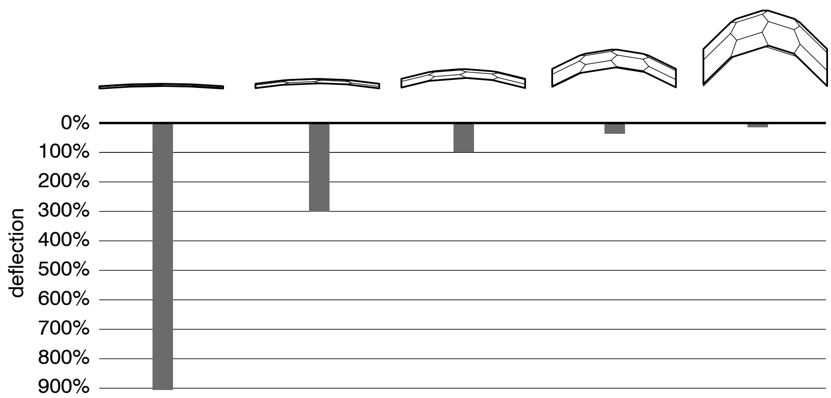

Figure 5.3: Deflection as a function of the rise of a plate shell spanning from wall to wall, with the height of consecutive structures differing by a factor of two.

segmentation, forces can be distributed nearly equally along the supports, or they can be concentrated in specific locations [80].

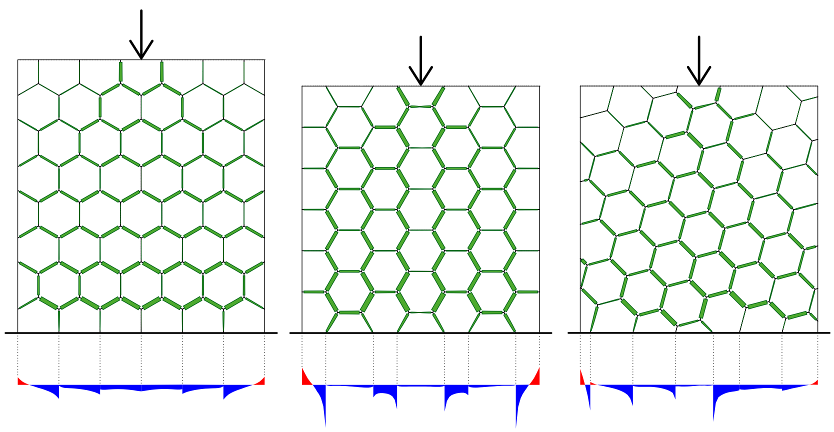

Figure 5.4: Forces exerted on a supporting line by various segmentations of a 2-dimensional segmented structure, loaded with a single point load at the top (figure after Li [80].

As shown in Fig. 5.4 (middle), support reactions are higher under the higher plates of the bottom row of plates than under the lower plates. In three-dimensional plate shells, support reactions depend on global geometry as well as on the segmentation pattern, but this phenomenon can still be used when designing plate shells: for example, Fig. 5.5 shows two segmentations of an arch-like shell, with the largest vertical support reactions occurring under the corner plates. When this corner plate is smaller than its neighbouring plate, the support forces are more evenly spread out, whereas when the corner plate is larger, the support forces are more concentrated. Which of these two solutions is preferable depends on the underlying structure and on the structural concept.

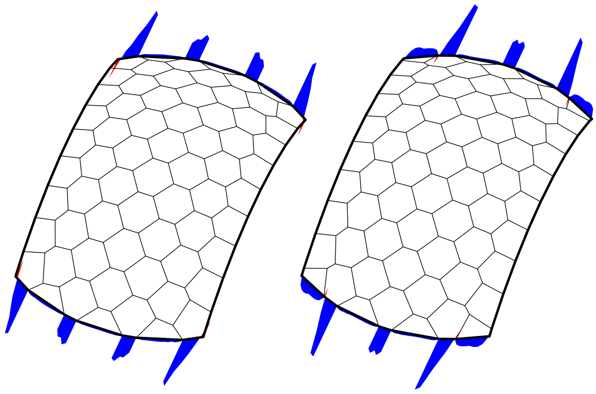

Figure 5.5: Forces exerted on a supporting plane by two different segmentations of an arch-like structure.

As joints are the least stiff part of a plate shell, a series of nearly collinear joints can result in strong deformations. Fig. 5.6 shows the effect of the angle of zigzag joints on the deformation of a flat structure: with angles of 0° (collinear), the deformation in this example is about twice as large as the deformation with sharp angles.

Short edges should be avoided whenever possible, as shear stresses in an edge are the result of the total shear force between two plates divided by the edge length, and thus short edges tend to lead to local stress concentrations.

Logically, the number of joints that need to be traversed between supports can be expected to affect stiffness, with fewer

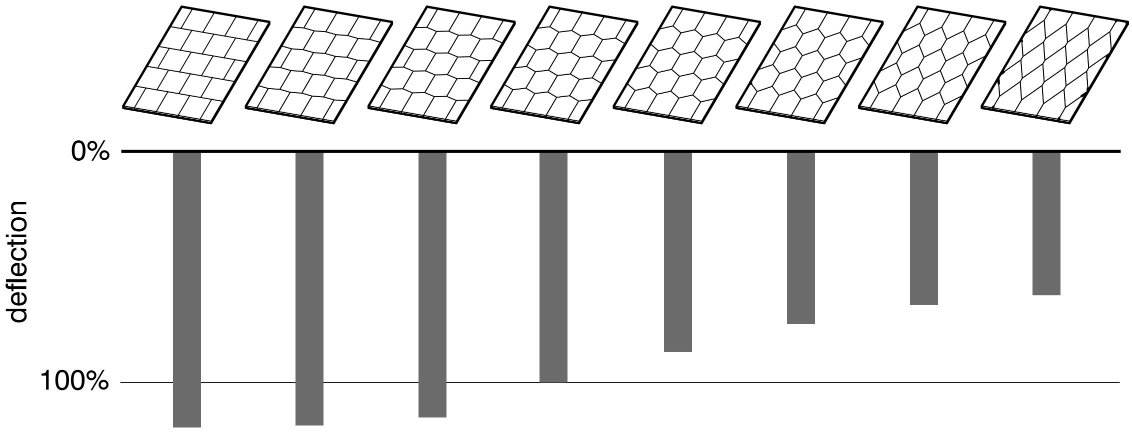

Figure 5.6: Relative vertical deformation of a flat segmented slab with various zigzag joint angles.

joints being preferable. However, when segmenting a given arch with fewer segments to achieve higher stiffness, the angle between the segments will be larger, and the zigzag depth will be smaller, which decreases stiffness. In the example shown in Fig. 5.7 (in which the total number of plates is nearly identical in each plate configuration), there is no correlation between the number of joints that need to be traversed and the vertical deformation of an arch-like shell.

5.4 Geometric support strategies

This section discusses strategies to support plate shells using structural supports that are present in existing buildings. As sections through plate shells are typically segmented approximations of curves while existing supports are usually linear or point supports, geometric strategies to reconcile these differences are needed.

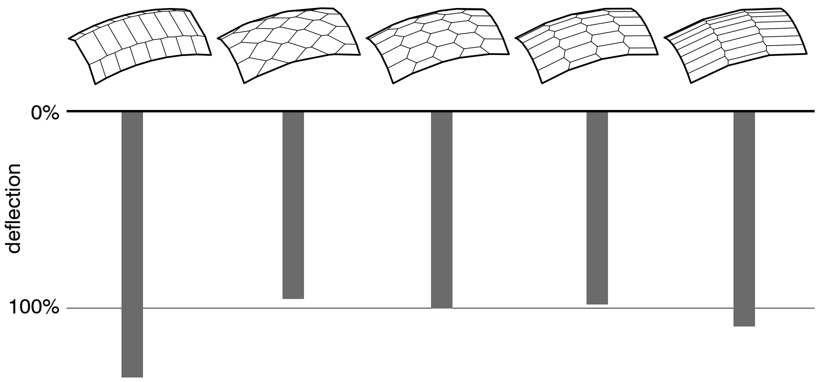

Figure 5.7: Deformation of various segmentations of an arch-like shell, using 24 or 25 plates.

5.4.1 Linear supports

5.4.1.1 Intersecting with a vertical plane

When linear supports (such as walls or beams) are present, a shell can be intersected with the vertical plane the support is contained within. The area below the intersection curve can then be filled in with a load-bearing material (see Fig. 5.8). The wall can take the vertical forces, but horizontal forces resulting from thrust will lead to bending. Supports on opposite sides will therefore need to either be connected or be supported in the perpendicular direction, except in symmetrical situations where two shells meet a linear support from opposite sides or when the plate shell is supported by walls on all sides.

5.4.1.2 Using local approximately planar areas

When two segments of a polyhedron are coplanar, any segment that borders these two segments will also be coplanar with the segments, unless the two edges of the new segment are collinear. Therefore, a polyhedron that approximates a synclastic double curved surface cannot locally turn into a planar segmentation,

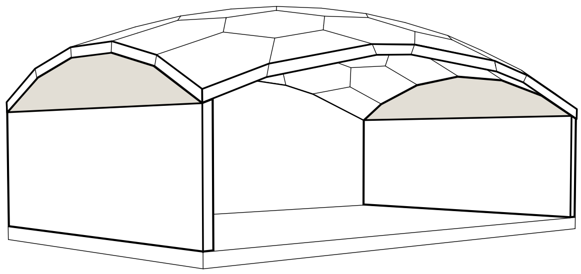

Figure 5.8: A shell supported by a wall, with the area between the wall and the intersection of the shell being filled in with load-bearing material.

which means that such a shape cannot meet a linear support exactly. However, as in reality both the plate shell and the supporting structure have a non-zero thickness, approximating a straight intersection line may be enough to create a structurally functional connection. Fig. 5.9 shows such a configuration, in which the deviation from the line of support is around 0.6 % of the span. However, the strongly anisotropic curvature leads to a series of almost collinear edges, thus requiring significant bending stiffness in the connections.

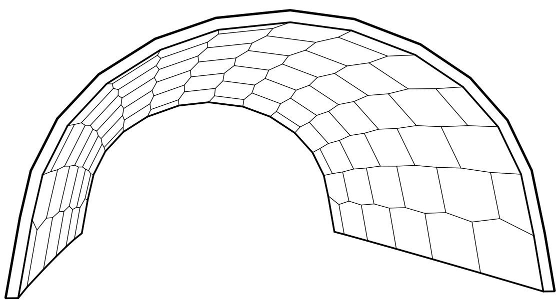

Figure 5.9: A polyhedral shell with approximately (but not exactly) linear supports.

5.4.1.3 Connecting synclastic shells to linear supports using anticlastic areas

Anticlastic areas at the base of predominantly synclastic shells can be used to make a shell meet linear supports. When generating a segmentation, the low curvature that occurs near the support typically results in stretched segments and/or nearly collinear joints, but a benefit of the example shown in Fig. 5.10 is that it approximates the linear support line more closely than the example shown in Fig. 5.9: the horizontal deviation in Fig. 5.10 is less than 0.3% of the span.

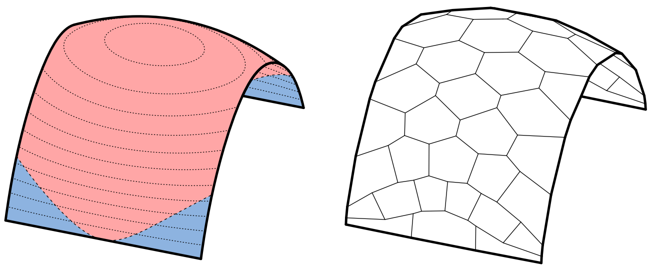

Figure 5.10: Synclastic shell connecting to a linear support using anticlastic areas (left) and a segmentation generated on this surface (right).

5.4.1.4 Alternating segment directions

Fig. 5.11 shows a tunnel-like polyhedron consisting of chevron-shaped segments. This shape intersects the ground plane in a shallow zigzag pattern. The depth of the pattern depends on the angle between rows of plates and the dimensions of the plates: logically, larger plates result in larger deviations from a linear support. Shallower angles between the plates would lead to smaller deviations and an even more pronounced zigzag pattern in the shell, which increases cut-off waste. The zigzag line of the example shown in Fig. 5.11 deviates from a straight support line by just under 1.4% of the span.

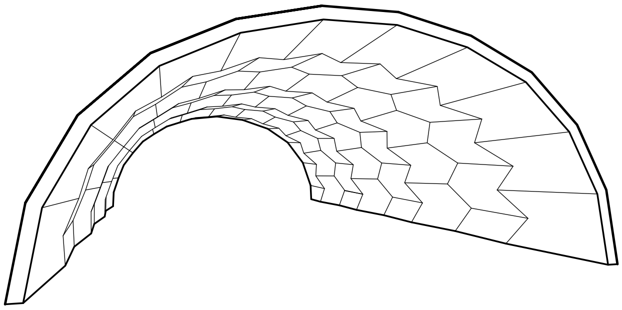

Figure 5.11: A tunnel-like polyhedral configuration, intersecting the ground plane in a shallow zigzag pattern.

5.4.2 Horizontally intersected shells

When no specific measures are taken to match linear supports, the intersections between plate shells and an existing flat roof structure are generally approximately curvilinear. Existing structural supports are unlikely to match such shapes, and thus loads need to be transferred to existing or new supports using bending in the existing roof structure (except when all supports of the plate shell are horizontally connected). Unless the existing roof surface is exceptionally rigid, the existing roof structure will need to be structurally reinforced.

The most straightforward way to reinforce a flat roof is to add beams in the main span direction and/or to reinforce existing beams. This way, the plate shell can be quite freely designed, as long as its support lines are roughly perpendicular to the beam structure (see Fig. 5.12, left). However, due to the relatively large number of beams, this solution is heavy and costly. If the beams are placed on top of the existing roof surface, this complicates the installation of thermal insulation and waterproofing on the flat roof surface outside, and on the inside of the shell, the new floor surface would need to be raised.

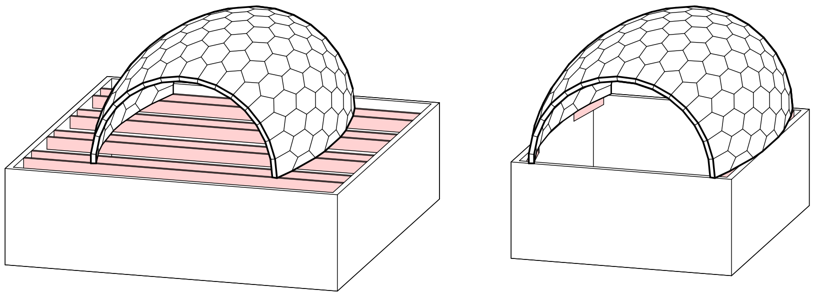

Figure 5.12: Shell structure supported by beams running in the main span direction (left) and beams placed at the corners of a roof (right). The example on the right assumes a floor (not shown) that structurally connects the walls.

When the plate shell is designed such that its intersection with the horizontal surface is tangential to existing load-bearing walls, supporting beams may only be needed in the corners, as illustrated in Fig. 5.12 (right).

5.4.3 Corners

When a plate shell only comes down at the corners of an existing flat roof surface, geometric complexity is reduced significantly, as only a few plates connect to the existing structure. An additional advantage is that at corners, thrust forces can potentially be resolved by in-plane forces in the walls.

Various corner plate configurations are shown in Fig. 5.13. Single plates can be supported by one of the walls or rest on both walls in a corner. When using two plates, each plate can be supported by one of the walls. By placing a diagonal beam in the corner, configurations with two or three plates can be realized. An example of a shell that is supported in this way is shown in Section 5.7.2.

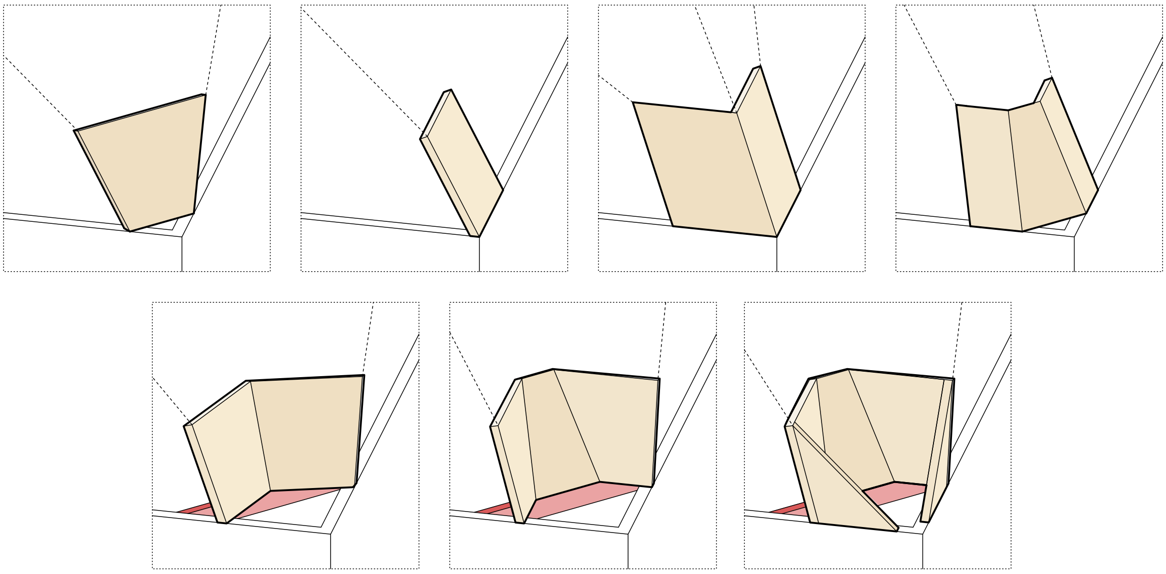

Figure 5.13: Examples of ways a shell can meet a corner of an existing building, including a solution used by Almegaard (bottom right). The configurations on the bottom row require a diagonal beam to be placed in the corner.

5.4.4 Columns and funnel configurations

Columns can be used to support plate shells in multiple ways: funnel-like plate shells (also shown by Almegaard [5]) can spring from points on a slab that are supported by columns (or walls), columns can be used to support plate shells at kinks where multiple surfaces meet, and plate shells can hang down from columns in tent-like configurations. These configurations are illustrated in Fig. 5.14.

Some of these solutions can lead to the accumulation of rainwater and/or snow and should thus only be employed when adequate measures are taken, either by integrating a downspout or by constructing a second surface that prevents rainwater and snow from entering funnels or trenches (see Fig. 5.15).

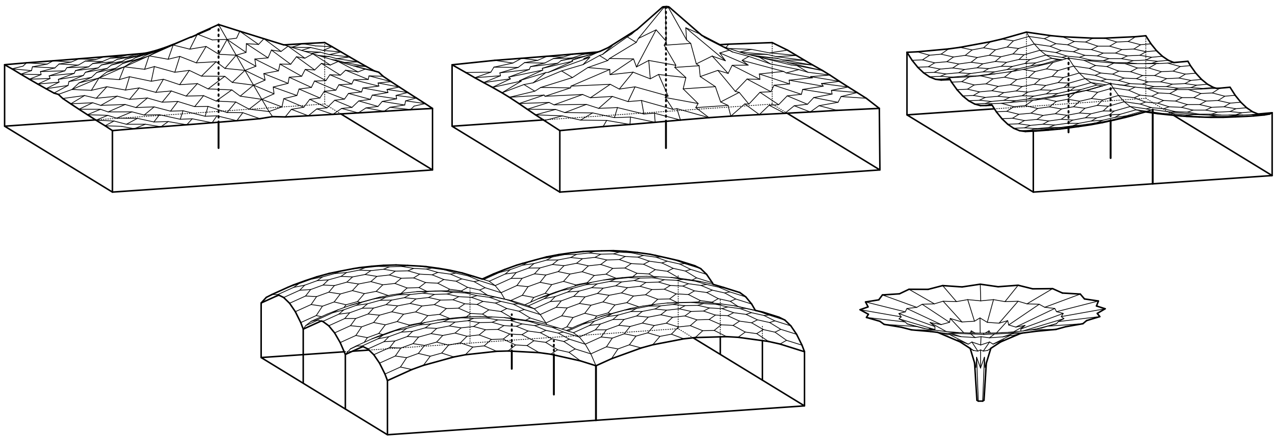

Figure 5.14: Examples of plate shells that use existing or new point supports in a horizontal surface: anticlastic plate shells hanging from a column (top left, top center), multiple synclastic shells (top right, bottom left), and a funnel-like configuration (bottom right).

5.5 Daylight

This section discusses various strategies to bring natural light into a space enclosed by a plate shell.

5.5.1 Windows in open sides

Any open side of a plate shell can potentially be used as a partially or entirely glazed façade. Depending on the orientation and geographic location, there may be a risk of overheating, which can be mitigated by including a cantilever in the plate shell. When aligning the mullions of a glass façade to the joints in the plate shell, window frames can be constructed out of four straight elements.

5.5.2 Skylights within plates

Standard skylights can be placed within plates, either as the main source of daylight or in addition to other openings. Round sky-

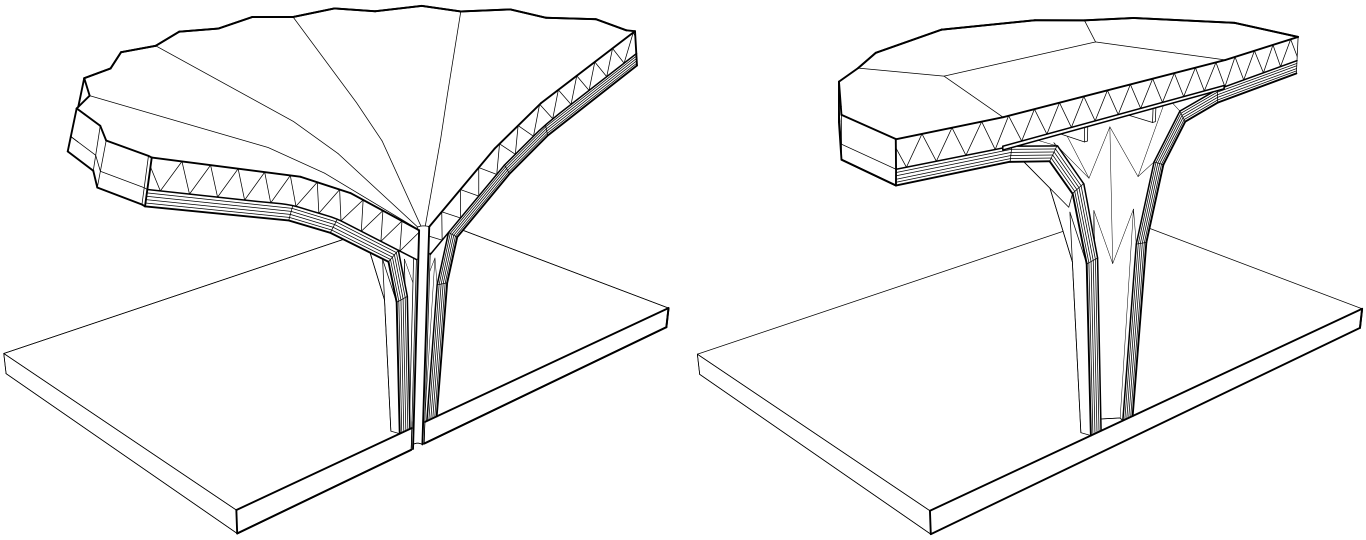

Figure 5.15: Prevention of water and snow accumulation by integrating a downspout (left) or by closing off a funnel (right).

lights have the aesthetic benefit of not interfering with the segmentation pattern (see Fig. 5.16, left).

As skylights are generally designed for flat roofs, water tightness is not guaranteed for strongly sloped roof surfaces. In Germany, the norm DIN EN 1873 (which is referred to by many skylight manufacturers) only applies to roofs with a slope of at most 25° [39] and skylights should thus only be applied to such roof surfaces, unless guarantees have been obtained that the window is suitable for a wider range of roof angles.

5.5.3 Removed plates or lanterns

Instead of placing skylights in a plate, an entire plate could be replaced by a window or lifted to create a lantern. While this results in more complex details, replacing a plate with a window also lets in more light. An illustration comparing such a solution with skylights is shown in Fig. 5.16 (right).

Figure 5.16: Visualization of an interior space with round prefabricated skylights (left), with rotated plates (middle), and with plates replaced by lanterns (right).

5.5.4 Rotated plates

By rotating individual plates along one of their edges and closing the resulting opening with glass, openings can be created. This solution is shown in Fig. 5.16 (middle). The opening direction can be chosen in such a way that mainly diffuse light enters the space.

5.5.5 Funnels

Multiple plates can be arranged in funnel configurations, so that the roof locally opens up to the sky. An example is shown in Fig. 5.17 (right).

5.5.6 Windows in sawtooth roofs

Instead of a contiguous shell, a series of shells can be used in a configuration similar to a sawtooth roof (see Fig. 5.17) (left). When the orientation is right, this can result in large amounts of diffuse daylight. A benefit of this solution is that the inside of the plates is lit by daylight, so the contrast between the plate shell and the sky is less strong than in other solutions. Roof drainage needs to be carefully considered when using this roof type.

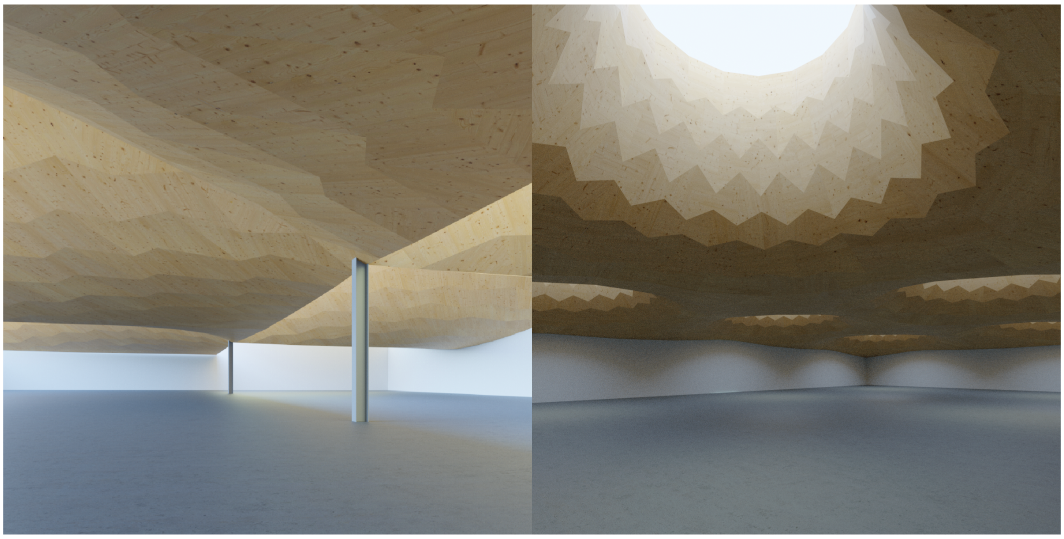

Figure 5.17: A roof in which daylight can enter between anticlastic shell segments (left) and through funnel-shaped openings (right).

5.6 Air duct integration

This section discusses strategies to integrate air ducts in plate shells.

5.6.1 Flexible ducts through hollow cassettes

As discussed in Section 4.13.3, flexible ducts can be led through the inside of hollow plates, provided that there is enough space between the top and bottom plates of the cassettes. To cross from one cassette to the next, edge elements need to be omitted locally; while this weakens the structure to some extent, edges do not need to be continuous in order for plate action to take place [146].

5.6.2 Duct alignment along kinks

When a plate shell design includes kinks, ducts could be constructed along these kinks. By including an intermediary row of plates between the shell segments, the duct can be constructed under this row, as illustrated in Fig. 5.18 (right).

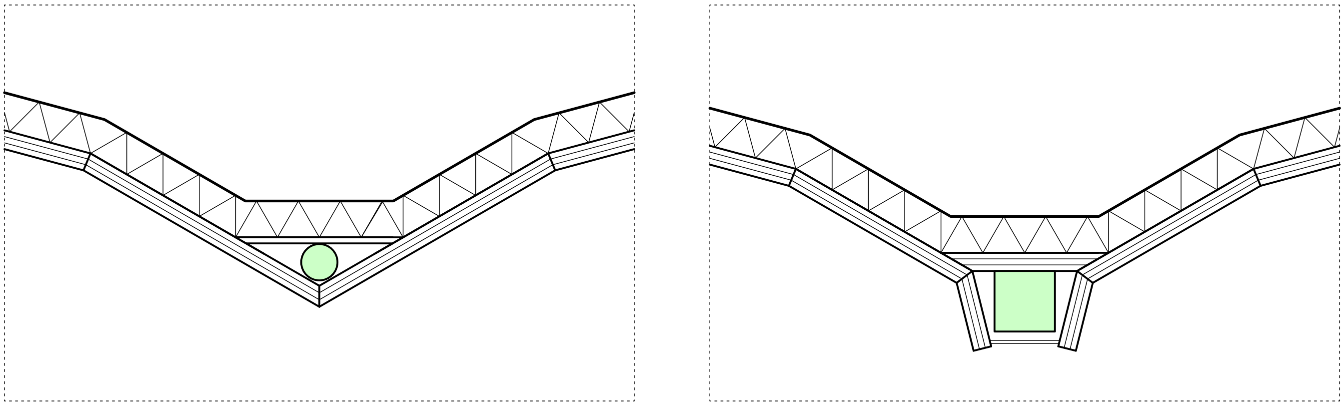

Figure 5.18: Detail showing possible integration of an air duct above (left) or below (right) the structure at a kink in a plate shell.

In principle, ducts could also be placed above the plates instead of under the plates, as in Fig. 5.18 (left). However, this severely limits accessibility and would complicate fire fighting if a fire occurs within or around the duct.

5.6.3 Duct alignment along an ordered row of plates

When a plate shell features ordered rows of plates, a duct can be constructed under a single row of plates. This way, the duct geometry remains relatively simple, particularly when the middle row of a symmetrical structure is followed: then the duct only has to include a series of small kinks perpendicular to its length (see Fig. 5.19 (left)).

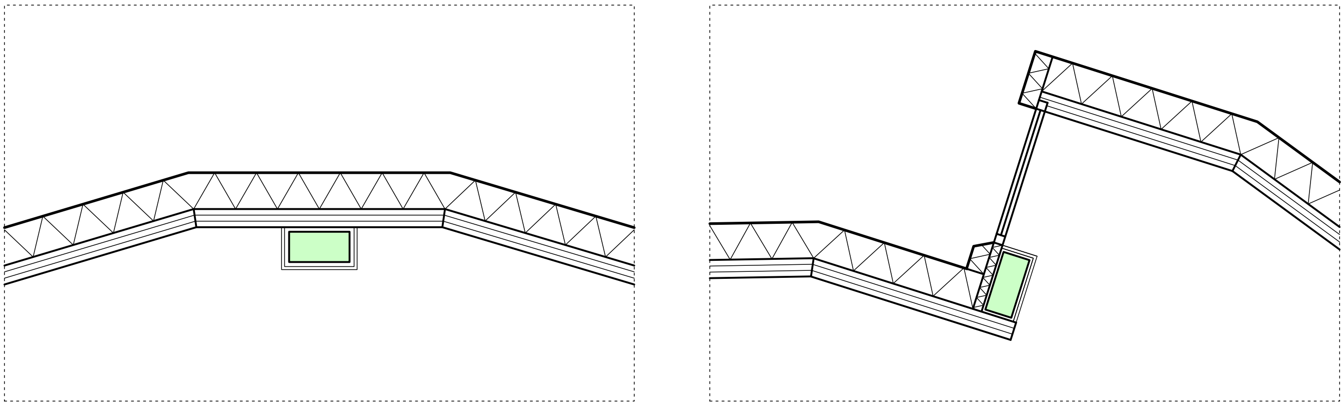

Figure 5.19: An air duct placed under a row of plates in a symmetrical plate shell (left) and placed along an open edge (right).

5.6.4 Duct integration along shell edges

In plate shells featuring open edges that are visible from the interior (for example, sawtooth-like roofs), air ducts can be placed along the open edges. An example of this is illustrated in Fig. 5.19 (right).

5.6.5 Duct integration in funnel columns

When a plate shell features funnel-shaped columns that consist of multiple plates, ducts could be placed within the columns (similar to the way downspouts can be placed in such columns, as illustrated in Fig. 5.15 (left)). The ducts could then be connected to channels that run under the floor structure.

5.7 Typologies

This section shows a selection of plate shell typologies and discusses their suitability for the vertical extension of existing buildings. The selection of types is intended as an illustration of the variety of the design space of plate shells, not as an exhaustive overview.

5.7.1 Axially symmetric structures, ellipsoids, and geodesic domes

Spherical and concentric designs (illustrated in Fig. 5.20) have a round ground plan and can thus be placed on an existing supporting structure that is also round, on a slab that is sufficiently stiff (by itself or after reinforcement), or on a circular beam that is placed on columns.

Segmentations can follow the axial symmetry of the design (resulting in multiple groups of identical plates, with plate size depending on the distance to the axis of symmetry), use a geodesic division (resulting in multiple groups of identical plates that have the same dimensions, independent of their position of the shell), or follow a less regular pattern.

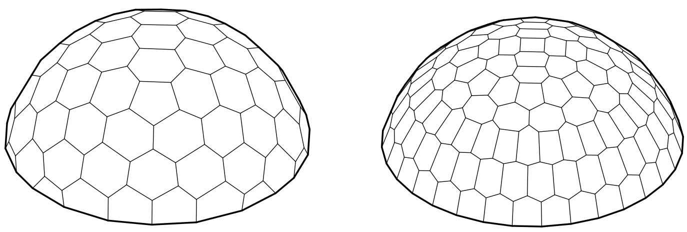

Figure 5.20: Axially symmetric plate shell designs featuring geodesic segmentation (left) and a modified meridian segmentation (right).

5.7.2 Predominantly synclastic shells

For vertical building extensions, predominantly synclastic shells (such as those shown in Fig. 5.21) have multiple advantages over other shell types. They can be supported by linear or point supports present in most buildings (see Section 5.4), there is no risk of rainwater accumulation, and multiple assembly sequences can be used (see Section 4.3).

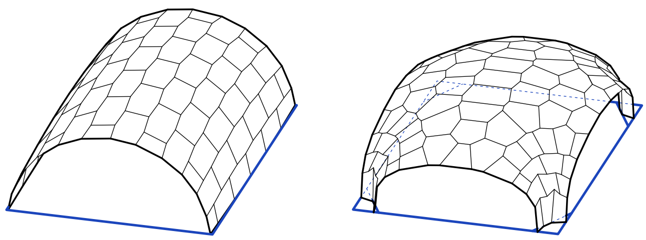

Figure 5.21: Barrel-like shells supported by linear supports (left) and supported at four corners (right).

5.7.3 Hyperbolic paraboloids

As hyperbolic paraboloids are ruled surfaces, plate shells that approximate such shapes can be designed so that their outer edges are planar or approximately planar. This can be beneficial when connecting to existing structures and may simplify details, such as gutter solutions.

A simple example of a hyperbolic paraboloid shape is a ruled surface between two walls (see Fig. 5.22). More complex designs may consist of a combination of multiple such arrangements, for example, by mirroring. In such a design, a column could be placed under the point where the surfaces come together, as in Fig. 5.14 (top left).

5.7.4 Funnel configurations

Funnel shapes can be created by arranging plates in an axisymmetric configuration. The narrow sides of the funnels can either be used as supports (shown in Fig. 5.23; see also Section 5.4.4) or as openings in a roof structure (shown in Fig. 5.24 and Fig. 5.17 (right)).

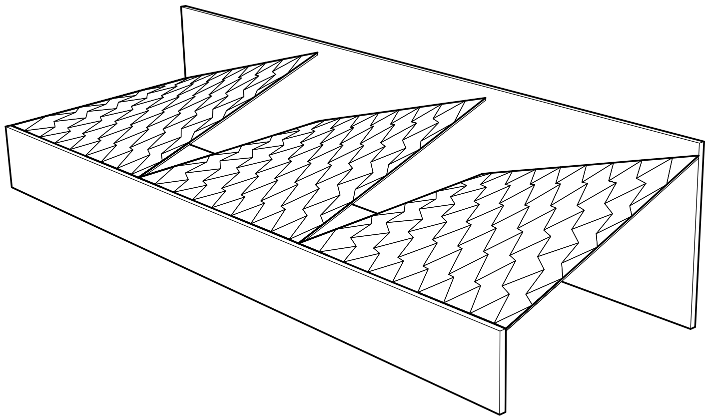

Figure 5.22: A plate shell consisting of multiple hyperbolic paraboloid surfaces spanning two walls.

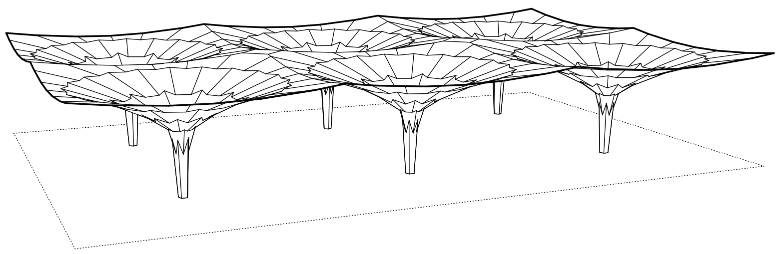

Figure 5.23: Funnel shaped columns turning into a roof.

5.7.5 Surfaces featuring gradual curvature transitions

Various plate shell types feature transitions from synclastic to anticlastic areas, including certain axisymmetric arrangements, horizontally curved barrel vaults, arrangements based on series of rows of plates and irregular shapes (see Fig. 5.25).

Axisymmetric plate shells with a curvature transition can be used in situations as described in Section 5.7.1, but as the example in Fig. 5.25 shows, the lower part of such structures tends to spread out horizontally and therefore this type can be made to fit a larger range of support conditions than just circular supports. However,

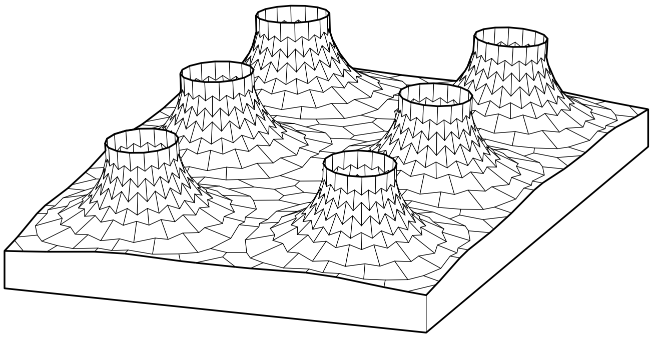

Figure 5.24: Funnel shapes forming openings in a roof.

bending moments will occur because of the limited curvature in the lower part of these structures, making this plate shell type less structurally efficient than most other plate shells.

Curved barrel vaults lead to anticlastic curvature on the inside and synclastic curvature on the outside, with a transition at the top. The simplest example of such geometry is a regular segmentation of a torus, as shown by Wang [139], who also presents a regular segmentation on a deformed torus. Using a similar segmentation pattern, barrel vaults following a curved trajectory can also be created, as illustrated in Fig. 5.25 (top right).

Examples of a curvature transition in a structure that consists of rows of plates with identical shapes when projected on the ground plane are shown in Section 6.2.3. Such plate shells could span between parallel walls, provided that rainwater runoff is taken into account.

Finally, an example of a plate shell featuring a synclastic and an anticlastic area, without any symmetry axes and without the segmentation pattern being aligned to the parabolic line is the Forstpavillon in Schwäbisch Gmünd (illustrated in Fig. 5.25 (bottom right)).

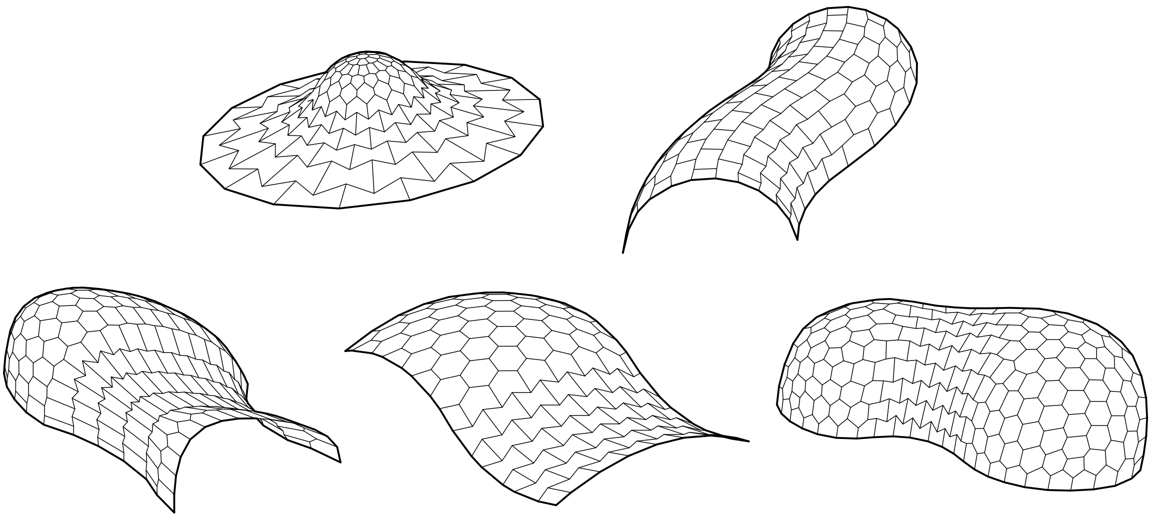

Figure 5.25: Plate shells featuring curvature transitions: an axisymmetric arrangement (top left), a horizontally curved barrel vault (top right), two structures featuring transitions along a row of plates (bottom left, bottom center), and the Forstpavillon in Schwäbisch Gmünd (bottom right).

5.7.6 Kinks and cantilevers

By combining and intersecting multiple shells, plate shells with kinks can be created. In addition to contributing to the stiffness of a design and partially cancelling out thrust forces, there are spatial advantages: Compared to a single synclastic shell, a combination of multiple synclastic shells that come together in arch-shaped kinks leads to a more consistent ceiling height (see Fig. 5.26). Unnecessarily high floor heights under the highest point of the shell and/or impractically low floor heights at the lowest point of the shell are thus avoided.

Kinks can also be used to create cantilevers, which can help stiffen open shell edges; this has been done in the BUGA Wood Pavilion [7]. Additionally, cantilever geometry can help keep out direct sunlight from high sun angles while providing more space for glazed façades (see Fig. 5.27).

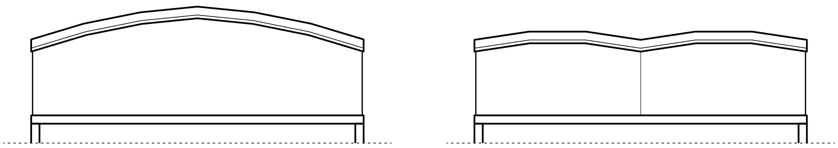

Figure 5.26: Section through a single shell and through a shell consisting of two synclastic shells.

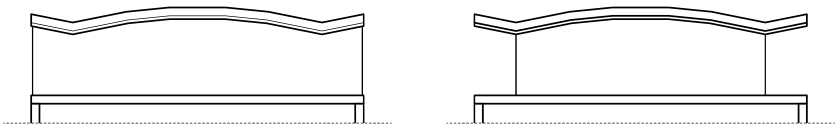

Figure 5.27: Cantilevering geometry provides structural stiffness and allows the creation of a large glazed façade (left) or, conversely, can help shield the façade from direct sunlight (right).

At kinks, segmentation patterns can be mirrored, or plates can be staggered. These options are illustrated in Fig. 5.28.

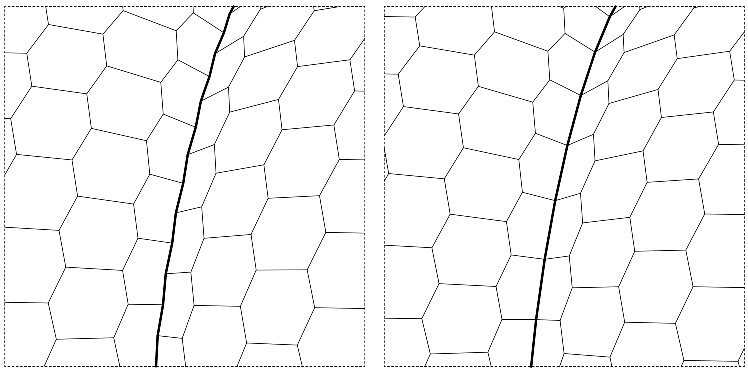

Figure 5.28: Segmentation pattern at a kink between surfaces, with staggered plate positions (left) and mirrored plate positions (right).

5.7.7 Tunnel-like configurations

By linearly connecting multiple shells, tunnel-like configurations can be created. This can be done by using synclastic shells that come together in kinks or by combining synclastic and anticlastic areas (see Fig. 5.29).

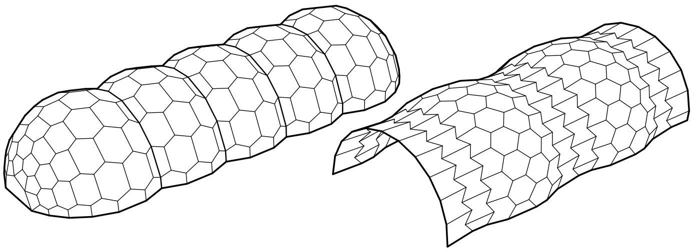

Figure 5.29: Linear plate shell featuring kinks based on the Spaceplates design [103] (left) and linear plate shell featuring alternating synclastic and anticlastic areas (right).

5.7.8 Sawtooth roofs

Connecting multiple shells that have different heights at opposing sides results in openings that let in daylight (see Fig. 5.30 and Fig. 5.17).

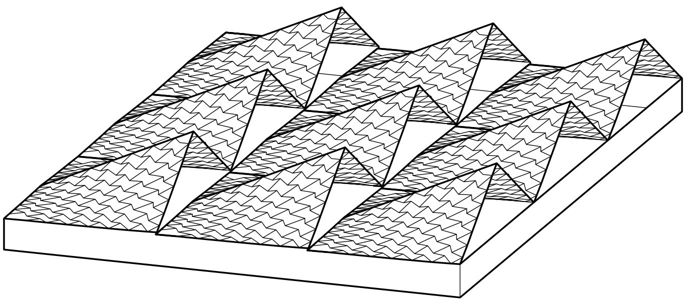

Figure 5.30: A sawtooth roof formed by multiple anticlastic plate shell segments.

5.8 Architectural joint details

During the prefabrication process, the edges of plates may be somewhat rough as a result of cutting or milling operations. Sanding can be used to achieve a more finished result, but a mill or router can also be used to create specific edge profiles. This can help protect the visible edges during transport, handling, and assembly, as the visible edge is less likely to come in contact with tools and other objects, and as the edge can be made less sharp and more robust. It will also create a different visual appearance, stressing the plate shapes and joint pattern, while making imperfections in the joints less visible. Several edge profiles are shown in Fig. 5.31; the effect on the visibility of the segmentation pattern is illustrated in Fig. 5.32.

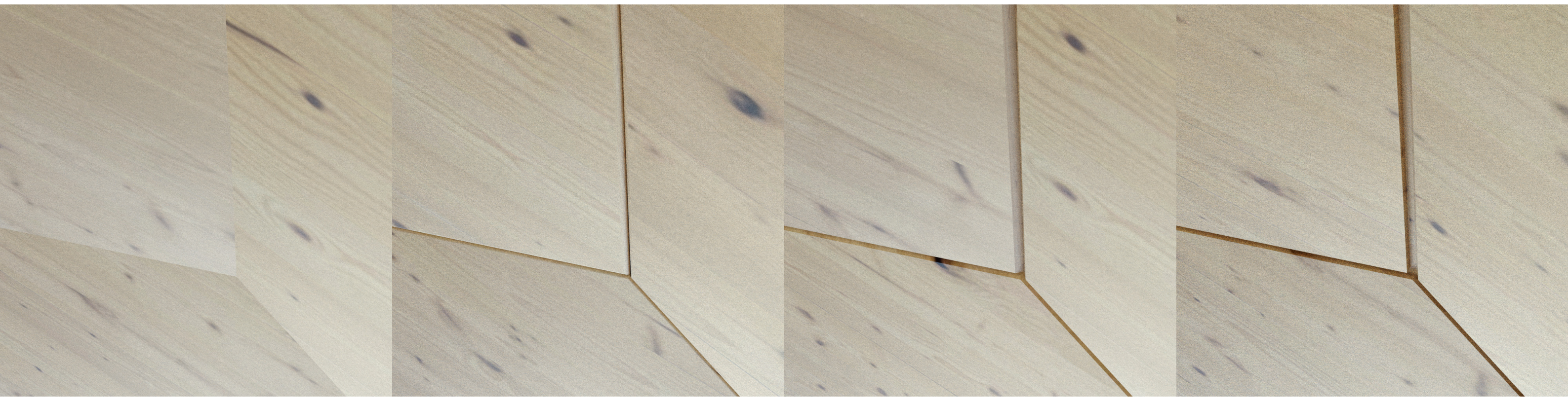

Figure 5.31: Joint details: butt joint (left), rounded edge (center left), 45° chamfer (center right), and straight shadow gap (right).

When a joint features finger joints, edge details as discussed above can either follow the finger joint geometry or be created in a straight line without taking finger joints into account. With sufficient width, it would be possible to hide the finger joint detail in a shadow gap.

Figure 5.32: Appearance of plates with butt joints (left) and plates with a shadow gap (right).

All joint edge details except butt joints will reduce structural performance as the structural height of the joint is reduced. Edge details should thus not be made deeper than necessary.

5.9 Architectural expression

Timber plate shells feature a combination of specific architectural qualities that set them apart from other construction systems. Among these qualities are a non-orthogonal spatial vocabulary, the material presence of wood surfaces, and the visual expression of structural and construction logic.

The spatial vocabulary of plate shells has been illustrated in Section 5.7; most of the examples would be difficult to realize with other construction systems. Timber plate shells thus enable the construction of spaces rarely used in contemporary construction practice. In this way, timber plate shells expand the spatial vocabulary that is available to architects and engineers.

Timber plate shells have a strong material presence when left unpainted, as the entire visible surface consists of a single material. The designer can influence this appearance by specifying the visual quality of the wood on the visible surface or even by including a thin layer of a preferred wood species. The visible surface can also be varnished, oiled, or painted.

When using hollow components that are open on the visible side, the structure is likely to be perceived as lightweight, as the only material thickness visible is the thickness of the bottom plate. For solid timber plates, the thickness of the structure can only be evaluated at the edges; the visual impression can therefore be influenced by the design of edge details.

The clear and direct expression of the structural system and the construction method is another quality of timber plate shells: individual plates brought to the construction site can still be visually discerned in the finished building. This quality is shared with some of the oldest building materials still in use today, such as timber beams, roof tiles, and bricks.

5.10 Conclusion

This chapter discussed various topics related to the architectural design of timber plate shells, including structural considerations, daylight, spatial conditions and integration of HVAC installations.

Examples of suitable applications for timber plate shells are projects with spans over 10 m where low weight is a requirement, projects where substantial material cost savings can be achieved (larger spans with sufficient height and with hinged supports on multiple sides), projects where the visual appearance of timber plates is valued, and projects that use spatial typologies that can effectively be constructed using plate shells.

In most cases, solid plates are preferable over hollow components, as solid plates are easier to construct, feature much better fire resistance and soundproofing, and provide more carbon storage.

In case fire resistance is not a concern, hollow components are a logical choice when an extremely light structure is required, when sound absorption is required, when cables and/or lighting need to be integrated within the structure, or when disassembly of the structure is anticipated.

A practical way to add thermal insulation is using pre-formatted rigid thermal insulation plates that are placed on-site after the structure has been assembled and airtight tape has been applied. Alternatively, soft thermal materials in combination with battens can be used. On top of the thermal insulation, large EPDM surfaces can be applied. Optionally, an additional layer (for example, thin timber plates) can be added for aesthetic reasons.

As in all vertical densification projects, structural support conditions are a critical factor for the viability of a project. For shell-like structures, thrust forces are of particular concern. When such structures connect to an existing horizontal level, thrust forces can be resolved in that horizontal plane (either using the existing structure, or by adding tension elements in the floor). In situations where shells connect to an existing structure in column-like situations, existing walls perpendicular to the thrust direction could be utilized to channel forces downward. When building vault-like structures on top of walls, tension members may need to be introduced in the space.

Certain structural properties of continuous shells hold true for plate shells as well, such as shells with a higher rise resulting in lower thrust and areas with low curvature being less rigid. However, there are differences, which is illustrated by the fact that segmentation patterns influence stress distribution and the distribution of resulting forces in the supporting structure. Segmentation patterns where multiple edges are aligned should be avoided, as such patterns result in low bending resistance. Short edges can result in high stress concentrations.

A complication that occurs when combining double-curved shell-like structures with orthogonal supporting structures is that horizontal and vertical sections of such structures tend to be curves, not straight lines. For walls, this is not necessarily problematic, but where shells meet horizontal surfaces, shells typically cannot meet existing linear supports (such as beams), and consequently, the shell can either be supported only locally, or intermediate structures would need to be employed. Sections through areas with low Gaussian curvature may approximate straight lines, but such areas do not have the structural benefits of more strongly curved shells. Examples of possible solutions are given in Section 5.4.

Regarding daylight, various ways to keep one or more of the sides of the shell open are shown. Additionally, ways to let daylight enter through the roof are illustrated: creating openings within plates, rotating plates, leaving plates out, or using compound shell structures with larger openings between them.

Large HVAC channels can only be integrated well in timber plate shells when the placement of channels is taken into account in the global design. Examples of solutions (such as placing channels at kinks in the plate shell) are shown in Section 5.6.

To lower the risk of damage to plate edges and corners during transport and assembly, a fillet, rebate or chamfer can be milled into visible plate edges. This will also make the segmentation pattern more clearly discernible.

Various spatial configurations have been shown, illustrating that plate shells can be used to create a wide range of designs, from closed spherical shells to designs featuring kinks and openings.

Multiple custom design tools (using methods discussed in chapters 6 and 7) have been used to create these examples.

The architectural character of timber plate shells is a valuable addition to the architectural vocabulary. The architectural quality of timber plate shells not only lies in the ability to create spatial typologies that are difficult to realize with other construction systems, but also in the strong material presence and in the direct link between visual appearance and construction logic.

6

Geometric design of trivalent polyhedral structures

This chapter discusses design methods for trivalent polyhedral structures. Before describing these design methods, four related topics are discussed: general benefits of trivalent polyhedral structures, curvature-related geometric principles, geometric constraints, and plate intersection methods.

6.1 Comparison of trivalent, tetravalent, and hexavalent polyhedral structures

This section compares structural, economic and geometric aspects of trivalent structures (valence 3, hexagon-based), tetravalent structures (valence 4, using four-sided segments), and hexavalent structures (valence 6, using triangular segments).

6.1.1 Structural comparison between structures with valence 3, 4 and 6

Trivalent polyhedral structures are generally structurally stable, even when the edges between surfaces have no bending stiffness [142]. This is not necessarily the case for predominantly hexavalent structures and predominantly tetravalent structures. Thus, trivalent polyhedral structures have a clear structural benefit in this regard.

With sufficient bending stiffness, each of these three types of polyhedral structures can be made structurally stable. To establish if trivalent structures retain their structural benefits compared to tetra- and hexavalent structures when using joints that feature significant bending stiffness, various segmentations of a base shape are compared using FEM analysis. As will be seen, the benefits of trivalent structures decrease when using joints with high bending stiffness, but the extent to which this happens strongly depends on the global geometry and the segmentation pattern.

Fig. 6.1 shows the deflection of five different segmentations of a three-legged shell spanning 12 m under a uniform vertical area load. The number of plates is similar for all segmentations and the assigned material is 16 cm CLT. The results with two different joint types are shown: a joint with crossing screws every 20 cm (resulting in relatively high bending stiffness) and a joint with a bending stiffness that is 100 times lower. The resulting deflection when using high bending stiffness varies, with the highest deflection (a hexavalent segmentation) being 68% higher than the lowest deflection (a trivalent segmentation).

As expected, the results in deflection are even larger when the bending stiffness of the joints is low: triangular segmentations show a deflection that is almost nine times higher than the hexagonal segmentation.

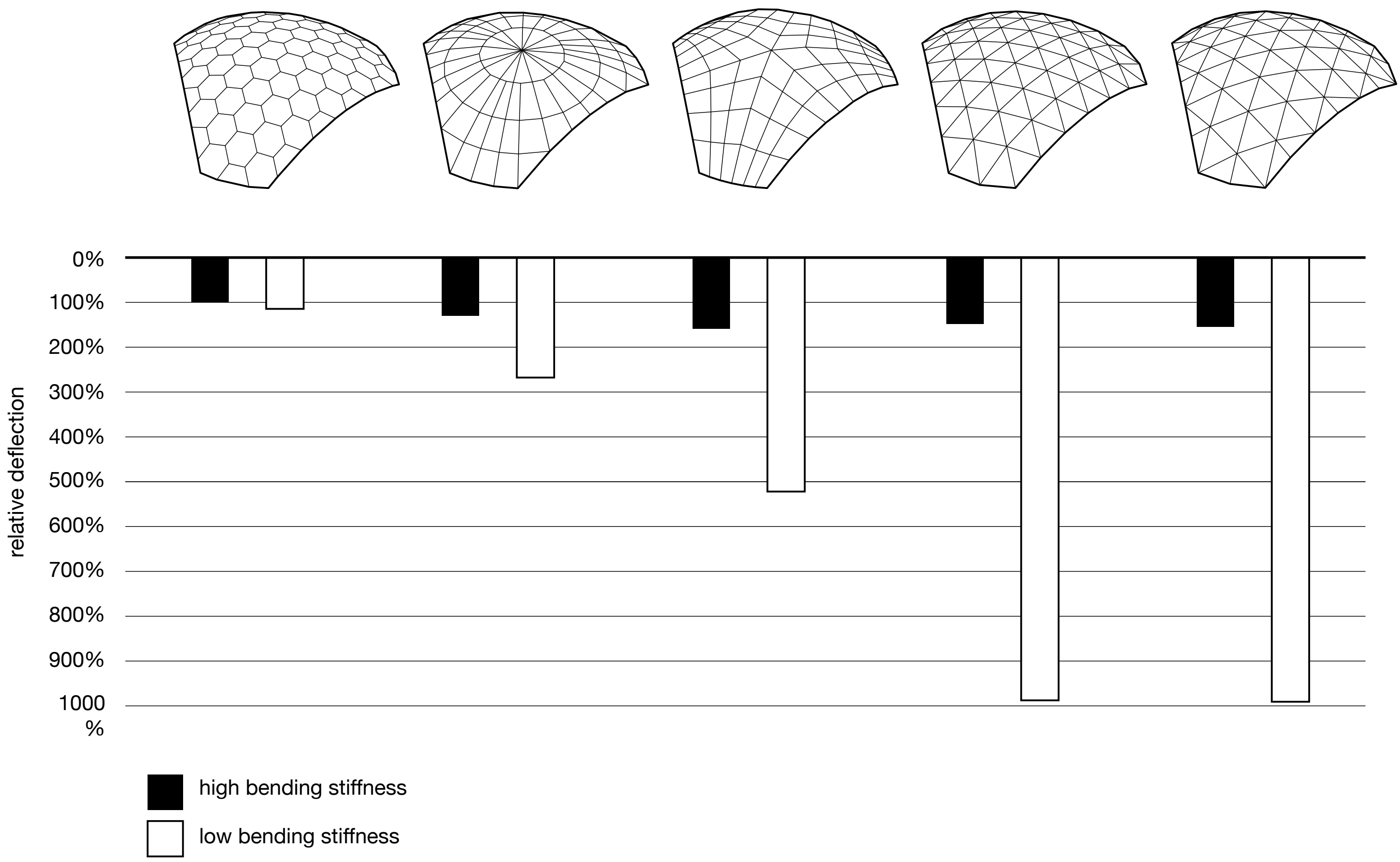

Figure 6.1: Relative vertical deflection of segmentation patterns with valence 3, 4 and 6 of a shell structure supported on three sides.

Deflection of the tetravalent segmentations strongly depends on the segmentation pattern, in particular when the bending stiffness of the joints is low. As illustrated in Fig. 6.2, areas where joints are arranged in linear or curved patterns can lead to folding of the structure. Trivalent segmentations have the benefit that with the exception of kinks in the surface or extremely anisotropic surface curvature, such collinear joint configurations do not occur.

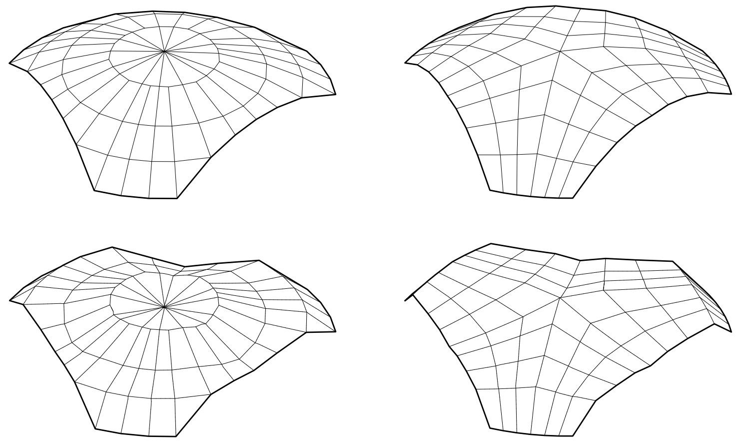

Figure 6.2: Original geometry of tetravalent segmentations (top) and visually exaggerated deformed shapes under vertical loads (bottom).

6.1.2 Cost comparison between structures with valence 3, 4 and 6

Apart from cost differences due to different structurally required dimensions, the most relevant factors for a cost comparison between structures with a valence of 3, 4 and 6 are material cut-off waste and the surface-to-edge ratio. The latter is relevant because it affects the fabrication costs of the plates, the number of fasteners required on joints (and associated labour costs), and the fabrication and installation cost of additional layers (such as thermal insulation and waterproofing).

Cut-off waste of triangular plates depends largely on nesting efficiency: without taking nesting into account, regular triangles lead to at least 50% cutting loss when cutting plates out of a rectangular slab, whereas this could be reduced to almost 0% by combining two triangles on a rectangular slab. Conversely, square or rectangular plates could result in almost no cutting loss, but in practice, plates will not be perfectly rectangular or will not match the exact stock material dimensions, and therefore some cutting loss will occur. Cut-off waste for regular hexagonal plates from rectangular slabs is at least 12.5%; further considerations for hexagonal plates are discussed in Section 4.5.

For components of a given size, squares and hexagons have a significantly shorter edge length than triangles. For example, for components of 4 m^2, a regular hexagon has an edge length of 7.55 m, a square has an edge length of 8 m, and a regular triangle has an edge length of 9.12 m. Thus, when segmenting a shell with a fixed number of panels, a hexagon-based segmentation will lead to the shortest total edge length.

When the component size is defined by transport considerations (for example, having a maximum width of 2.2 m), squares and regular hexagons have an equal surface-to-edge ratio (0.55), which is much better than that of triangles (0.37).

6.1.3 Joint geometry comparison of structures with valence 3, 4 and 6

When three plates with a certain thickness come together, their side surfaces come together in a single line at their intersection point, a property called *exact offset*. When more plates come together, exact offsets cannot be created unless specific geometric conditions are fulfilled. Structures with the exact offset property (including trivalent plate shells) lead to simpler plate shapes and clear intersection points at both the top and bottom surfaces. This phenomenon is illustrated in Fig. 6.3.

On synclastic surfaces, plate corners in tetravalent or hexavalent configurations can be modified relatively easily by removing a small volume of wood using milling or sawing. This does induce additional fabrication time, in particular as a similar fabrication step has to be carried out for the thermal insulation layer. On anticlastic surfaces, adjusting the corner geometry of plates is

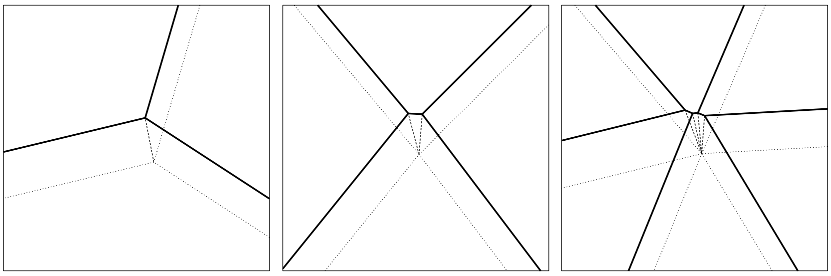

Figure 6.3: Intersections between three, four, and six plates.

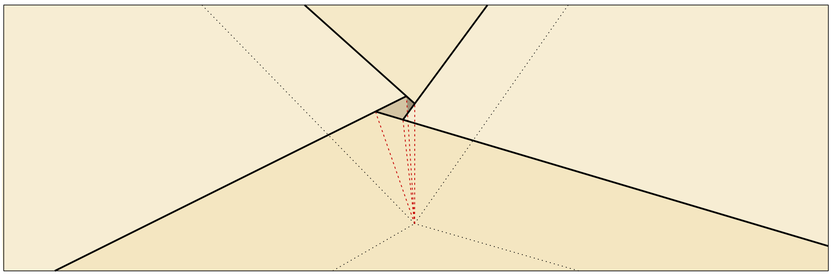

Figure 6.4: Corner detail of four plates coming together in an anticlastic configuration, resulting in a hole.

more complex because, at each corner, at least one plate would need to feature a small ridge that protrudes from the joint surface (see Fig. 6.4).

If a tetravalent or hexavalent polyhedron represents the inner surface of a structure, the inside of the structure will feature exact corners. If the polyhedron represents the outer surface of the structure, corner points on the inside will turn into small edges, with typical lengths ranging from just millimetres up to multiple centimetres.

6.1.4 Design freedom comparison of structures with valence 3, 4 and 6

Between structures with valence 3, 4, and 6, hexavalent structures are by far the easiest to design: as the three corner points of a triangle by definition define a plane, any configuration of points can be used to construct a polyhedral shape. Thus, any curved surface can be approximated by placing points on the surface and creating triangular faces between them. Modifications of point positions (for example using spring relaxation to achieve more homogeneous edge length) will still result in a design with planar faces.

For structures consisting of quadrilateral faces, approximating a design surface is more complicated, but there are at least two approaches that can be followed. Schober [112] demonstrates different ways to generate translation surfaces, which are surfaces created by extruding segmented edges. Glymph et al. [50] show how these methods can be applied to approximating design surfaces. A different approach is shown by Liu et al. [87], who introduce methods to modify quadrilateral meshes with non-planar faces such that the result is a quadrilateral mesh with exact offsets.

Structures with trivalent geometry can be created in various ways, as discussed in Section 2.3.8 and Chapter 7. One of these ways (described in Section 7.5.1) is similar to the translation surfaces method for tetravalent structures. Except for specific geometric arrangements where planes are arranged such that four planes intersect in one point, polyhedral structures resulting from the intersection of planes will be trivalent. Therefore any geometric design method that uses planes to define plates is likely to result in trivalent geometry.

6.2 Relationship between curvature and segmentation patterns

A well-known property of trivalent polyhedral approximations of double-curved surfaces is that segments are convex on syn-

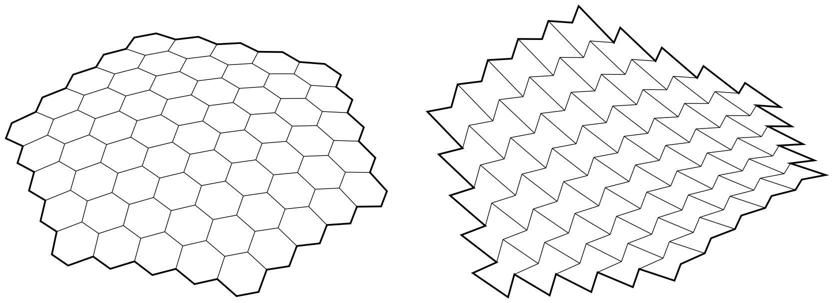

Figure 6.5: Examples of visually regular segmentations of a synclastic surface (left) and an anticlastic surface (right).

clastic surfaces (surfaces with positive Gaussian curvature) and non-convex on anticlastic surfaces (surfaces with negative Gaussian curvature) [82; 130]. In other words, polyhedral segments on structures approximating synclastic surfaces feature internal angles that are all smaller than 180° (for example, near-regular pentagons or hexagons), whereas polyhedra approximating anticlastic surfaces include internal angles larger than 180°, such as bowtie shapes (Fig. 6.5).

This section focuses on ordered patterns, in which plates are arranged on triangular grids formed by curves in three directions, as illustrated in Fig. 6.6. The findings of investigating regular arrangements apply to irregular arrangements as well, but less regular plate arrangements feature a wider range of local plate configurations, complicating the design of plate arrangements in conditions where curvature leads to tight constraints (see Section 6.2.3).

6.2.1 Influence of curvature on zigzag patterns

In polyhedral structures, the shape of a segment consists of line segments of the intersection lines between the segment's plane and its neighbouring segments' planes, and thus, it is defined by the

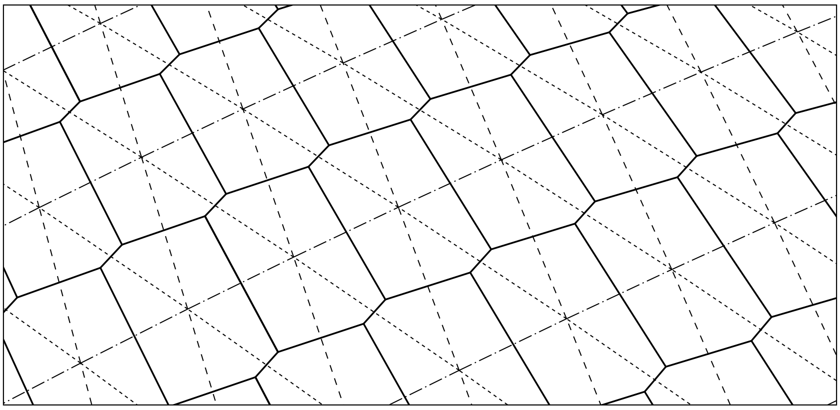

Figure 6.6: Segmentation based on a triangular grid of curves, projected on a sphere. Note that a triangle grid can be defined by the direction and spacing of just two of the three curve directions.

location and orientation of the planes that neighbouring segments lie in. For ordered segmentations, the locations and orientations of these planes directly follow from the curvature of the approximated surface and the directions and scale of the triangle grid.

For patterns aligned to the principal curvature direction, the depth of zigzag patterns (as illustrated in Fig. 6.7) can geometrically be shown to be a function of the width of a segment and the angles with neighbouring segments:

$$d_{zigzag} = 0.5 \cdot d_{width} \cdot sin(\beta) \cdot cot(\alpha) \tag{6.1}$$

From Equation 6.1, we can see that for an angle α of 90°, the cotangent is zero, and thus the resulting zigzag depth is also zero. For angles α of 0°, the cotangent approaches infinity; consequently, the zigzag depth becomes very large when the angle α between plates is small (except when angle β is also very small, as in that case sin(β) is close to zero). Such large zigzag depths can result in self-intersection of the segments and thus in invalid polyhedral shapes (Fig. 6.8).

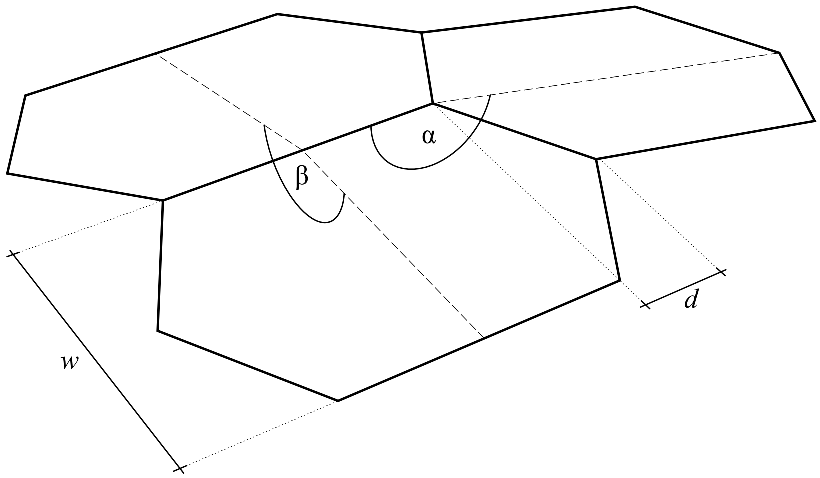

Figure 6.7: Diagram showing parameters used in equation 6.1.

Whether a segment self-intersects depends on the zigzag depth in relation to the segment length. Self-intersection can often be prevented by increasing the distance between rows of plates. This results in longer segments and also in larger angles between the rows of plates, which diminishes the zigzag depth. (Fig. 6.9).

While self-intersection of segments may occur in areas with low curvature, it is not the low curvature itself but the proportion between curvature values in the two principal curvature directions that is at the root of this behaviour. As can readily be observed by scaling a polyhedral shape along the normal direction of a segment, identical segment shapes can occur independently of absolute curvature strength.

6.2.2 Relationship between curvature, grid pattern and segmentation shape

When a triangular connectivity graph is not aligned to the principal curvature direction or the three internal angles of this grid are all different, asymmetric polyhedral segments appear.

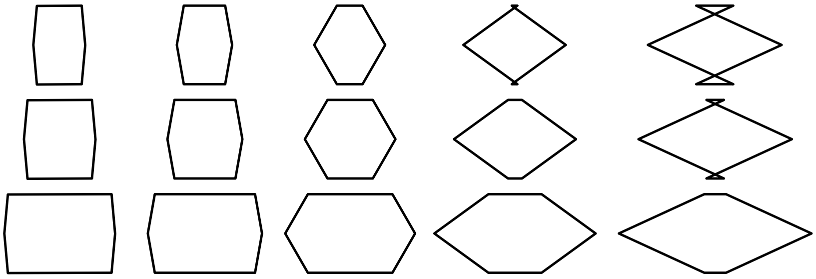

Figure 6.8: Plate shapes resulting from different proportions between plate angles: large α and small β (left), α and β of similar magnitude (center) and small α and large β (right). Whether a certain combination of angles results in self-intersecting shapes depends on the plate spacing, which in this figure varies between the top, middle and bottom rows.

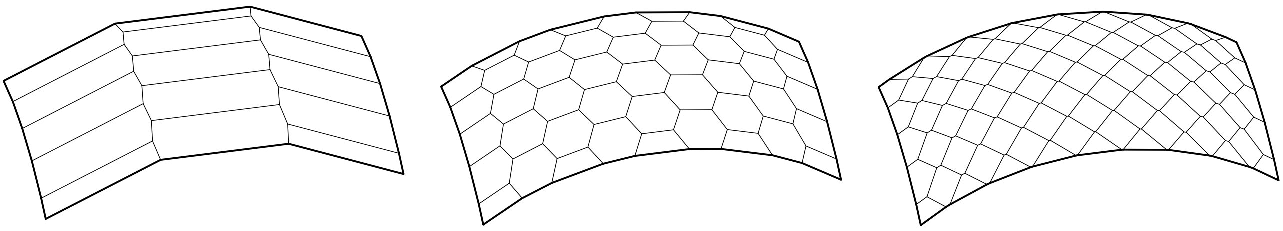

Figure 6.9: Series of arch shells, with a fixed number of plates in the short direction and various numbers of plates in the span direction.

One way to define a triangle grid is by defining one of the three grid directions, the angles between this direction and the other two grid directions, and one of the three spacing values. When keeping the spacing values constant, just three parameters remain. An underlying surface (aligned to a given coordinate system) can be generated using two curvature values, but as only the proportion between the curvature values is of interest, the surface can be defined using just a single parameter. Thus, four parameters suffice to characterize all possible combinations of regular segmentation patterns and local curvature conditions.

Fig. 6.11 shows which combinations of surface curvature proportions and grid patterns (without any shear) result in non-intersecting segment shapes, with the axis parameters being il-

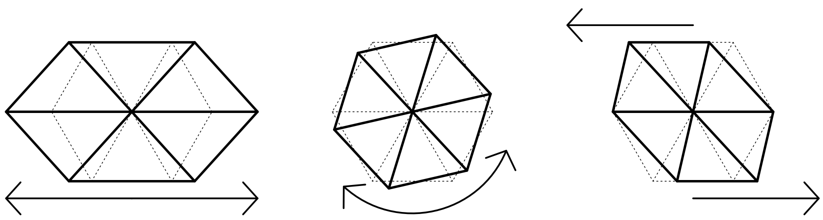

Figure 6.10: Parameters used in Fig. 6.11 and Fig. 6.12: pattern stretch (left), rotation (middle) and shear (right).

lustrated in Fig. 6.10. One can see that when the curvature in both principal curvature directions is equal or nearly equal, many patterns lead to valid segmentations (marked with a black rectangle in Fig. 6.11). However, when the curvature in two directions is less equal, only certain combinations of grid directions and spacing result in valid segmentations. As synclastic and anticlastic surfaces can lead to different types of self-intersecting shapes, the range of valid combinations differs depending on the sign of Gaussian curvature (see Fig. 6.12).

While figures 6.11 and 6.12 show conditions that lead to segments that do not self-intersect, this does not guarantee that the segments are well-shaped. In the outer zone of the marked area, some edges of the segments tend to be very short. In other areas, the segments may be extremely stretched or may feature a very high edge-to-surface ratio, as illustrated in Fig. 6.13.

6.2.3 Curvature transitions

At the parabolic line (the curve marking the transition from synclastic to anticlastic regions), creating segmentation patterns is more challenging than on either synclastic or anticlastic surfaces. There are various reasons for this: segment shapes on either side of the parabolic line are different (convex or concave), the curvature can be strongly anisotropic (leading to situations as shown in Fig.

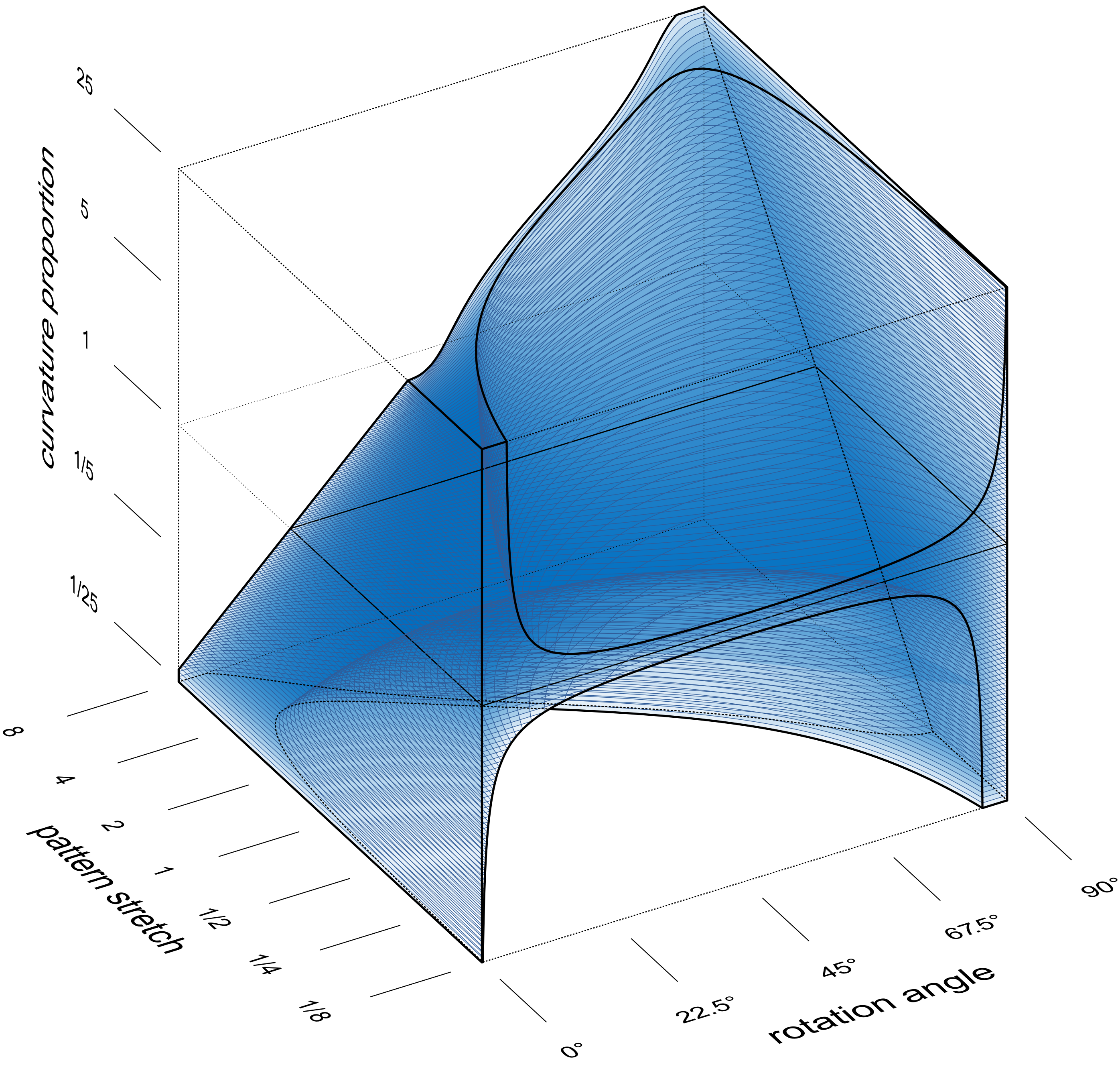

Figure 6.11: 3d diagram showing what curvature and grid combinations lead to valid (non-self-intersecting) segmentations on synclastic surfaces.

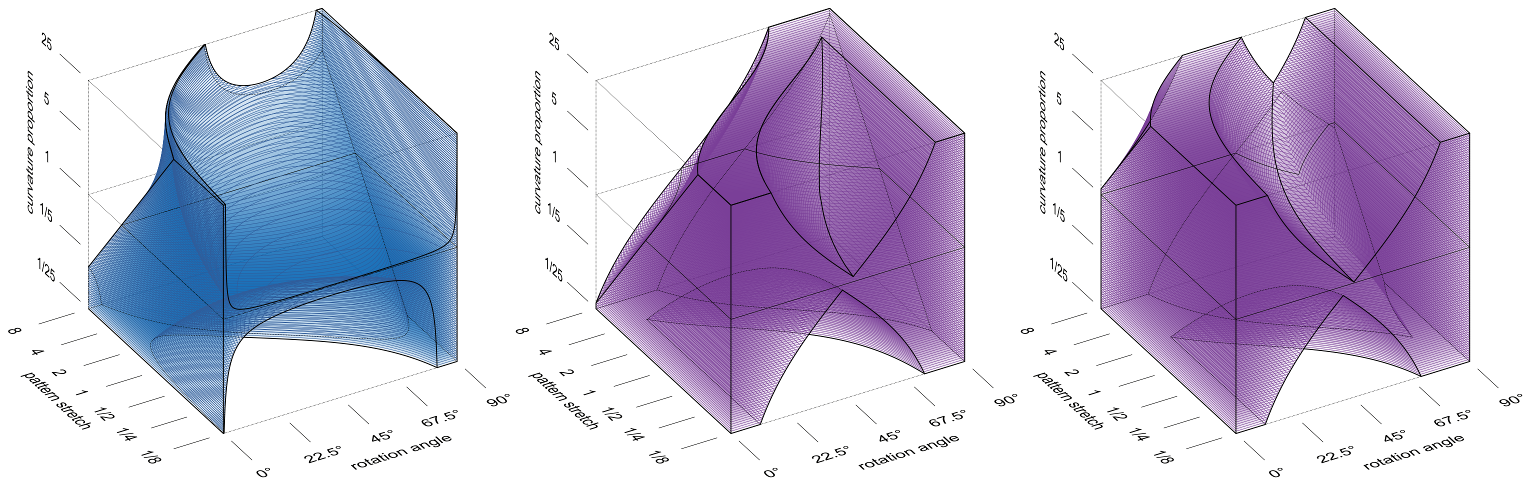

Figure 6.12: 3d diagrams showing what curvature and grid combinations lead to non-intersecting segmentations on synclastic surfaces with a sheared pattern (left), on anticlastic surfaces (middle) and on anticlastic surfaces with a sheared pattern (right).

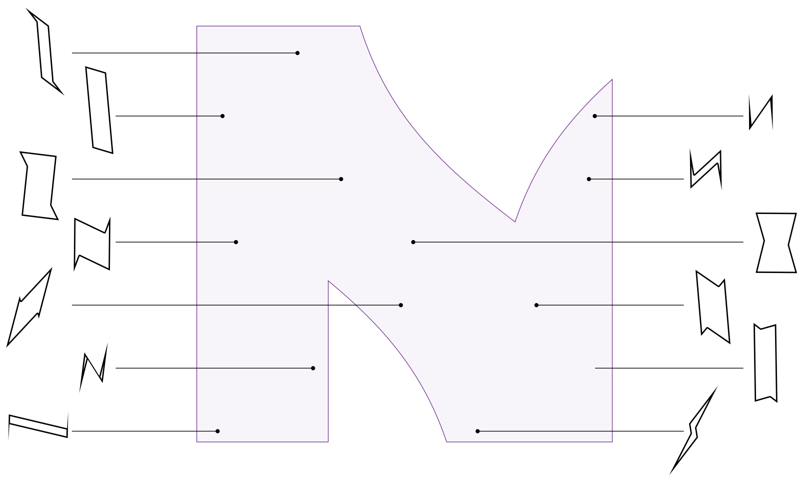

Figure 6.13: Horizontal slice of diagram 6.12 (right) with examples of the resulting shapes.

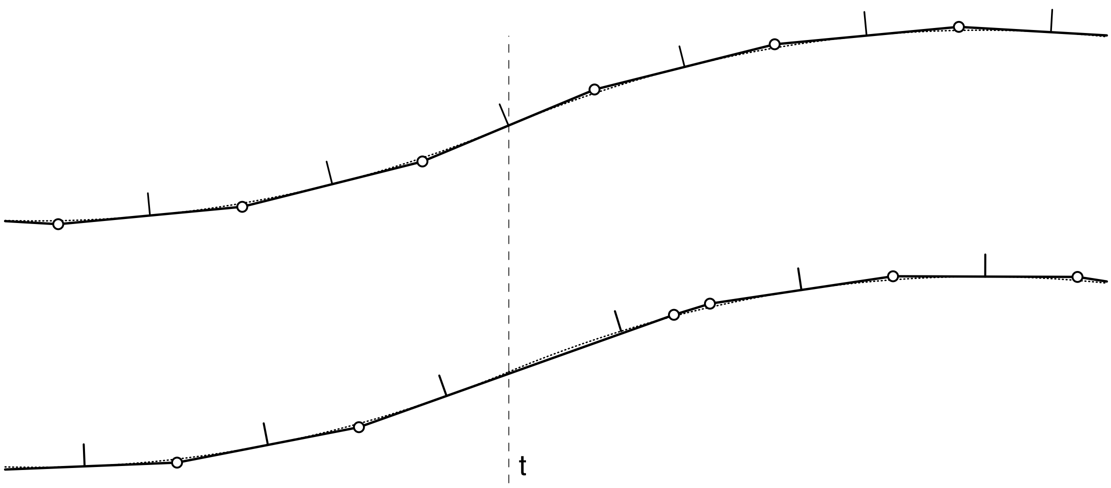

Figure 6.14: Intersections between tangents of a curve around curvature transition t. When the spacing of the points where tangents are generated (marked with perpendicular lines) does not include the transition point t, irregular segment sizes will occur (bottom).

6.15), tangent planes on both sides of the parabolic line can be exactly parallel, and intersections between tangent planes on different sides of a parabolic line can lead to irregular plate shapes or invalid shapes. The latter point is illustrated in Fig. 6.14.

In areas with highly anisotropic curvature, the intersection line between tangent planes tends to align to the weaker curvature direction, except when the points at which the tangent planes are taken are themselves close to being aligned to this curvature direction. In this latter case, small changes in the position of the points where tangent planes are created will lead to strong rotation of the intersection line, which complicates the design of segmentations in such areas (Fig. 6.15).

When principal curvature directions are aligned to the parabolic line, segments can be placed on a triangular grid that is aligned to the parabolic line, as illustrated in Fig. 6.16. Even more

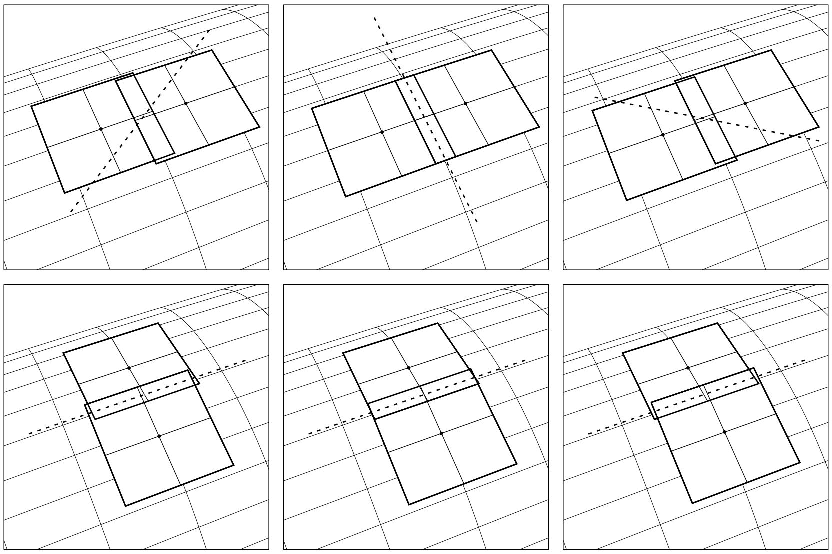

Figure 6.15: Intersection lines between tangent planes on a surface with strongly anisotropic curvature: when planes are placed in the direction of weakest curvature, changes in position can lead to large changes in the intersection line between planes (top); when planes are placed in the direction of strongest curvature, small changes in position lead to barely perceptible changes in the intersection line (bottom).

regular transitions can be generated when not using a base surface, as illustrated in Fig. 6.17.

When curvature lines are not perpendicular to the parabolic line, a regular grid of segments could cross the parabolic line at an angle, but the phenomenon illustrated in Fig. 6.14 can lead to irregular segment sizes. This can be prevented by adjusting the grid spacing in such a way that grid points are always placed on or near the parabolic line (Fig. 6.18) (also shown in Fig. 13 in Li et al. [82]). However, the angle between the parabolic line and principal curvature directions may be different at different parts of a surface, making it difficult to define a grid that results in valid geometry at each point on the surface.

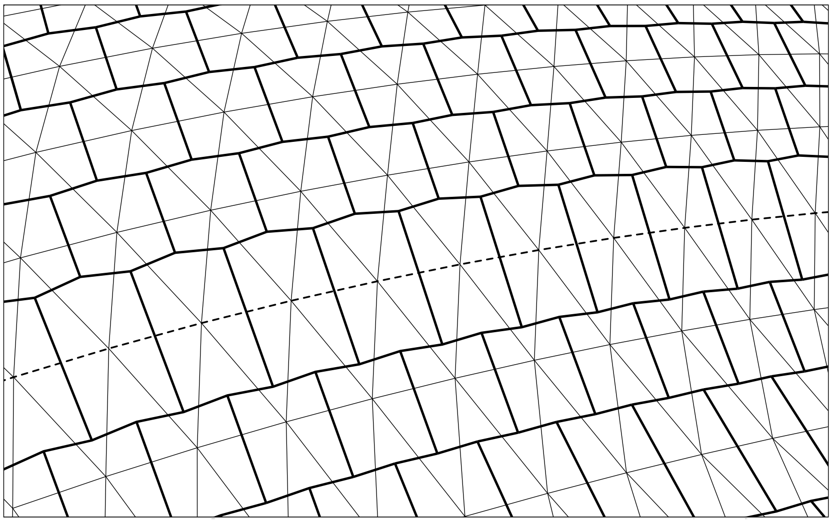

Figure 6.16: Segmentation pattern around the parabolic line on a surface where principal curvature directions are aligned with the parabolic line.

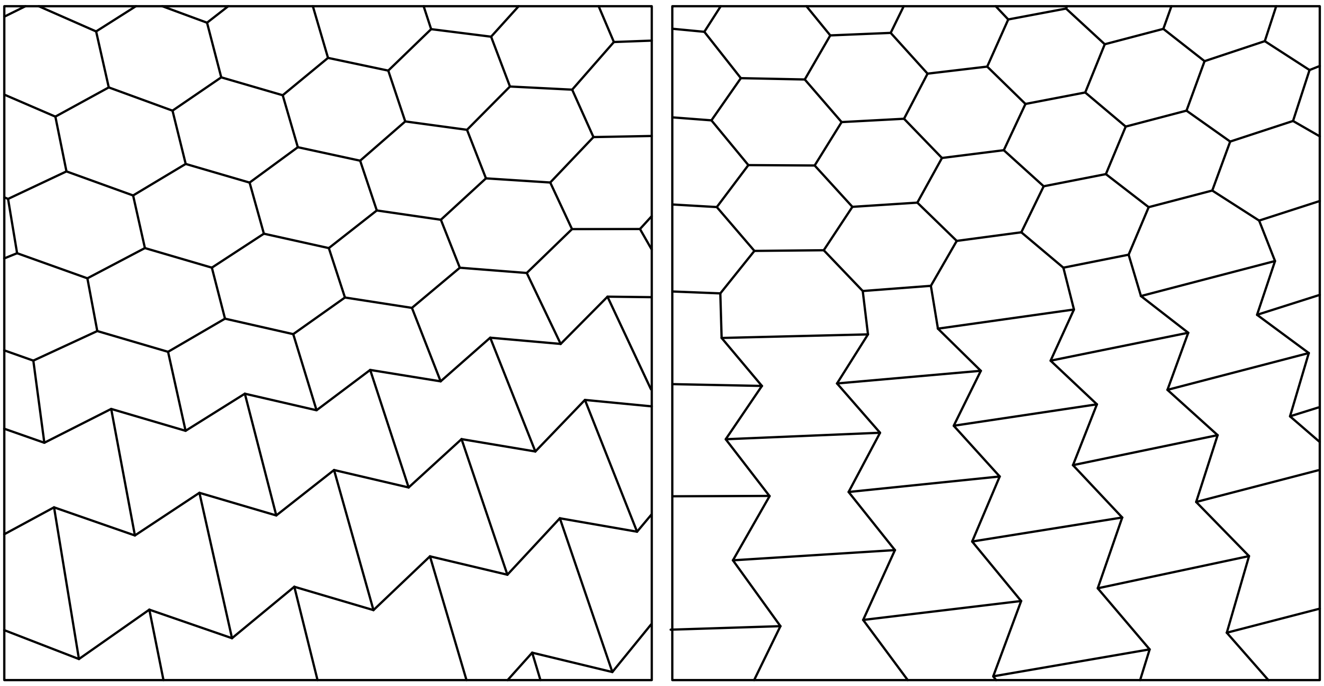

Figure 6.17: Transitions from synclastic to anticlastic areas, with bowtie-shaped segments aligned to the parabolic line (left), and perpendicular to the parabolic line (right), generated using the method described in Section 7.3.

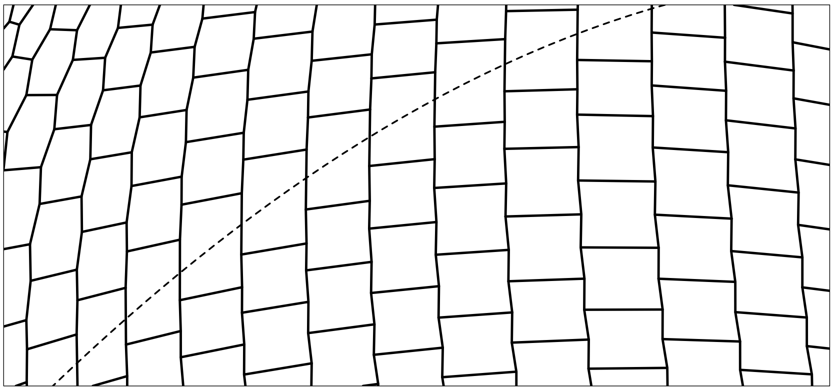

Figure 6.18: A segmentation of a curvature transition on a surface where the principal curvature directions are not aligned to the parabolic line (indicated with a dashed line).

6.2.4 Surface evaluation

When designing plate shells based on a guide surface, it is useful to be able to evaluate if the surface can be nicely and/or easily segmented and to visualize segmentation constraints. This section discusses various ways to visualize expected segmentation constraints on a surface.

6.2.4.1 Gaussian curvature

While Gaussian curvature (Fig. 6.19, left) indicates the type of segment shapes one can expect in a segmentation pattern, Gaussian curvature does not provide information on the proportions of segments. This can be illustrated by selecting a single segment from a polyhedral surface, then scaling the polyhedral surface and its base surface in the direction of the normal of the selected segment. The segment itself will not change shape, but the Gaussian curvature will change. Thus, Gaussian curvature by itself cannot be relied on to evaluate segmentation constraints of a surface, and low Gaussian curvature does not necessarily indicate segmentation constraints.

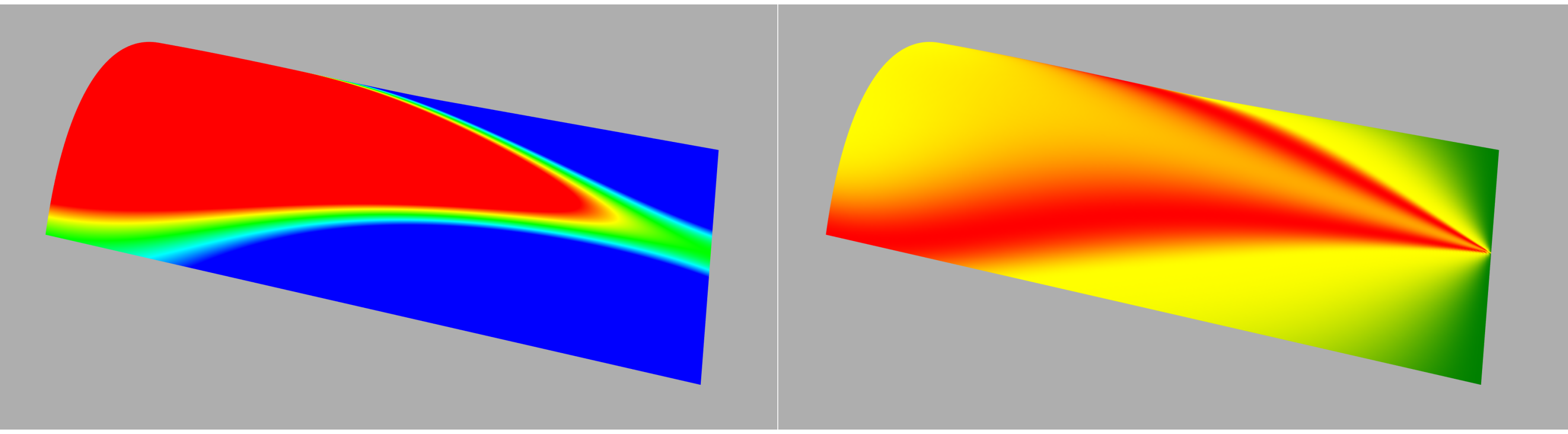

Figure 6.19: A surface coloured based on Gaussian curvature (left) and curvature anisotropy (right).

The transitions between synclastic and anticlastic areas are marked by parabolic lines, which feature Gaussian curvature of 0. As these transitions can cause strong constraints in segmentation patterns, these curves are very useful when considering segmentation options, although parabolic lines by themselves do not provide enough information to evaluate if a surface can be segmented easily.

6.2.4.2 Curvature anisotropy

As discussed in Section 6.2.2, large differences between curvature strength in the principal curvature directions of surfaces lead to strong constraints on the direction of intersection lines between tangent planes. Visualizing curvature proportions (Fig. 6.19, right) can help identify such areas.

6.2.4.3 Curvature lines

Visualizing curvature lines (curves following principal curvature directions) can be useful to generate regular-looking segmentations [82] and can help identify irregularities in the surface. Fur-

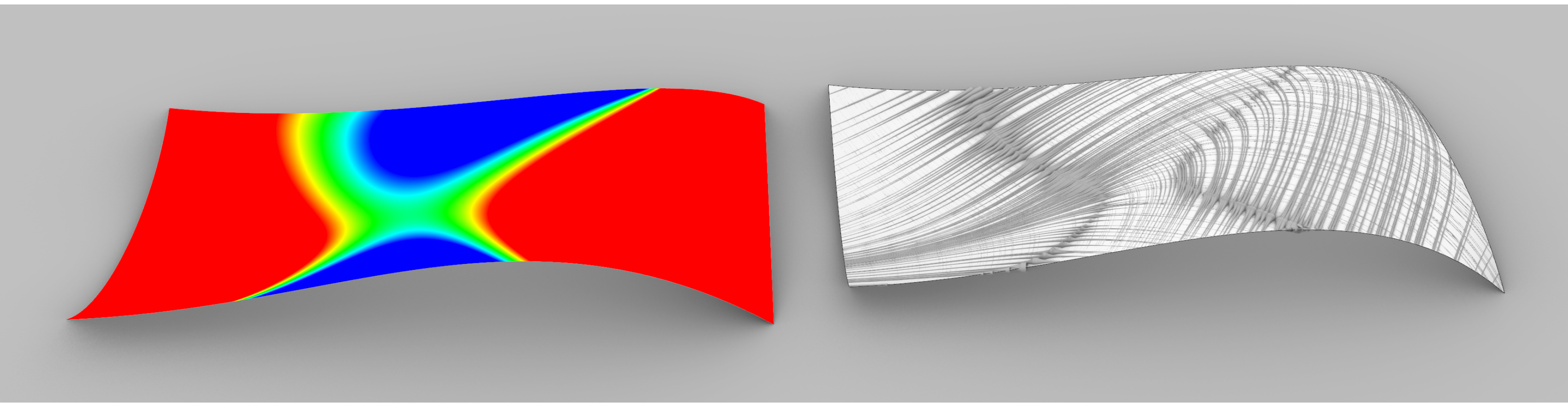

Figure 6.20: Visualization of Gaussian curvature (left) and curvature anisotropy in combination with principal curvature directions (right). Thick curve segments indicate strong curvature anisotropy.

thermore, for segmentations at parabolic lines, it is helpful to know if curvature lines are perpendicular to the parabolic lines. Thus, curvature lines are a useful tool to inspect and evaluate a surface, in particular in combination with parabolic lines.

Combined visualizations of principal curvature directions and curvature proportions can be created by adjusting the colour and/or thickness of curvature lines based on local curvature anisotropy. This is illustrated in Fig. 6.20 (right).

6.2.4.4 Dupin asymptotic directions

Wang et al. introduced the use of the Dupin indicatrix and its asymptotic directions as an indicator that can be used to evaluate the validity of segmentation patterns that approximate a surface: for a segmentation to be valid, not all directions of a triangle grid should occupy the same segment between asymptotic lines of the Dupin indicatrix [139]. At the parabolic line, the angle between asymptotic directions can become very small, which strongly constrains the possible segmentation patterns (Fig. 6.21).

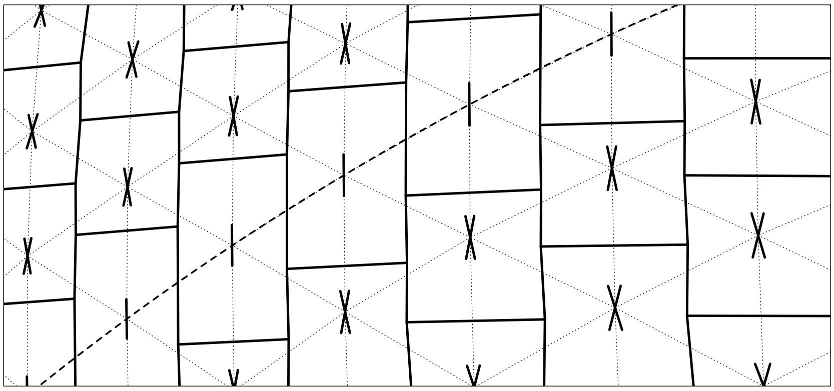

Figure 6.21: Triangular grid leading to a valid segmentation and the asymptotic directions of Dupin indicatrices. On the parabolic line, the angle between asymptotic directions is very small, and the orientation of the triangular grid is strongly constrained as one of the grid directions has to stay between the asymptotic lines.

Displaying asymptotic directions of Dupin indicatrices at many positions on a surface can help evaluate the segmentation constraints. As the large number of lines can make it difficult to spot problematic areas (Fig. 6.22, left), the visualization can be simplified: for each point, a line can be drawn in the weaker principal curvature direction, with its length being defined as the inverse of the angle between the asymptotic directions (Fig. 6.22, right). One can use the latter method to spot areas that are difficult to segment, and then study these areas in more detail using the visualization type shown in Fig. 6.21.

6.2.5 Segment size

As perfectly regular hexagon patterns are two-dimensional, placing ordered hexagon patterns on double-curved surfaces leads to distortions in segment shape and/or gradual changes in segment size. This is shown in Fig. 6.23 (left), in which the difference in surface area between the largest and smallest hexagons is about a factor of two.

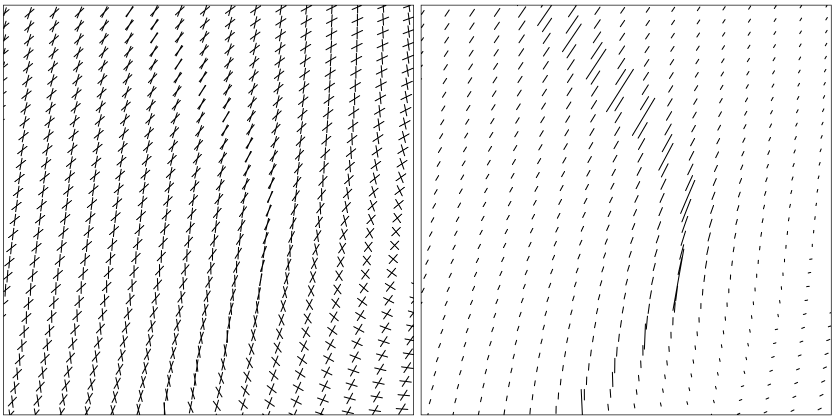

Figure 6.22: Two visualizations based on Dupin indicatrices: On the left, the asymptotic directions of Dupin indicatrices are shown. On the right, the inverse of the angles between these directions is indicated by the length of lines in the weaker principal curvature direction.

Introducing pentagons can lead to more equal plate sizes throughout segmentations. This can be seen in geodesic arrangements (Fig. 6.23, center), such as the archetypal football pattern, but also in less regular segmentation patterns (Fig. 6.23, right). Strategically placed pentagons are also used in a method to produce more evenly sized segments around umbilical points introduced by Li et al. [82].

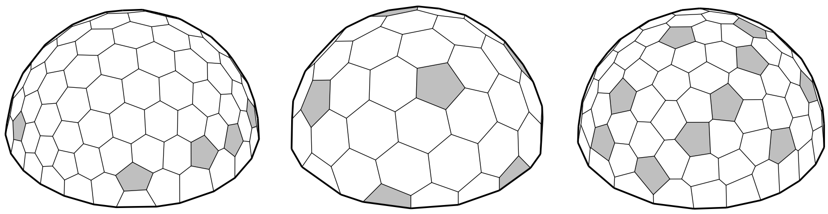

Figure 6.23: A segmentation with a hexagonal pattern showing increasing plate size towards the zenith (left), a geodesic segmentation with consistent plate sizes, regardless of the position on the sphere (middle), and an irregular segmentation with equal-sized plates (right).

6.2.5.1 Row-by-row segment size adjustments

In structured hexagonal segmentation patterns on strongly curved surfaces, one can easily adjust the spacing between rows of segments to keep the length or width of segments constant. But to control segment proportions, the number of segments per row may need to be adjusted as well. Figure 6.24 shows how this can be accomplished: a row of segments can be replaced by a row containing one segment less. This operation results in one five-sided segment and one seven-sided segment. In order to create the most regular segmentation, the modified row may need to be shifted sideways to ensure that the five- and seven-sided segments are aligned.

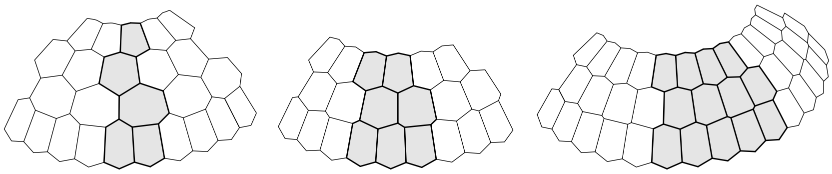

Figure 6.24: Examples of decreasing the number of segments in a row by half (left), by a third (middle), and by a fifth (right).

Adjusting the number of segments per row leads to less evenly sized edges. When edges become shorter than deemed desirable, a plate can be moved down along its normal direction or moved in the direction of the short edges. However, the former modification results in differences in plate size, and the latter modification results in tilted edges (Fig. 6.25).

6.2.6 Curvature control

As illustrated in sections 6.2.1, 6.2.2, and 6.2.3, surface curvature is vital when using a base surface as the starting point of a plate shell design: most importantly, strongly anisotropic curvature should be avoided. The most straightforward way to avoid such

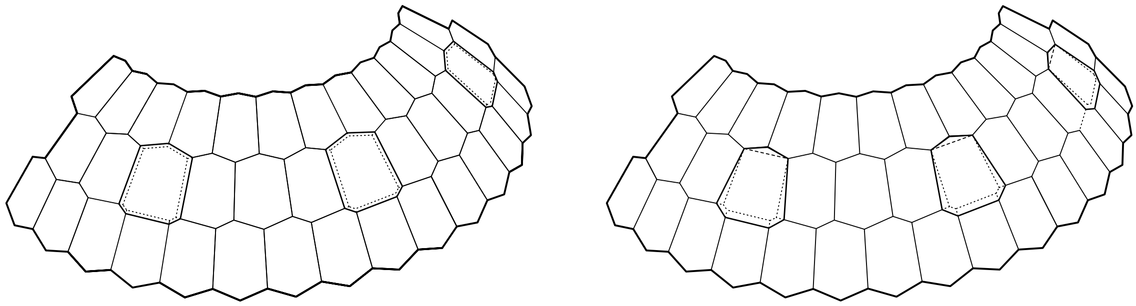

Figure 6.25: Possible modifications to lengthen short edges: moving a segment along its normal (left) or rotating a segment (right).

surface curvature conditions is by ensuring there are no areas that feature low curvature in any of the principal curvature directions.

One pragmatic approach to ensure usable curvature is by creating designs consisting of ellipsoids. When using intersecting shells, a large variety of designs can be created using such shapes. However, this approach is not very flexible, as shapes cannot be easily modified to accommodate structural or spatial requirements.

Creating NURBS surfaces by manipulating control points can easily lead to strongly anisotropic curvature, even when a surface has a visually smooth appearance. To avoid creating such curvature accidentally, curvature anisotropy can be visualized while modifying the surface using visualization methods discussed in Section 6.2.4.

When constructing a surface by extruding a curve along a path or revolving a curve around an axis, the curves should be C^1 continuous but not C^2 continuous at the point where the curve's curvature changes sign: the curve itself should be continuous, but the change in curvature should be sudden and not approach zero near the transition. This way, the resulting surface will also feature clear curvature transitions instead of zones with low curvature (see

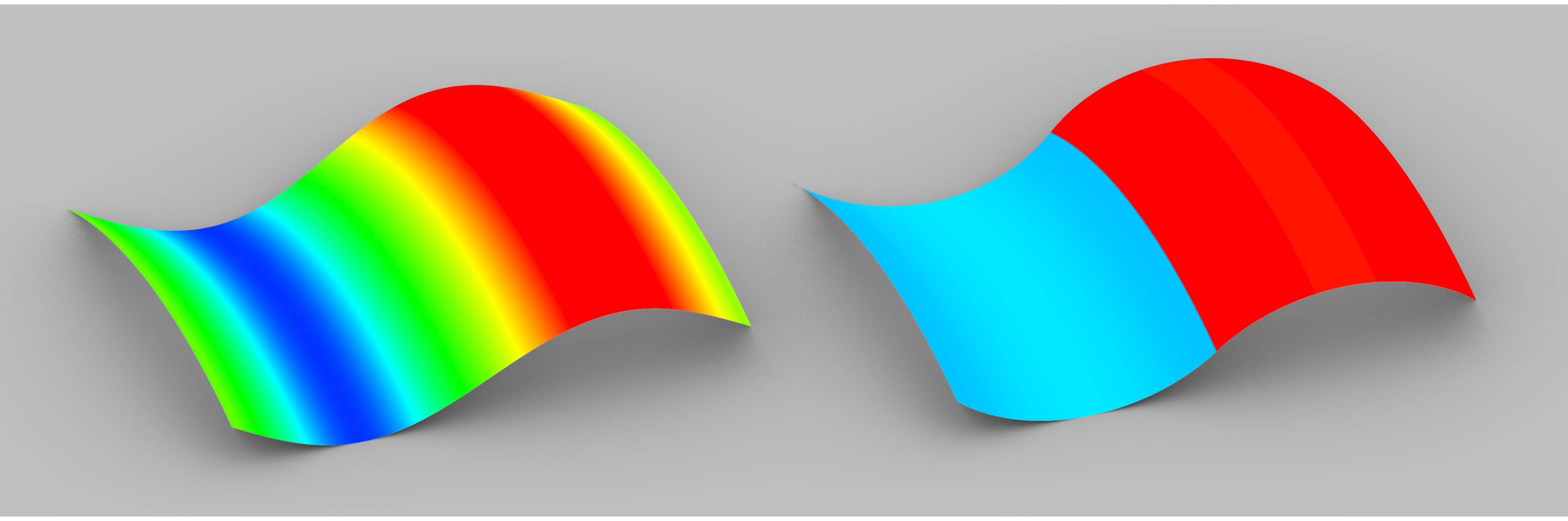

Figure 6.26: Gaussian curvature of a surface created by extruding a sine wave along a curved path (left) and of a surface created by extruding a curve consisting of two arc segments along a curved path. The clear change in curvature of the latter curve results in an equally clear change from strongly synclastic to strongly anticlastic curvature in the latter surface.

Fig. 6.26). One way to fulfil this criterion is by constructing (or by rationalizing) a curve from arcs.

6.3 Geometric constraints

This section discusses geometric constraints that may need to be respected when designing plate shells.

6.3.1 Dimensional constraints

As discussed in Section 4.4.3, hard limits on minimum and maximum dimensions can be posed by material dimensions, fabrication processes, transport and assembly processes. Apart from these hard limits, plate dimensions also strongly affect economy, as the number of plates needed for a structure directly affects fabrication time, the number of connectors and assembly time.

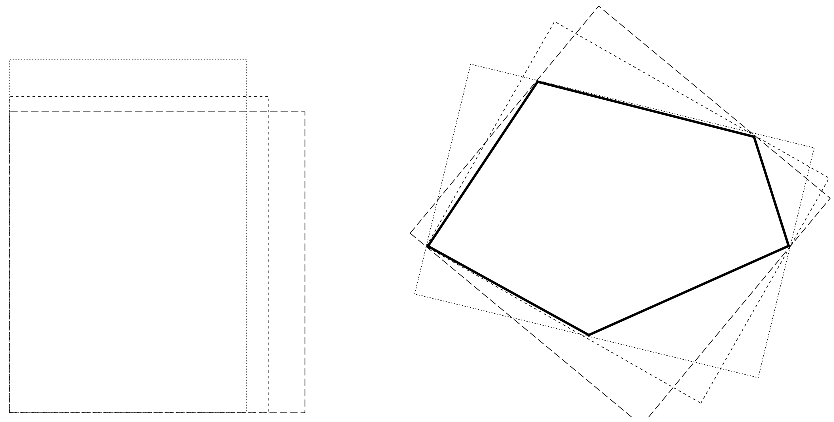

Figure 6.27: Bounding boxes with minimum width, minimum height and minimum area.

For structured patterns, Wang et al. propose setting a minimum distance between rows of segments to control segment size [139]. Logically, a maximum distance can be set as well.

For irregular segmentations, required stock sizes can be checked by fitting bounding rectangles around all plates. In agent-based design methods, these results can be used to adjust the segmentation (see Section 7.2.1). As there may be different dimensional constraints in different directions (as with most timber stock material), multiple bounding box orientations should be evaluated (see Fig. 6.27) unless a specific fibre orientation has been defined for structural or aesthetic reasons.

6.3.2 Assembly order constraints

On anticlastic surfaces and at kinks between synclastic surfaces, certain assembly orders may be geometrically impossible, particularly when finger joints are used (see Section 3.2.2). To minimize the necessary adjustments of finger joint geometry, one could define a preliminary assembly order while designing the segmentation, which can then be used to visualize assembly limitations.

6.3.3 Plate angle constraints

In case plate fabrication or assembly processes limit the possible range of angles between plates (see Section 4.4.3), these angles can be easily visualized during the design process, for example by colouring edges where angles are too steep. This can also be done for any joints that are shorter than what is deemed acceptable from a structural point of view. When using an agent-based design method, this information can be used to inform agent behaviours that affect the segmentation (see Section 7.2.1).

6.4 Plane intersection

Given a set of planes, there are various methods to define which planes should intersect. For sets of planes based on synclastic surfaces, methods exist that reliably provide good results for a large range of base surfaces: incremental slicing and Manahl's method (see Section 2.3.8.5). For anticlastic surfaces, the number of available intersection methods is smaller, and none of the methods provide valid results for all sets of planes. In particular, when plane spacing and curvature proportions do not match, unusable segmentation patterns can occur.

6.4.1 Multiple valid solutions for anticlastic surfaces

A general difficulty in the development of more robust plane intersection methods is that multiple valid connectivity graphs can coexist for sets of tangent planes on anticlastic surfaces (see Fig. 6.28). While multiple valid segmentations can be compared and evaluated (for example using the proportion between total surface area and edge length), the connectivity graph that leads to the best local segment shape at a certain tangent plane may not result

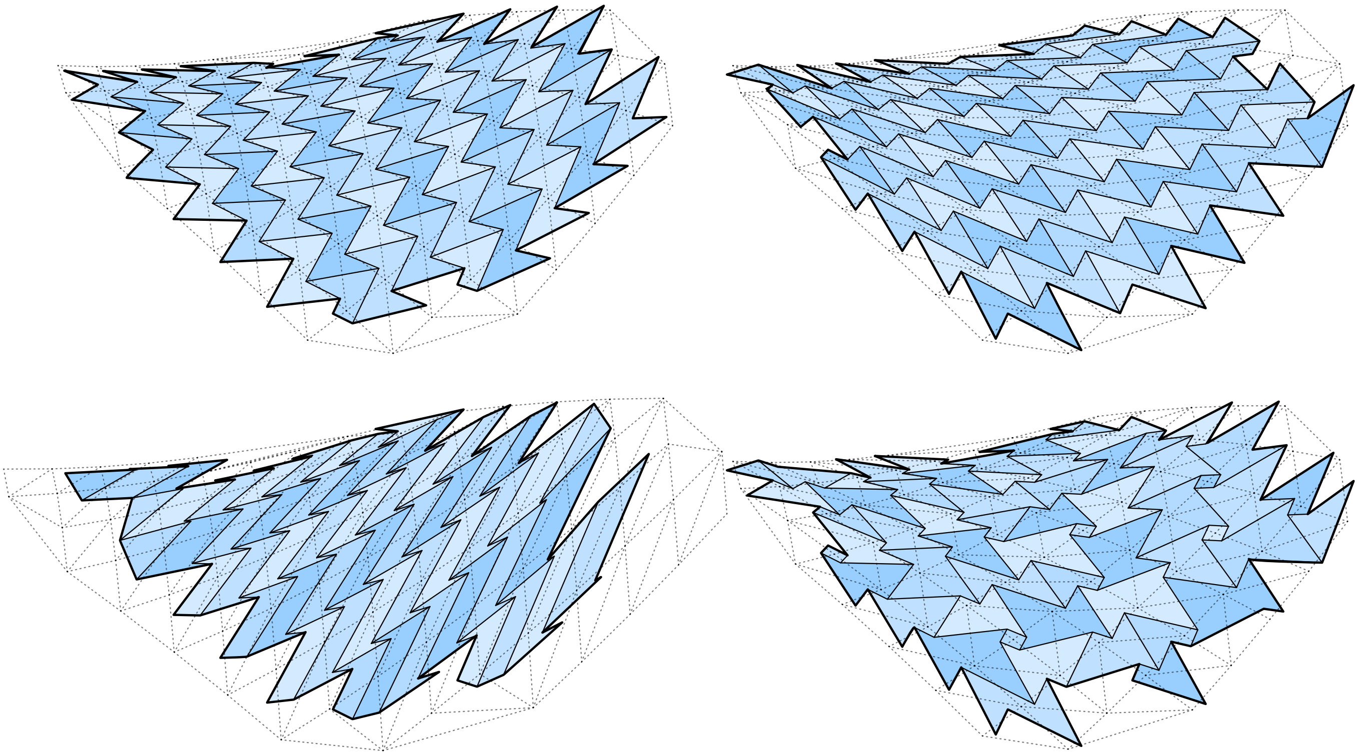

Figure 6.28: Four different connectivity graphs and segmentation patterns for a single set of planes.

in the best global segmentation, due to the cascading effect that connectivity modifications have on neighbouring segments.

Thus in addition to the open question of how to consistently generate valid connectivity graphs for anticlastic surfaces, there is currently no way of knowing if the found segmentation is the best possible one. Furthermore, it is impossible to tell if the shape of a single segment is the best possible option without considering the effects that modifications of the connectivity graph have on other segments in the segmentation, including (but not limited to) directly neighbouring segments.

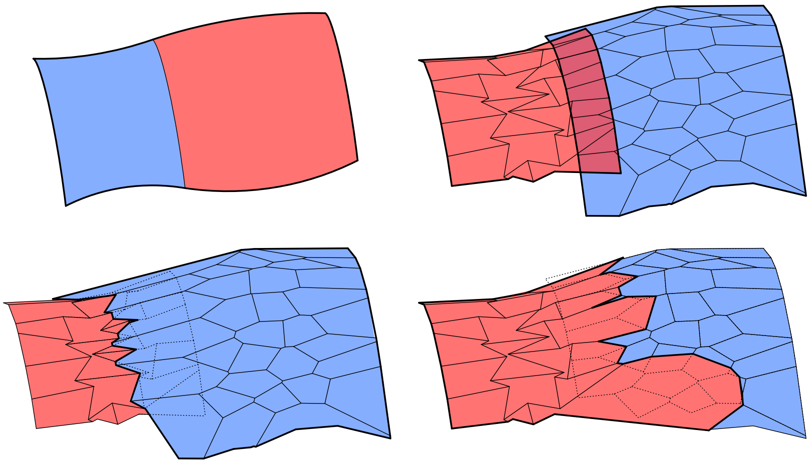

Figure 6.29: A surface containing synclastic and anticlastic areas (top left), which are first segmented separately (top right). While the segmented areas on both sides of the parabolic line are valid, intersecting the two segmented areas would trim off some of the segments (bottom left, bottom right).

6.4.2 Combination of multiple intersection methods

As some intersection methods only work on synclastic surfaces while others work on all surfaces but are less robust, one could divide a surface into synclastic and anticlastic areas and create segmentations for these individual areas before intersecting the local segmentations with each other. Apart from combining the most suitable intersection methods for each area, this approach has the benefit that potential segmentation issues around parabolic lines can be clearly visualized (see Fig. 6.29).

Based on the observation that valid segmentations of partial surfaces do not necessarily result in a valid segmentation of the entire surface (see Fig. 6.29), one could first define planes on both sides of parabolic lines in such a way that a valid segmentation occurs at the parabolic lines, and then define the remaining tangent plane positions.

6.5 Evaluation of geometric design methods

This section discusses the practical applicability of geometric design methods introduced in Section 2.3.8 for the design of timber plate shells.

6.5.1 Geodesic segmentations

Geodesic segmentations are limited to spheres and spheroids. While intersecting spheroid segments can be used to create quite a range of designs, geodesic segmentations do not allow much control regarding segment placement at the intersection curves. Consequently, the shapes and sizes of plates at intersections between spheroid segments will vary greatly, unless the intersections are designed specifically to avoid this (which would greatly limit the design space).

With contemporary fabrication methods (see Section 4.4), the advantages of using only a small set of different plate shapes do not weigh up to the disadvantages of strongly limiting the design space. Additionally, agent-based methods (see Section 6.5.8) are very suitable for controlling plate size near intersections of spheroid segments, so there is no reason to accept the lack of control over plate size and shape at intersections of geodesic segmented shells.

Thus, unless the geodesic pattern itself is deemed a desirable design feature, there is no compelling reason to use geodesic patterns as a tool for the design of segmented timber shells.

6.5.2 Meridian segmentations of spheres

Regular meridian segmentations of spheres suffer from similar limitations as geodesic segmentations: there are only limited ways to combine multiple shells without creating uncontrolled plate shapes at intersections. For meridian segmentations, the only way to arrange multiple shells in a way that leads to well-controlled transitions is by using linear arrangements, as Pavlov did in the design shown in Fig. 2.2.

The design space of this system can be expanded by including torus geometry or by using less regular section and/or axis curves, as illustrated in Section 7.5.1.

6.5.3 Polar reciprocation

As discussed in Section 2.3.8.2, polar reciprocation can be used to generate or modify polyhedral structures. In order to generate polyhedral geometry using this method, a 2D or 3D triangular grid structure needs to be created, which is then used to create a dual polyhedron. Two-dimensional grids result in shapes similar to paraboloids and are thus limited in scope. Three-dimensional grids can be used for a larger range of designs, but only a small subset of three-dimensional grids leads to valid polyhedral geometry when carrying out polar reciprocation. Dual shapes often do not resemble each other, and the effect of the transformation strongly depends on the position of the pole point. Therefore, generating suitable dual geometry from scratch is far from intuitive and not viable as a design method.

Modifying existing polyhedral geometry by modifying a dual structure is more intuitive than creating such a dual structure from scratch, particularly when using computational tools that show the result of modifications in real-time. For example, moving a vertex in the dual shape by a small distance along an edge often results in a modified polyhedral shape that is still valid. However, as points in the dual shape correspond to surfaces in the polyhedral geometry, such a change only changes the location and orientation of a single surface (see Fig. 6.30). In this case, there is no practical reason to use the dual shape, as the modification could equally easily and more intuitively be applied to the original geometry.

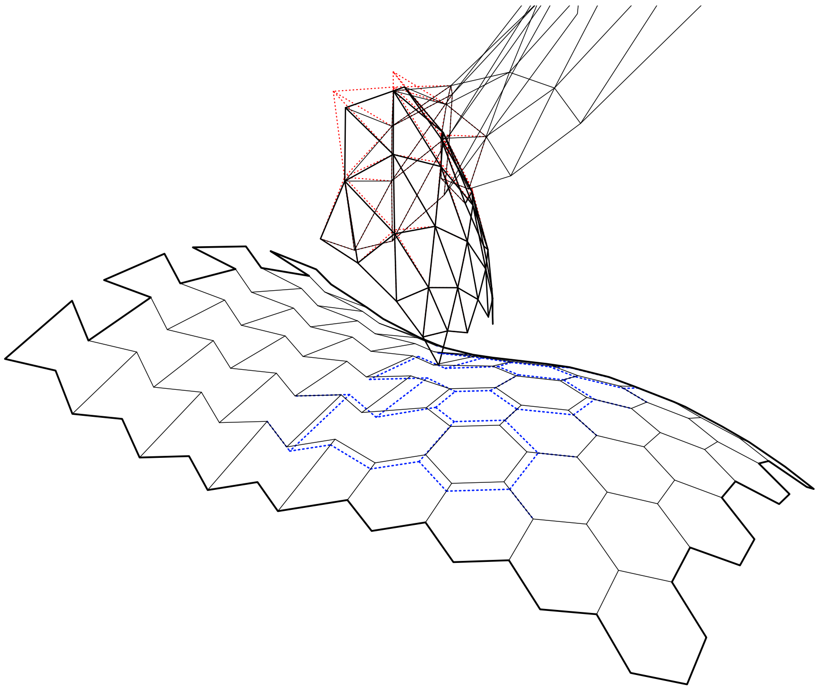

Figure 6.30: Segmentation around a parabolic line and its dual shape (in solid lines), with dotted lines marking a modification of the dual shape (in red) and the resulting segmentation (in blue).

Modifying multiple points in the dual structure could be more useful. As illustrated in Fig. 6.31, some features of original polyhedral geometry can be recognized in the dual geometry (in particular curvature transitions), and one could therefore select and modify larger parts of the original shape. However, such modifications can easily lead to invalid geometry and this method does not provide practical benefits over modifying the original geometry directly.

On a side note, when creating many tangent planes on a base surface, a dual shape with an equal amount of points can be created using polar reciprocation. A mesh can be created of the dual

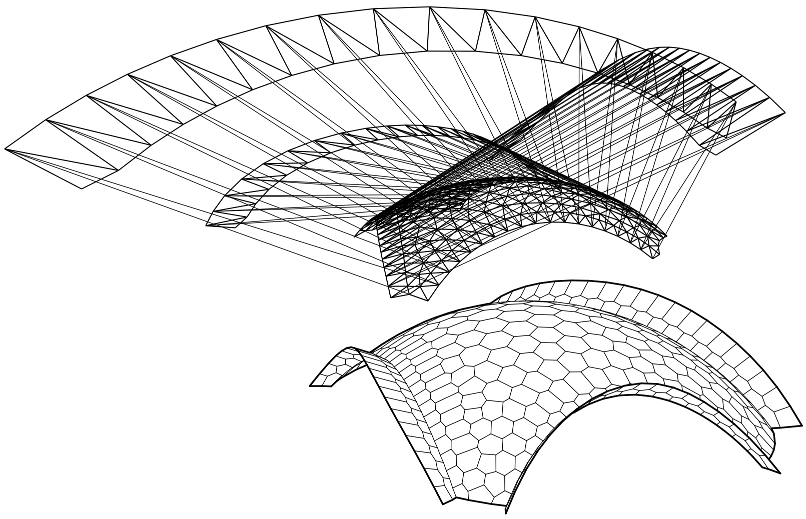

Figure 6.31: The BUGA Wood Pavilion model (bottom) and a dual shape using polar reciprocation (top). Kinks in the original geometry result in visually disjoint geometry in the dual shape.

points by first creating a triangulated mesh of the points on the base surface (for example, using Delaunay triangulation) and then constructing an equivalent mesh using the dual points combined with connectivity information of the original mesh. Constructing such a mesh allows studying the dual shape of a base surface without having to construct a trivalent polyhedron first.

As Wester demonstrated [146], using different pole points when applying dual reciprocity can lead to variations of a polyhedral design. While conceptually interesting, this approach requires a design to exist in the first place. It is hard to conceive a situation where one is able to create a design that does not fulfil the design objective, which after the proposed transformation would fulfil the design objective. Although the process of designing a shape by modifying another shape is fascinating, polar reciprocation is thus only of limited use as a design method.

6.5.4 Planarization

As discussed in Section 2.3.8.10, various optimization methods can generate polyhedra from initially non-planar segmentations or create valid segmentations based on initially self-intersecting polyhedra. As non-planar segmentations are much easier to generate than planar segmentations, using such methods has the benefit that the designer can create a segmentation that is close to the envisioned outcome, without having to ensure planarity.

Fig. 2.9 shows an example of a surface that has been segmented using four different methods, all based on the same points on the surface. With the selected positions, TPI results in many invalid segments. When first generating non-planar contours and planarizing these contours by incrementally moving corner points towards the approximated planes of the segments they are part of, a similar but partially improved result can be obtained.

Using the Kangaroo solver [98] to planarize an initially non-planar segmentation of the design shown in Fig. 2.9, a variety of results can be generated, depending on the start geometry, the chosen geometric constraints, and the weighting factors. The illustrated segmentation is valid, but deviates significantly from the target surface. Additionally, the resulting polyhedron features multiple areas where many edges are close to being aligned, which leads to strong kinks in these areas.

The result obtained using VTPI is also a valid segmentation and is a closer approximation of the input geometry than the solution generated with the Kangaroo solver. On the downside, the polyhedron contains some very short edges. The result could be improved by including an edge functional, as Zimmer et al. demonstrated [151], but as the examples shown in Zimmer et al. show, pronounced kinks may occur, similar to those shown in the Kangaroo example shown in Fig. 2.9.

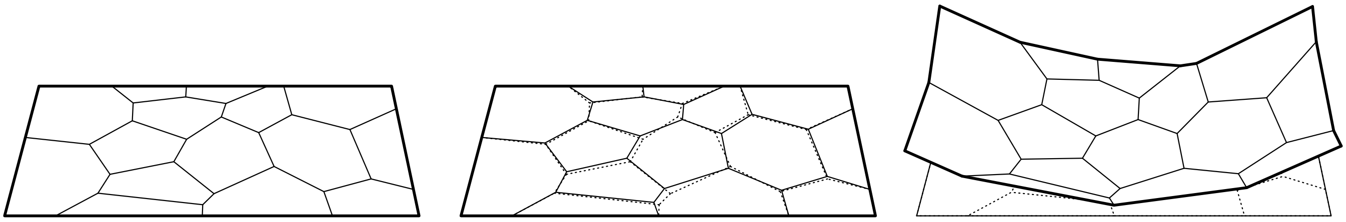

Figure 6.32: A manually drawn 2D projection of a segmentation pattern (left), the result after spring relaxation (middle), and a reconstructed polyhedral shape (right).

While segmentation methods that require a planarization step allow the segmentation of base surfaces that are difficult or even impossible to segment with other methods, the planarization process often leads to inelegant distortions of plate shapes and to the occurrence of kinks in the global geometry. This currently limits the practical use of such methods to applications where the aesthetic appeal of the segmentation pattern is not a primary concern, except when the designer anticipates the results of the planarization method, for example, by integrating kinks as design features.

6.5.5 Reciprocal force diagrams

Hartz et al. [56] show three examples of polyhedral structures generated by using the force density method to find a two-dimensional equilibrium and then reconstructing a three-dimensional shape with this two-dimensional shape as its projection (see Section 2.3.8.3). One of the examples features trivalent segments and consists of three synclastic domes that appear to be paraboloids; as Hartz et al. rightly point out, this shows that the use of reciprocal force diagrams can be used as a design tool for polyhedral shapes. Similar results can also be produced using spring relaxation [98], as shown in Fig. 6.32.

A successful example of the application of a technically different but conceptually similar approach is given by Adriaenssens et al. [2]: For the glass roof of the Dutch Maritime Museum, after first defining the two-dimensional geometry, the three-dimensional shape of the roof is generated in a subsequent step.

Force diagrams of anticlastic shapes would require both tensile and compression elements. Finding equilibrium for such shapes is non-trivial, as the equilibrium tends to be unstable. Thus, without the development of form-finding tools that would find such unstable equilibria, the application of this method is limited to synclastic shapes.

6.5.6 Structured patterns

Structured patterns that use a grid of curvature lines to place tangent planes (see Section 2.3.8.6) can lead to regular-looking, visually pleasing designs [82; 139]. However, as touched upon by Li et al. and discussed in Section 6.2.3, transitions from synclastic to anticlastic areas can lead to irregular plate shapes. In some cases, this could be ameliorated by adjusting the grid spacing to the intersection points of one set of curvature lines with the parabolic line, but this may not be feasible when the direction of the parabolic line strongly changes in relation to the principal curvature direction.

On base geometry featuring only synclastic or only anticlastic curvature, this segmentation method works well, particularly when surface curvature changes only gradually. For geometry featuring parabolic lines, the relation between principal curvature directions, parabolic lines, and segmentation spacing should already be considered when designing the base surface, for example, using visualization methods as shown in Section 6.2.4. Similarly, the alignment of curvature line grids in relation to surface edges should also be considered while designing the base surface.

6.5.7 Point clustering

As discussed in Section 2.3.8.9, point clustering methods do not always produce valid output (due to incorrect neighbourhood information), and design control is limited. The lack of design control could potentially be ameliorated by the development of more interactive design tools, but adjusting the clusters with the intention of adjusting the planes that are fitted through the points in order to improve the intersection pattern between these planes is less direct and thus less predictable and reliable than operating on the planes directly, in particular because Cutler and Whiting describe the process they developed as being indeterministic [32]. Compared to using tangent planes, re-clustering points is also a less predictable intervention than moving a point where a tangent plane is taken. Therefore, this method provides the designer with less control over the design than methods that use tangent planes, without offering more reliable output.

6.5.8 Agent-based methods

As demonstrated by the Forstpavillon in Schwäbisch Gmünd [74] and the BUGA Wood Pavilion in Heilbronn [7], agent-based design methods can be used to create designs with well-controlled plate sizes and edge lengths. However, it should be noted that for both projects, various alternative base geometry designs have been developed and tested before deciding on a design that worked well with agent-based tangent plane placement. Transitions at the parabolic line in the Forstpavillon required some manual adjustment of the tangent plane positions, whereas the BUGA Wood Pavilion does not feature anticlastic curvature at all.

In principle, agent behaviours that only act locally and specifically aim to create well-controlled transitions at parabolic lines could be developed. However, a general challenge when working with agents is that agent behaviours are defined on the level of individual agents, whereas the desired outcome is evaluated by the designer on a more global level. Additionally, even when most of the geometry has been resolved nicely, local areas may require subsequent manual adjustments. A challenge when working with agent-based methods is that the global behaviour of a group of agents becomes increasingly unpredictable when increasing the number of agent behaviours. During the development of the Forstpavillon and BUGA Wood Pavilion projects, no set of behaviours has been found that is robust enough to lead to well-controlled plate arrangements at parabolic lines on a broad range of input shapes.

Agent behaviours can be based on various factors, such as distance to other plates, surface curvature, and distance to guide curves, but can also be based on an agent's plate size and shape. For behaviours that use this latter information, plane intersection methods must be robust, as a valid plate shape needs to be generated at every iteration of the process to be able to use behaviours that use geometric properties of the plate shape. As discussed in Section 2.3.8.5, robust methods exist for some synclastic surfaces, but for anticlastic surfaces, the tangent plane intersection method itself may affect the results, as multiple valid solutions can coexist (see Section 6.4.1), making defining agent behaviours that lead to a good segmentation design very challenging.

An advantage of agent-based methods is that some plates can be marked as non-movable, while these plates are still taken into account for the behaviour of neighbouring plates, thus allowing exact design input in locations where this is required, while using the agent system to generate the segmentation in all other areas. This method was used for the BUGA Wood Pavilion, where plates at the kinks in the base geometry were placed at regular intervals and fixed. This approach could also be used to create fixed tangent plane positions around parabolic lines.

For the BUGA Wood Pavilion, the agent-based design tool has been developed in such a way that tangent plane positions can be adjusted manually while the agent system is active, which provides the designer with a lot more control. This property is discussed in more detail in Section 7.2.1.

All in all, agent-based methods can lead to good results on suitable base surfaces, but unless agent behaviours are developed that specifically deal with parabolic lines, tangent plane positions near parabolic lines may need to be predefined using a different method.

6.6 Local manual editing

Once a polyhedral shape has been created, local adjustments can be made in various ways, such as rotating or moving a segment or adding or removing segments.

By moving a segment along its normal, a segment can be made larger or smaller without affecting edge directions. When rotating a segment along an edge, only the edge used as a rotation axis remains unaffected. A segment can also be rotated along other axes, such as a diagonal axis. These adjustments are illustrated in Fig. 6.33.

Given an existing segmentation, new segments can be created by defining a plane through three points on existing edges, as illustrated in Fig. 6.34. When removing segments, the remaining hole can be closed by extending neighbouring segments (except

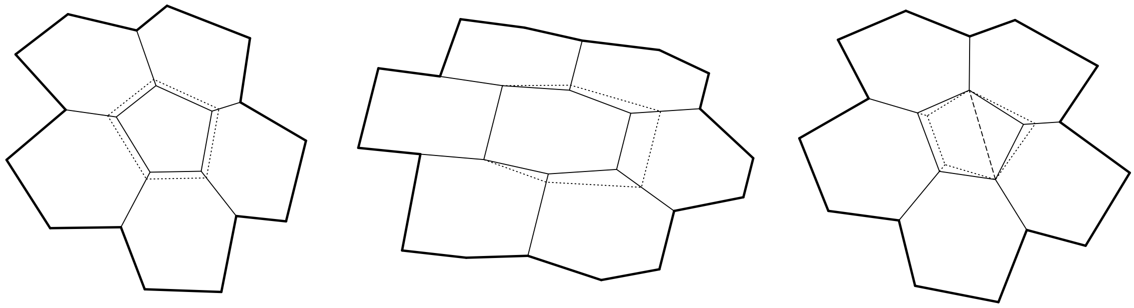

Figure 6.33: Modification of a polyhedron by moving a segment along its normal (left), by rotating a segment along an existing edge (middle) and by rotating a segment along one of its diagonals (right).

in rare situations where lines between neighbouring segments do not intersect).

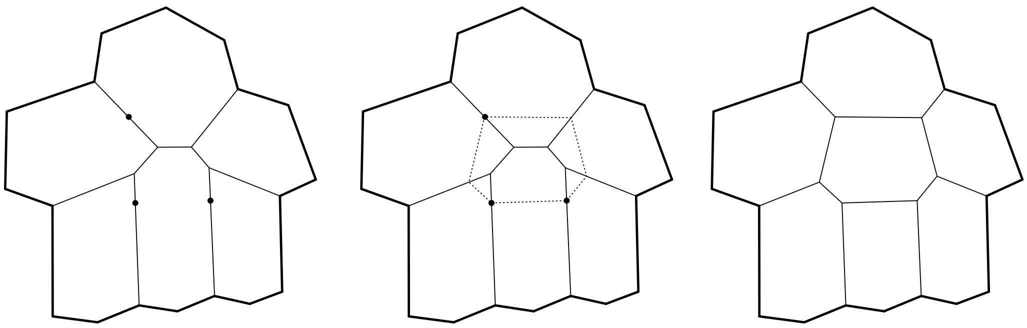

Figure 6.34: Modification of a polyhedron by constructing a new plane from three points that are placed on existing edges.

6.7 Conclusion

This chapter discussed various topics related to the geometric design of trivalent polyhedral shapes after first comparing trivalent plate shells to tetravalent and hexavalent (triangulated) structures. Trivalent plate shells are shown to be stiffer than tetravalent and hexavalent structures consisting of an equal number of plates. Trivalent and tetravalent structures have a better surface-to-edge ratio than hexavalent structures. Compared to polyhedral tetravalent structures, trivalent structures have the benefit that edges are generally not collinear, which helps prevent deformations that show folding. A further advantage of trivalent structures is that joint geometry is geometrically simple, thanks to the exact offset property. Finally, a larger range of design methods is available for trivalent polyhedral shapes than for tetravalent polyhedral structures, as intersections of planes result in trivalent geometry in the vast majority of cases.

Surface curvature strongly affects the design freedom of trivalent segmentation patterns: when the absolute value of curvature in the two principal curvature directions is close to equal, there are many ways to segment a surface. However, when curvature is strongly anisotropic (considerably stronger in one principal curvature direction than in the other), segment placement is critical.

Evaluating whether a surface can be segmented easily is not an intuitive process. Some surfaces seem very smooth visually, but turn out to locally contain curvature that strongly constrains the placement of plates, particularly when visually fair plates are desired. Areas with strongly anisotropic curvature place the strongest constraints on segmentation design. Surfaces where Gaussian curvature abruptly changes sign at the parabolic line are preferable over surfaces where Gaussian curvature gradually approaches zero before changing sign. Methods to visualize areas where strong constraints on segmentation direction and/or spacing occur were introduced, including a visualization method that combines curvature anisotropy with principal curvature directions. Such visualizations can inform the designer, but as with any design task, some experience is needed to effectively design plate shells.

Geometric constraints may follow from available material dimensions, but in practice, transportation limits are more likely to define the maximum size of elements. Joint details can pose another geometric constraint on plate shell design, although the joint details proposed in Section 3.4 are flexible enough to be used in any plate shell designed in the context of this dissertation, except at kinks, for which specific details can be developed.

Plane intersection methods rely on intersecting planes with their neighbouring planes and therefore require topological information indicating which planes are neighbours. For synclastic situations, this information can be unambiguously generated, but multiple valid connectivity graphs can coexist in anticlastic areas. When surface curvature is isotropic or only slightly anisotropic, neighbouring planes can be estimated based on Cartesian distance or UV distance and local errors can be corrected in a consecutive automated process.

Whereas certain geometric design methods result in somewhat irregular patterns (featuring five- and seven-sided plates), other methods result in very structured patterns, featuring rows of plates. In the latter case, plate sizes tend to vary across the surface. The number of elements per row can be adjusted in a controlled manner to avoid large differences in plate size.

Designing a base surface and designing a segmentation should not be considered independent processes, as the success of the latter process largely depends on the result of the former. Thus, when designing a surface, areas that may pose difficulties during the segmentation process should already be identified. Furthermore, the methods to create a surface should be carefully chosen, particularly when designing surfaces that feature parabolic lines.

Various geometric design methods have been evaluated, all of which have limitations in the type of surface curvature they can be used for, the range of base surfaces that lead to valid results, the range of designs that can be created with them, the design freedom they allow, or the aesthetic appeal of the segmentations. This leads to two conclusions: the choice of a geometric design method depends on the specific design task at hand, and further development of design methods for plate shells is needed. The next chapter focuses on the latter topic.

7

Contributions to design methods for plate shell geometry

This chapter discusses a novel segmentation method for anticlastic surfaces, extensions to existing design methods for plate shells, and novel design methods for plate shells.

7.1 Segmentation of anticlastic surfaces using Gauss maps

This section introduces a tangent plane intersection algorithm for anticlastic surfaces that leads to valid segmentations in a larger range of curvature conditions (in particular, strongly anisotropic curvature) than the methods discussed in Section 2.3.8.5. Based on the observation that surface anisotropy strongly affects segmentation patterns, the method builds upon principles introduced by Manahl et al. [88].

7.1.1 Background

Surface curvature anisotropy strongly affects the range of possible segmentation patterns and thus also strongly affects the difficulty of finding a valid segmentation and the design freedom of the segmentation pattern (see Section 6.2.2). Segmentation methods have been demonstrated to benefit from compensating for anisotropic curvature: Li et al. compensate for surface anisotropy when generating the triangulation that defines the segment positions and connectivity graph [82], and Manahl et al. compensate for surface anisotropy when generating the connectivity graph on synclastic surfaces [88].

While Manahl's method cannot be used on anticlastic surfaces and Li's method allows very little freedom in tangent plane placement, the success of these methods suggests that isotropic curvature compensation needs to be an integral part of robust segmentation methods for anticlastic surfaces.

7.1.2 Use of Gauss maps

One way to show the orientation of planes without regard for distances is using a Gauss map, which is a mapping in which each plane is represented by a point on a unit sphere such that the vector from the unit sphere origin to the point equals the plane's normal vector. Using such a mapping, a Delaunay triangulation can be generated that only takes plane orientation into account and disregards distances. As shown in Fig. 7.1, this can lead to valid segmentations on certain areas of a surface, but just like when using Delaunay triangulation in Cartesian or UV space for

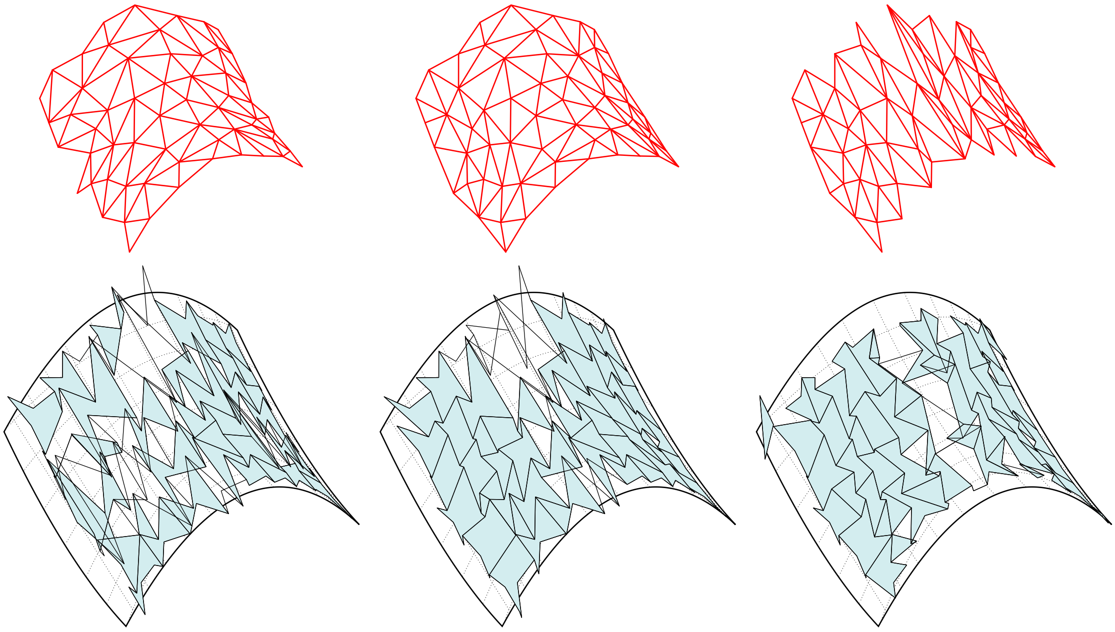

Figure 7.1: Comparison of connectivity graphs (top) and segmentations (bottom) generated using a UV-based Delaunay triangulation (left), a 3D Delaunay triangulation (middle), and a Delaunay triangulation on a Gauss map (right).

the connectivity graph, areas with highly anisotropic curvature are not resolved.

7.1.3 Proposed algorithm for segmentation of anticlastic surfaces

The Gauss-map-based segmentation becomes much more robust in areas with anisotropic anticlastic curvature when including a step to compensate for curvature, similar to Manahl's method. This step consists of scaling potential neighbouring tangent planes by the square root of the curvature anisotropy (defined as the absolute value of the division between the surface curvature values in the two principal directions) in the principal curvature direction before generating the Gauss map. This step needs to be executed for each tangent plane individually to be able to adapt to local surface curvature.

The resulting process (which will be referred to as curvature-adjusted Gauss map segmentation, or CAGM) consists of the following steps:

- Create tangent planes at all desired locations.
- Prepare an empty connectivity graph.
- At each tangent plane:
  - Select potential neighbouring tangent planes using a maximum distance and/or a maximum angle between surface normals.
  - Scale potential neighbouring tangent planes in the principal curvature direction by the square root of surface curvature anisotropy.
  - Create a Gauss map.
  - Identify for which points on the Gauss map connectivity has not been fully resolved.
  - Create a local connectivity graph for the selected points, using Delaunay triangulation on the Gauss map.
  - Add the connectivity information to the main connectivity graph.
- Intersect tangent planes using the connectivity graph.

The step of incrementally extending the connectivity graph is necessary to avoid contradictions that can occur when generating connectivity graphs for tangent planes individually. The incremental process can be executed in various ways, for example

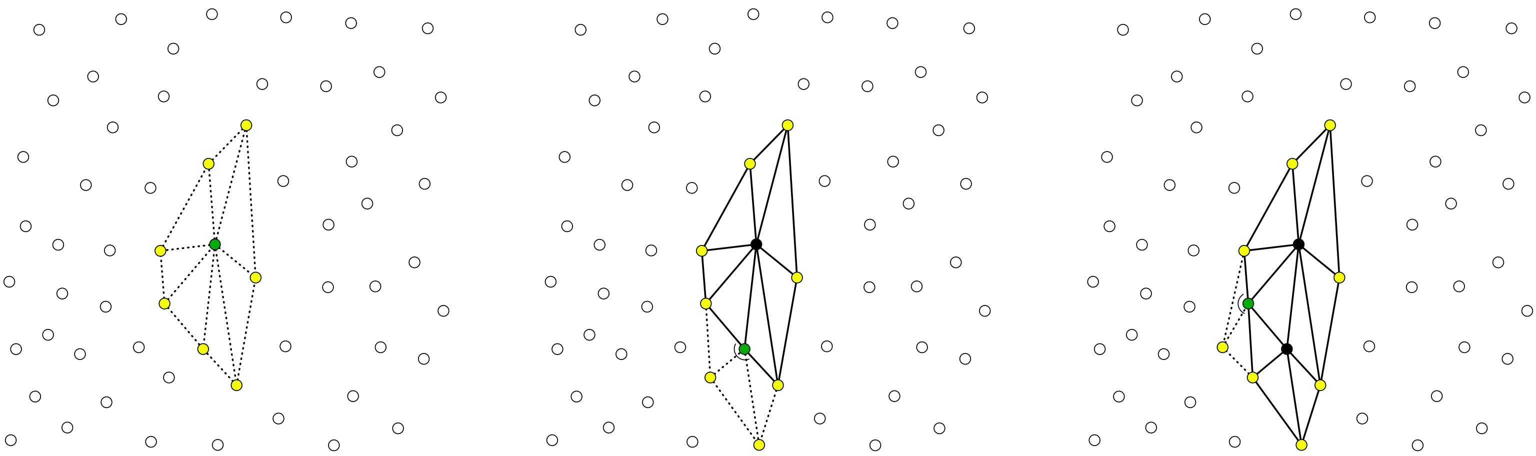

Figure 7.2: Incremental definition of a connectivity graph: starting with a single tangent plane, connectivity with neighbouring tangent planes is determined (left). Then, missing connectivity information around the partially connected tangent plane with the smallest external angle (marked in green) is determined step by step (middle, right).

starting at a central tangent plane and moving radially outwards. For the examples shown in the figures, the order is defined by picking the partially resolved tangent plane with the smallest external angle between neighbouring partially resolved tangent planes (see Fig. 7.2.

The Delaunay triangulation step in the process outlined above can either be created 3-dimensionally or approximated by a 2D Delaunay triangulation on the tangent plane on the unit sphere used for the Gauss map. A good approximation can be created by first projecting the neighbouring points from the Gauss map on this tangent plane and then moving these points towards (or away from) the origin of the tangent plane in such a way that the distances match the angles between the tangent plane normals.

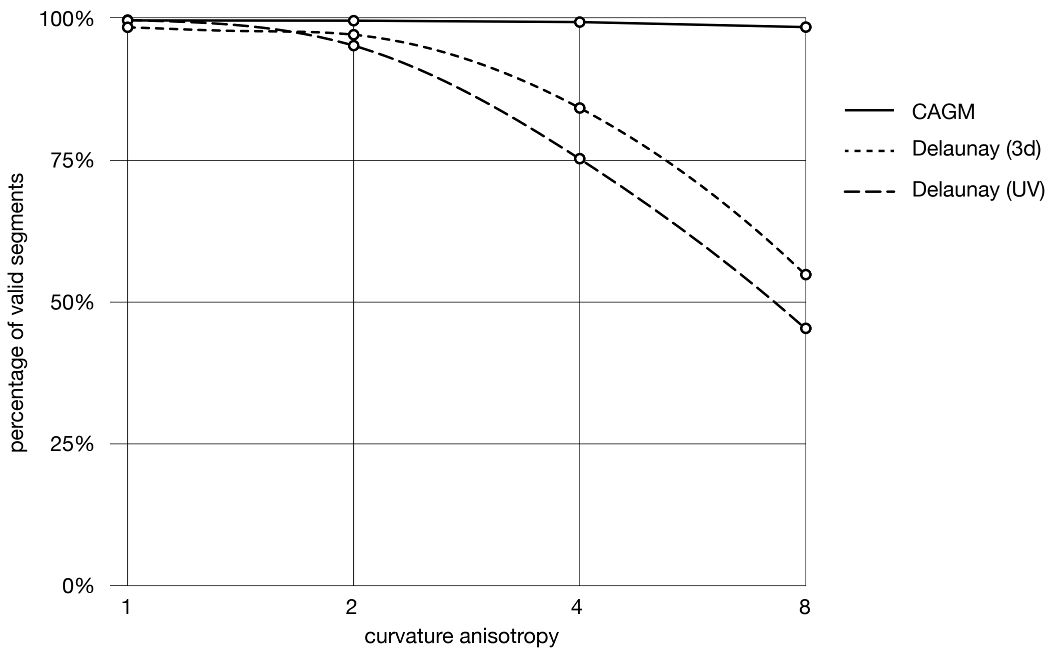

Figure 7.3: Percentage of valid segments created by three segmentation methods (UV-based Delaunay triangulation, 3D Cartesian Delaunay triangulation, CAGM) on a hyperbolic paraboloid surface with various levels of curvature anisotropy.

7.1.3.1 Robustness

Fig. 7.3 shows the robustness of the CAGM segmentation on anisotropic anticlastic surfaces compared to using UV-based or 3D Delaunay diagrams. This graph has been created by pseudo-randomly distributing points on a hyperbolic paraboloid 100 times, applying all three segmentation methods, and identifying what percentage of resulting segments is a valid (not self-intersecting) shape. An example of this setup is shown in Fig. 7.4.

On surfaces with isotropic curvature, the differences between the three segmentations methods are minimal. However, with increasing curvature anisotropy, CAGM keeps performing well, whereas the other two methods become less and less reliable: with a curvature anisotropy of 8, around half of the tangent planes

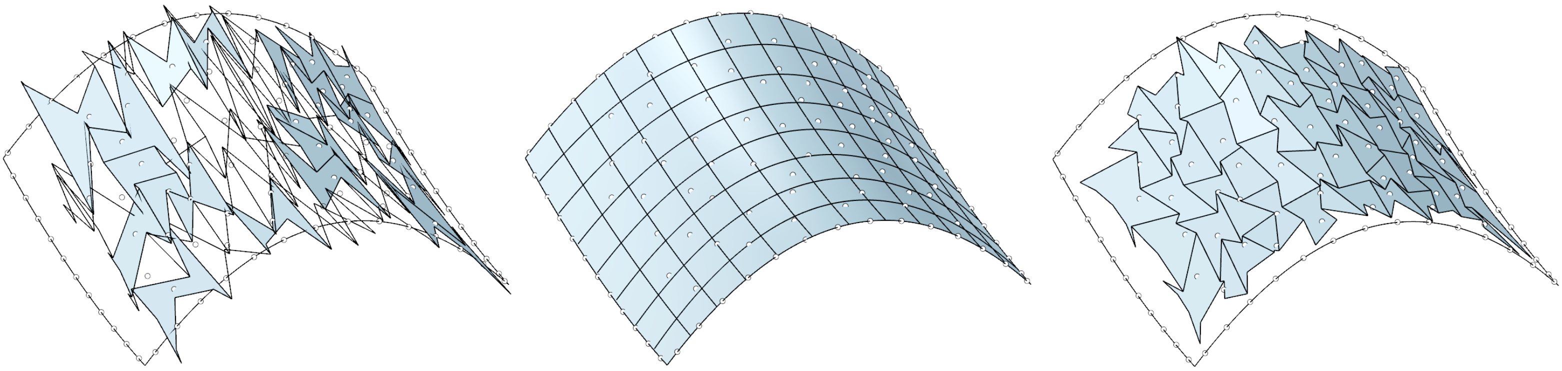

Figure 7.4: Comparison of a hyperbolic paraboloid surface (middle) that is segmented using a 3D Delaunay triangulation in Cartesian space (left) and using CAGM (right).

lead to invalid segment shapes when using Delaunay triangulation to generate connectivity graphs.

In segmentations created with CAGM, invalid segments can often be resolved by moving the corresponding tangent plane in any direction, as illustrated in Fig. 7.5. Depending on the approach to define tangent plane positions, such a modification could be carried out in various ways, including manually or using an agent-based system. Alternatively, instead of moving a tangent plane position, a post-processing step to adjust the connectivity graph as described by Troche could be used [130], or the tangent plane could be removed entirely.

7.1.3.2 Fairness

In situations where UV-based and/or 3D Cartesian Delaunay connectivity graphs lead to valid segmentations, either these segmentation methods or CAGM can be used to create a segmentation. As segment fairness is a major consideration when deciding which segmentation algorithm to use, the resulting fairness of these methods should be evaluated.

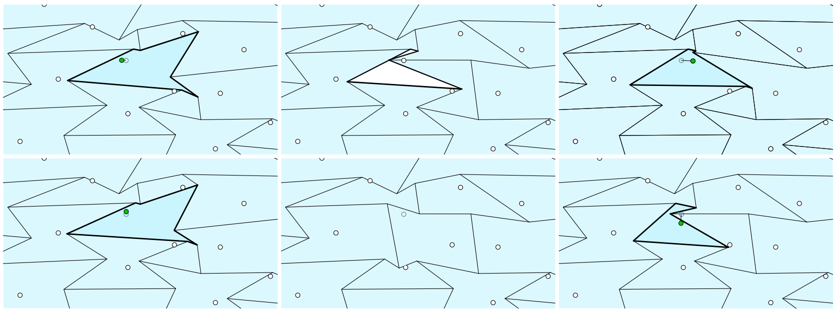

Figure 7.5: An invalid segment in a segmentation created using CAGM (top center) and resolutions by removing the invalid segment (bottom center) or by adjusting the position where the tangent plane is generated (left, right).

While evaluating fairness is partially subjective, various quantitative properties can be established. Comparisons of a number of such properties have been carried out for five pairs of segmentations of a hyperbolic paraboloid, using pseudo-random tangent plane positions that led to valid segmentations using 3D Cartesian Delaunay connectivity graphs as well as using CAGM. Each segmentation consists of 100 segments. The variation of each property (calculated as the average squared deviation of the mean value of the property) is shown in Table 7.1.

property	**3D Delaunay**	**CAGM**
variation in edge length (per segment)	0.661	0.654
variation in edge length (entire structure)	0.746	0.719
variation in number of edges per segment	0.833	0.701
variation in segment surface area	0.688	0.580

Table 7.1: Comparison of geometric features related to segment fairness for two segmentation methods: TPI based on a three-dimensional Delaunay triangulation and CAGM.

As can be seen in Table 7.1, the segmentations created using CAGM show a smaller variation in edge length, number of edges, and segment size than the segmentations based on 3D Delaunay connectivity graphs. Low values for each of these properties correlate to a more regular visual appearance.

Another factor of interest is the proportion between total edge length and total surface area, which for well-formed segments should be low. For the studied segmentations, CAGM results in an 8% lower total edge length compared to a segmentation based on 3D Delaunay triangulation.

In addition to properties of individual segments, relations between the shapes of segments and transitions in segmentation patterns also play a role in the fairness of polyhedra. Figure 7.6 shows a single anticlastic surface segmented using a direct 3D Delaunay triangulation (left) and CAGM (right). Apart from resulting in a locally invalid segmentation, the 3D Delaunay version shows a somewhat abrupt transition where segment orientation changes. In contrast, the CAGM solution shows a gradual transition in segment shapes.

7.2 Contributions to agent-based design

7.2.1 Interactive agent-based design

As discussed in Section 2.3.8.7, agent-based methods can lead to plate shell designs that mostly reflect the design intent, but locally imperfect solutions can occur. When letting an agent system run two times with slightly different starting configurations, there may be some areas where the designer prefers one of the results, while preferring another result in different areas. To allow the designer to locally nudge agents to modify local configurations, agent behaviours can be combined with direct input by the designer: by providing the designer with the option to move agents while the agent system is active, neighbouring agents can adapt to any changes that are made locally [52].

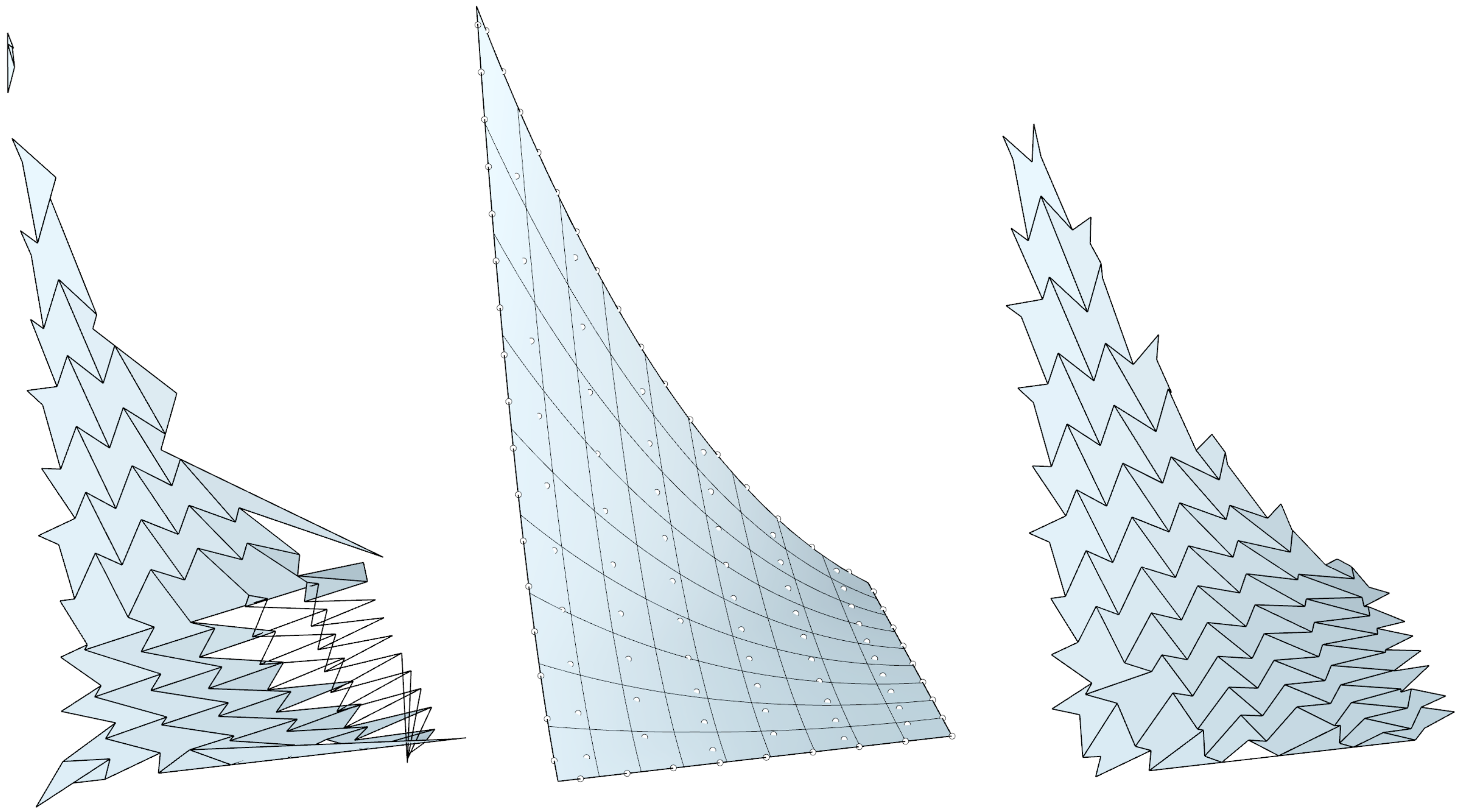

Figure 7.6: Segmentation of an anticlastic surface (center) using a segmentation based on 3D Cartesian Delaunay triangulation (left) and using CAGM (right).

In addition to locally modifying agent positions while an agent system is active, interactivity can also be improved by adjusting behaviours over time. Certain behaviours may be desirable when starting the agent system (for example, to create an even distribution of agents over the surface), whereas other behaviours may become more relevant later (such as behaviours that aim to refine plate shapes). The global strength of behaviours over time may also need to be adjusted. In addition to on-screen controls, agent behaviour strength and parameters can be controlled using a hardware interface with knobs and sliders [52].

7.2.2 Edge-based agent behaviours

For the Forstpavillon and the BUGA Wood Pavilion, agent rules were assigned to agents representing plate positions. The rules that agents were to adhere to were defined to achieve a segmentation that fulfils certain goals, including maximum plate dimensions and aesthetic criteria.

In addition to agents representing plates, agents representing edges can be created. These agents can exhibit behaviours that are based on edge properties but act on plates: for example, a short edge could push away the plates that it touches at its ends while attracting the plates on its sides [52]. Agent rules that lead to similar movements could be developed for plate agents as well, but when the goal is to modify edges, defining rules for edge agents is more straightforward. Furthermore, edge agents can be made to react to the results of structural calculations, for example by adjusting joint geometry to calculated forces.

Just like plate behaviours, edge behaviours can lead to emergent patterns. For example, by developing an edge behaviour that moves neighbouring plates in order to attain a target angle between these plates, plate shapes get elongated in areas with anisotropic curvature while approximating regular hexagon shapes in areas with near-isotropic curvature [52].

7.3 Interactive edge-adjusted height propagation

Both Wester and Almegaard show examples of polyhedra of which the projection in the floor plan consists of a regular pattern: hexagons [146], squares [146], and a combination of squares and four-pointed stars [6]. For trivalent polyhedra, the polyhedral shape can be reconstructed from the projection in the floor plan and the planes that two of the faces lie in, using a process called height propagation [104]. This creates an opportunity to explore polyhedral shapes by first drawing the projection, then defining two of the planes and finally constructing the three-dimensional polyhedron. As discussed in Section 6.5.5, Hartz et al. [56] show a method that works well for synclastic shapes. In this section, a method that also works for anticlastic shapes is introduced.

Figure 7.7 shows examples of polyhedral structures that are constructed from a two-dimensional projection, some of them resembling examples given by Almegaard [6], Wester [145], Manahl [88], and Bagger [12].

However, as already noted by Maxwell (see Section 2.3.8.3) and illustrated in Fig. 7.8 (middle), not all projections will result in valid polyhedral geometry: only projections that would be in equilibrium when considering them as a stressed net of cables and/or bars will lead to a valid polyhedron. Thus, when manually drawing irregular two-dimensional segmentations, invalid polyhedra are virtually guaranteed to result when using the height propagation method. However, when using an iterative process (creating segments one by one), any time a gap appears in the resulting

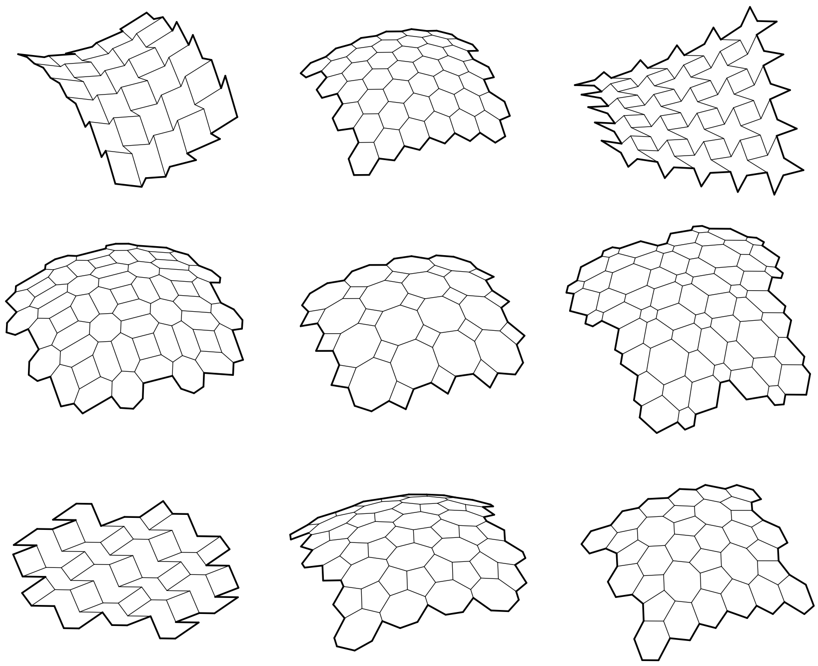

Figure 7.7: Examples of two-dimensional patterns that have been turned into three-dimensional polyhedra using height propagation.

polyhedral geometry, a projected segmentation can be adjusted to reflect the actual intersection situation (see Fig. 7.8). This is possible because the gap appears between two segments, and unless the segment planes are parallel, an intersection line can always be found. After updating the two-dimensional projection of the segmentation, the process can continue, and the next segment can be constructed.

Unfortunately, adjustments such as those shown in Fig. 7.8 lead to increasingly large deviations in the generation of consecutive segments. As a result, the final shape will deviate considerably from the intended shape, leading to results that may not be usable. However, as the height propagation process can be executed very fast using a script, the designer can update the segmentation while getting near-instant feedback on the result. By working from the

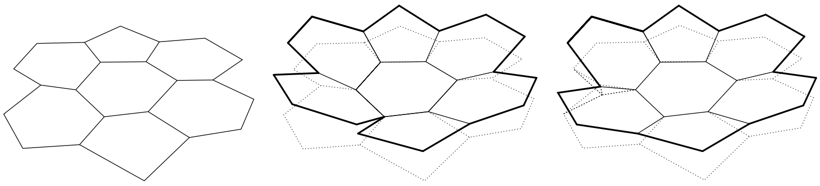

Figure 7.8: Steps in the geometric construction of a polyhedron based on a projection drawn by a designer (left). When an intersection line between two faces does not correspond to the drawn projected line (middle), the projection drawing is automatically adjusted and a valid polyhedron is constructed (right).

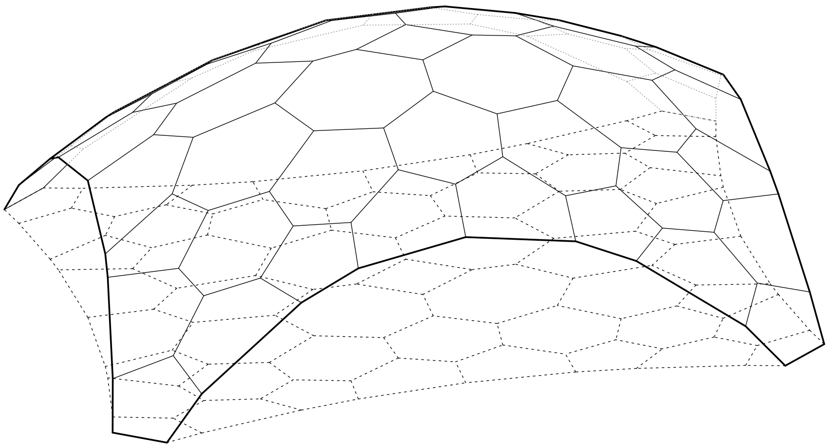

Figure 7.9: A plate shell designed using the height propagation method.

first segments that are generated to the last ones and adjusting the segmentation at any point where significant deviations would otherwise occur, height propagation can be employed as a practical design method, as illustrated by the example in Fig. 7.9.

This interactive height propagation method is most suitable for polyhedra consisting of relatively few plates, as the results of adjusting vertices are harder to foresee when many plates are used. As it provides near-instant results, using the method is an effective way to develop an intuition for the relationship between segmentation patterns and global geometry.

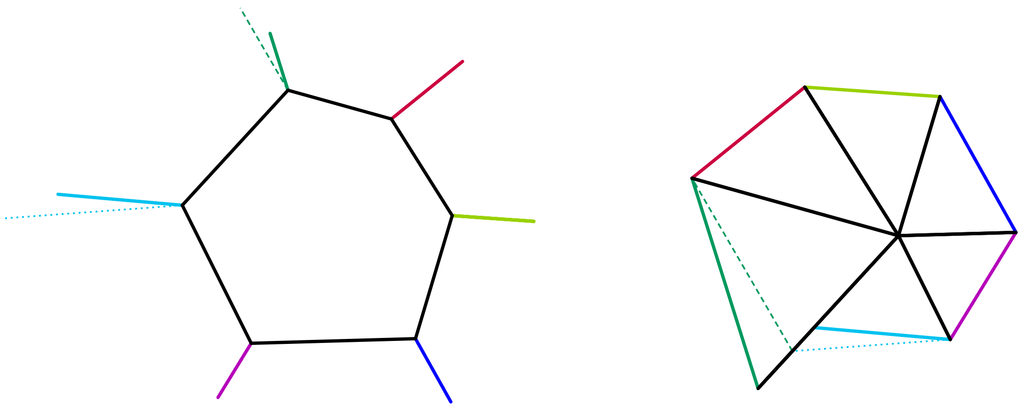

Figure 7.10: Two-dimensional sketch of the projection of a polyhedron (left) and the resulting imperfect force diagram (right). After closing the outer loop in the force diagram by adjusting one or two edges and updating the edge directions in the projection (marked with dashed lines), the projection can be used to create a valid three-dimensional polyhedron.

7.3.1 Force diagram adjustment

Instead of iteratively constructing a polyhedron from a projection and adjusting irreconcilable edge directions through the plane intersection process described in the previous section, edge directions can be adjusted by constructing a force diagram from a manually drawn segmentation projection that is interpreted as a cable net. Some triangles will not match up exactly in the resulting force diagram, but adjustments can easily be made to resolve this, as illustrated in Fig. 7.10. Compared to making manual adjustments to the form diagram, finding solutions using this method is considerably easier, as pairs of points representing a polygon simply need to be merged. However, mentally predicting the effect of changes is less direct, making the method less intuitive than the method using height propagation.

7.4 Parametric semi-regular meridian arrangement

As part of a design study for a vertical extension project consisting of a timber shell shaped similar to a horizontally placed truncated barrel (see Fig. 7.11), a meridian-like segmentation design was generated such that the segmentation pattern follows the boundaries of the surface. For economical reasons, the variation in plate dimensions was to be limited.

Fig. 7.12 shows the boundary situation where segmentation patterns meet a horizontal surface. A solution where plates are placed on the intersection points of principal curvature curves and section planes results in irregular plate shapes in the area where the shell touches the ground: the center plate is much wider than other plates and features a very short bottom edge. A similar situation occurs when spacing tangent planes evenly at section curves.

A solution was found using a parametric model, in which points were first regularly spaced on a series of section curves. The designer then modified the point spacing, using a spline curve to remap curve parameter values at which tangent planes were created (Fig. 7.12, right).

7.5 Incremental plane definition

Various design methods can be devised that make use of the fact that there is a difference between the number of corner points in a trivalent polyhedron (typically six) and the number of points necessary to define a plane (three). The general idea here is that strategic corners or edges of a polyhedral segment can be defined first (which defines the segment's plane), while the other corners and edges are only defined once the planes of neighbouring seg-

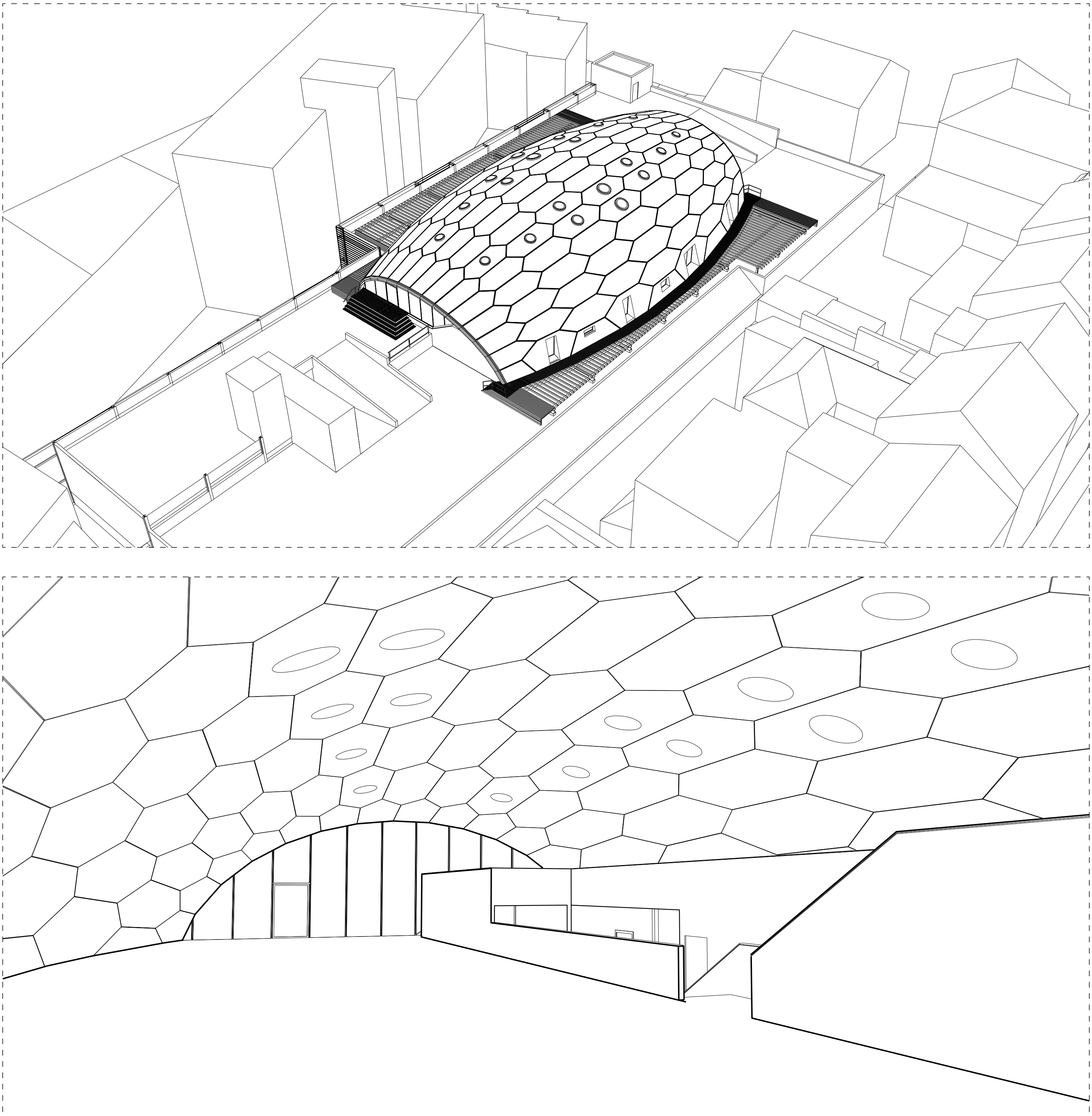

Figure 7.11: Bird's eye view and interior view of a vertical extension project.

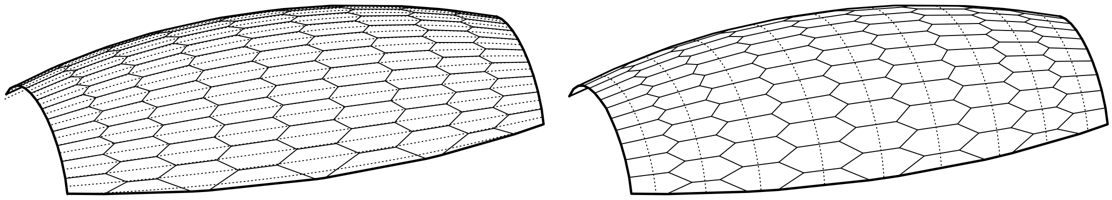

Figure 7.12: Comparison between a segmentation using principal curvature curves (left) and a segmentation where plane positions on section curves are modified by a designer (right).

ments have been defined. This section discusses several examples of this approach.

7.5.1 Row by row

As a first example of defining segment planes incrementally, consider a series of edges that lie between segments in a row of segments. Each pair of edges needs to lie in a plane, as otherwise, segments would not be planar. Generating such lines on a cylindrical or conical shape is trivial, but the lines need to be constructed carefully in less regular examples.

One possible approach is to first construct a series of points that are to end up on the edges, then construct planes through these points that are perpendicular to the global shape of the row of segments, as illustrated in Fig. 7.13. As soon as a single additional point is defined, a first plane can be constructed. By intersecting this plane with two of the planes generated in the previous step, the two edges of the first segment are defined. One of these edges can now be used together with one of the generated points to construct the plane for the next segment. By continuing this process, pairs of edges can be created for the whole row of segments. The remaining edges (those that do not lie between pairs of segments) can be created at will or using another incremental process, as discussed in the next paragraph.

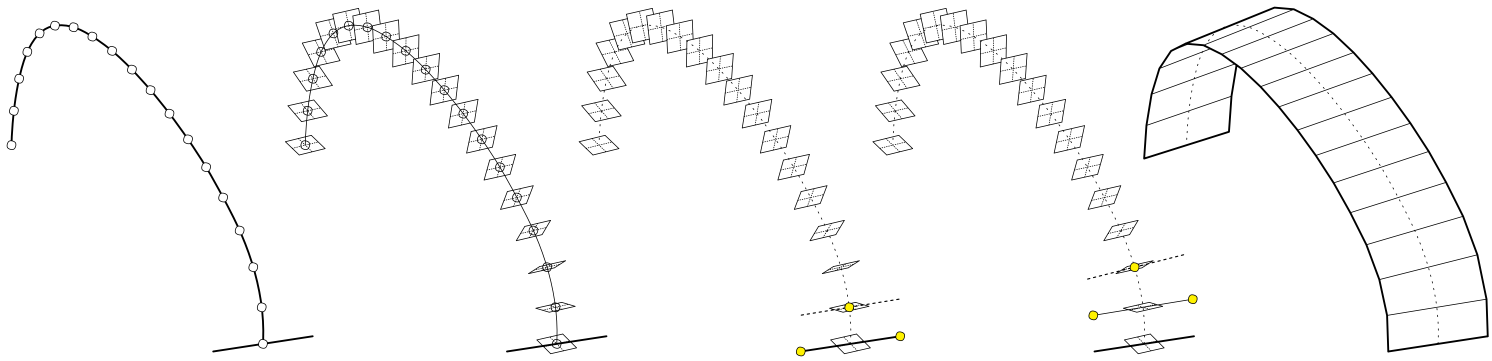

Figure 7.13: Incremental construction of a row of segments, using points at various positions on a curve plus the direction of the first edge (left). After constructing perpendicular planes (middle left), an additional edge can be created by intersecting one of the perpendicular planes with a plane constructed using three points (middle). This new edge and a point can be used to create the next plane (middle right); in this manner, a whole row of planes can be constructed (right).

Once the first row has been constructed, the second row of segments can be created by defining the lengths of the edges on the intersection lines, another series of perpendicular planes (between the existing planes), and two additional points. When repeating this procedure multiple times, tunnel-like configurations can be generated (Fig. 7.14).

A benefit of this incremental approach is that some geometric elements (the perpendicular planes and the starting points) can be freely defined; any of these elements can be placed at will. In the BUGA Wood Pavilion, this method has been used to control the segmentation of the protruding wings. After creating the planes that define the orientation of radial edges, the angle between the two rows of plates and the ensuing zig-zag pattern could be controlled with just two points for each opening (Fig. 7.15).

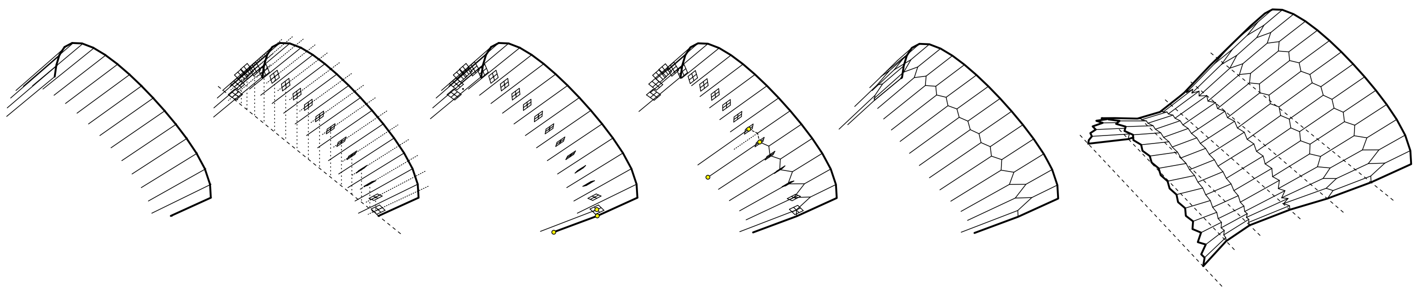

Figure 7.14: Incremental construction of a row of segments, starting from a series of edges in which each pair of edges is coplanar (left). After constructing a series of perpendicular planes above a line, the first pair of edges of the next row can be constructed based on a predefined edge direction in the ground plane. Using the endpoints on an edge and the next plane position, the row can be completed. The same procedure is then repeated for the remaining rows.

7.5.2 Explicit edge direction definition

For practical or aesthetic reasons, a designer may want to define the direction of certain edges. For example, in a structure containing multiple floors, the edges at all levels where a floor meets a plate shell may need to be horizontal. Starting from a partial plate shell design in which a certain critical area is not yet completed, such requirements can often be met by using construction planes or lines, and then geometrically constructing the missing plates one by one.

An example of such a process is illustrated in Fig. 7.16: here, the two bottom rows of a plate shell are to be created in such a way that some of the edges are exactly horizontal and some other edges are to fall within vertical planes that are perpendicular to the main axis of the building.

This manual geometry construction process starts by defining a horizontal intersection plane at the bottom of the first segment that is to be defined. The two bottom diagonal edges are still undefined at this point. After defining the bottom intersection plane for the neighbouring segments, the orientation of these segments can be

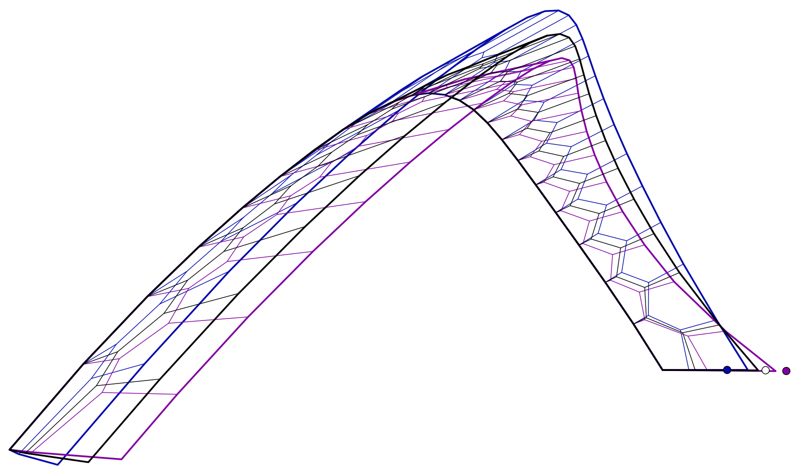

Figure 7.15: Design variations for one of the wings of the BUGA Wood Pavilion in Heilbronn. The variation between these three design variations was created by modifying the position of a single control point.

chosen so that the angle of the edges between the three generated segments visually matches the existing edge pattern. Once these two segments are defined, the segment below the middle segment can be created, again defining the orientation such that the diagonal edges with the neighbouring segment visually match the existing pattern. The edges on the sides can be created by intersecting the segment's plane with two vertical planes, whereas the bottom edge is created by intersecting the segment's plane with the ground plane.

7.6 Controlled pentagon placement combined with spring relaxation

Regular hexagons can be used to form planar two-dimensional patterns, but when combined with regular pentagons, truncated icosahedrons (which are a close approximation of spheres) can be created. Furthermore, when using agent-based methods to create

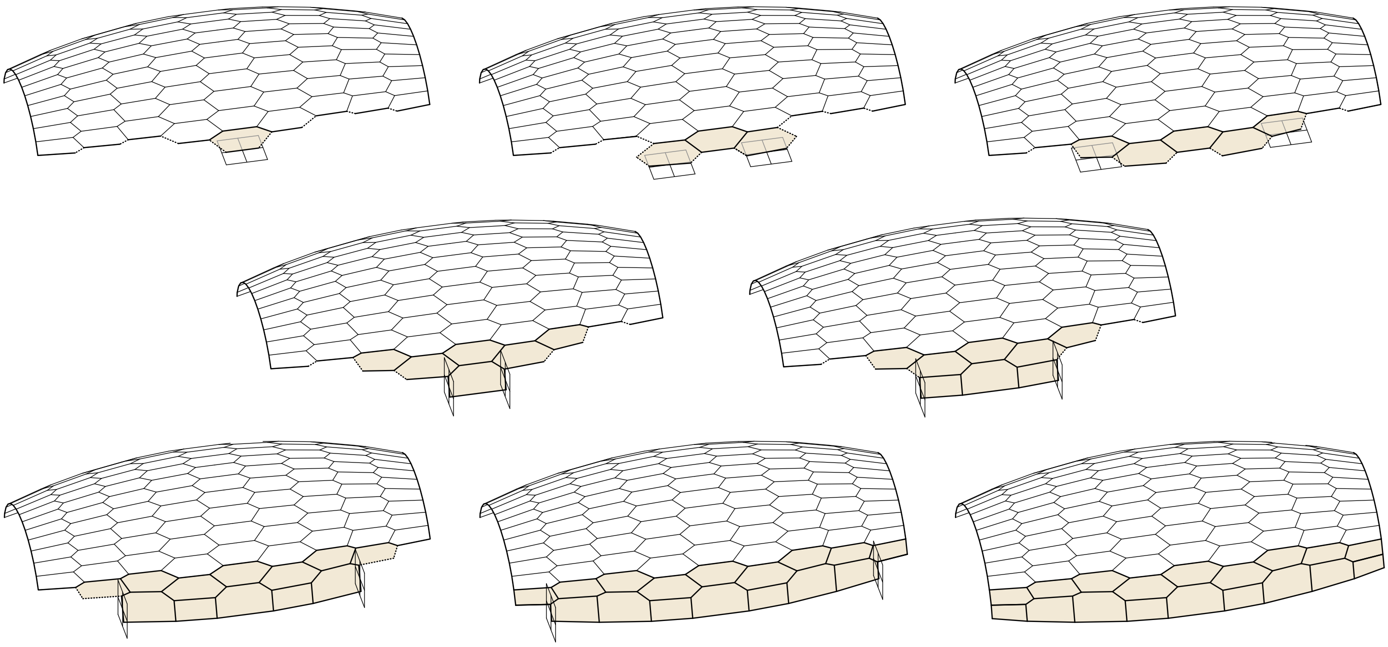

Figure 7.16: Geometric construction steps of segments with edges that lie within predefined planes. Dashed lines indicate edges that are not yet defined at a particular stage.

regular-looking segmentation patterns, five-sided segments tend to occur in areas with the highest curvature (although not exclusively there), as shown in Fig. 7.17. This suggests that it may be possible to control the global shape of a polyhedron by strategically placing five-sided segments in an otherwise hexagon-based pattern.

This idea can be tested using the following procedure: first, connectivity between points representing segments is defined in a two-dimensional graph, which for trivalent polyhedra consists of a triangulated pattern. Based on the graph, a two-dimensional segmentation is created, at this stage consisting of irregular pentagons and hexagons. Using spring relaxation with geometric constraints (or other constraint-based optimization methods), the geometry can be modified with two geometric goals: to minimize the vari-

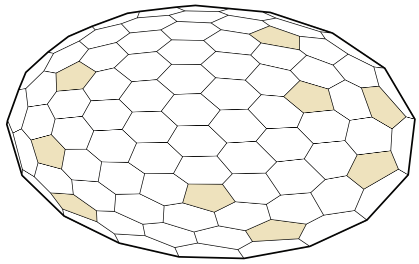

Figure 7.17: Occurrence of pentagons in a hexagon-dominant segmentation of a paraboloid (excluding pentagons near the edge of the segmentation). Image based on [52].

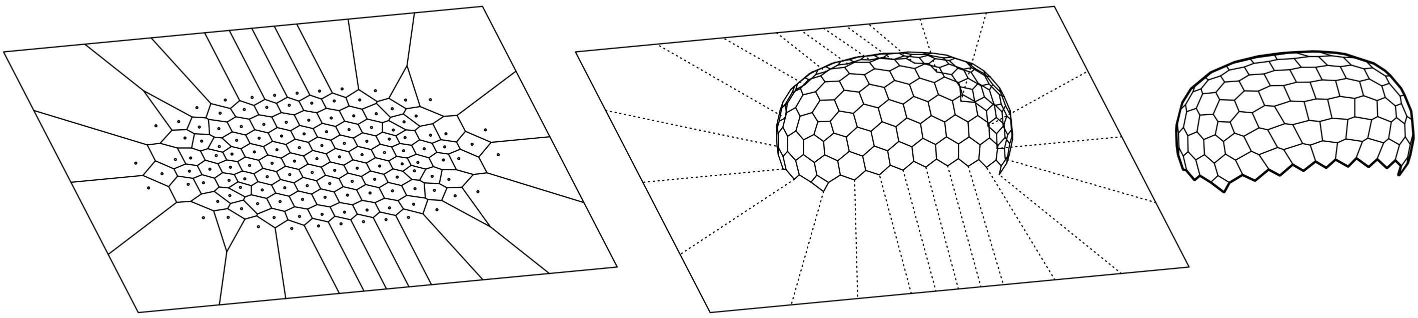

Figure 7.18: Steps to create geometry using controlled pentagon placement: Based on input points, a two-dimensional Voronoi diagram is created (left). From the cells in the Voronoi diagram, a 3D shape is generated using spring relaxation with a constraint to keep vertices on a circle (middle). Planarization is then used to create the final shape (right).

ation in edge length and to minimize the cumulative distances (or squared distances) of each segment's vertices to a circumscribed circle. After this, segments are planarized. This procedure is illustrated in Fig. 7.18; further examples are shown in Fig. 7.19.

In the segmentation shown in Fig. 7.18 (right), the surface area of segments remains consistent across the shape, regardless of local curvature. This property has economical and practical advantages and may also be desirable from an aesthetic point of view. The possibility to influence variation in segment size by adjusting the location of pentagon segments is also discussed by Li

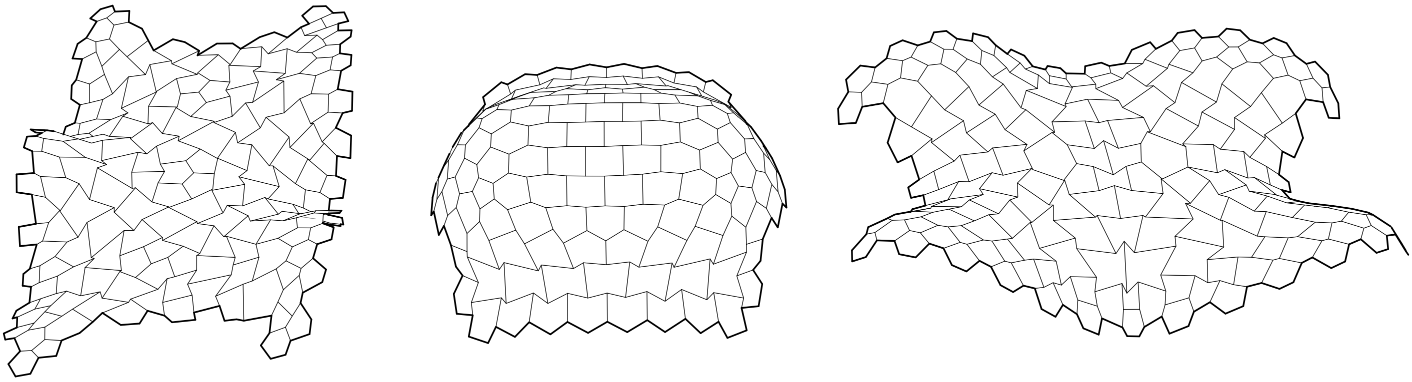

Figure 7.19: Polyhedral shapes created using controlled pentagon placement with spring relaxation.

[82], using a different method: triplets of pentagons or heptagons are used to decrease variation in segment size around umbilical regions.

While the fact that the method presented here does not depend on a base surface can lead to elegant curvature transitions, it does have the downside that a designer does not have direct control over the shape. Finding a connectivity graph that leads to geometry that matches the design intent takes trial and error, and except for adjustments to individual segments, detailed control can practically only be exerted during the relaxation stage, at which point the influence of planarization has not yet been determined. In practice, therefore, this method is more suited to the formal exploration of polyhedral shapes than to the design of plate shells with strong geometric constraints.

On a side note, the way an arrangement of pentagons and hexagons affects the resulting global shape (among other properties) has also been studied in the field of theoretical chemistry. Within this field, thousands of fullerene molecules have been digitally simulated [140]. As the geometry of these molecules could inspire polyhedral design, a selection of polyhedra based on these

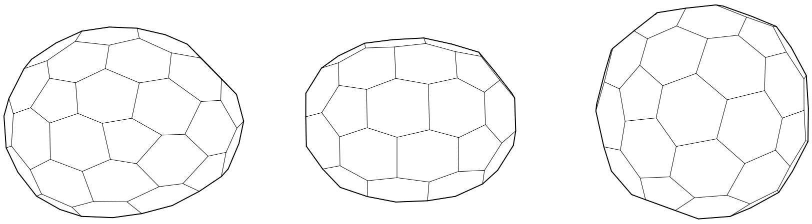

Figure 7.20: Examples of planarized fullerene geometry, based on data by M. Yoshida [140]

fullerenes is shown in Fig. 7.20. For this figure, the segments have been planarized using VTPI.

7.7 Vertex normal plane intersection

To define connectivity when using TPI based on a design surface, an explicit connectivity graph can be used, either in UV space or in Cartesian space. In the latter case, this connectivity graph can be seen as a mesh that in itself is a rough approximation of the surface; the vertex normals of such a mesh are approximately perpendicular to the original design surface. Instead of generating planes from tangent planes of a base surface, planes could therefore be created using the positions and vertex normals of a connectivity graph. Consequently, polyhedra can be designed without using a base surface by manually modelling the connectivity mesh, resulting in a method that will be referred to as Vertex Normal Plane Intersection (VNPI).

When using TPI, one has to define a base surface, tangent plane positions, and connectivity, which means that a designer may have to go back and forth between creating the base surface, modifying plane positions, and adjusting connectivity. With VNPI, all necessary geometric information is included in a single mesh object, resulting in a less complex workflow. Furthermore, mesh modelling has the advantage that it can be used for global designs that are difficult to model using NURBS surfaces, such as models that would require combining multiple NURBS patches. Kinks in the surface can also be integrated easily. Computationally, the method is very fast, allowing near-instant feedback while modelling.

In the proposed workflow, vertices can be moved to modify the design geometry without modifying connectivity between segments; when necessary, connectivity can be adjusted by flipping mesh edges between pairs of triangular faces. Tools such as mesh smoothing, mesh relaxation and subdivision can all be used to modify the mesh; such tools are readily available in various 3D modelling programs that designers commonly use.

Vertex normals can be defined implicitly (using geometric information from connected faces and/or edges) or explicitly (by creating an additional edge that points in the normal direction of a point). This allows the designer to automatically generate vertex normals in most of the model while specifying normal directions for specific vertices, such as those near umbilical points, near parabolic lines, or at boundaries.

Fig. 7.21 shows an example of a mesh that has been modelled manually (bottom) and the resulting polyhedron (top); a further model is shown in Fig. 5.24. While this example shows that VNPI can be a useful tool for the design of plate shells, considerations regarding anisotropic curvature (such as discussed in Section 6.2) remain true even when no base surface is present. This means that moving a vertex by a small distance can result in large changes in the resulting polyhedron. Modelling a mesh that results in a valid polyhedron therefore takes time and skill; for complex surfaces, a designer will need to have a strategy regarding parabolic lines and anisotropic curvature.

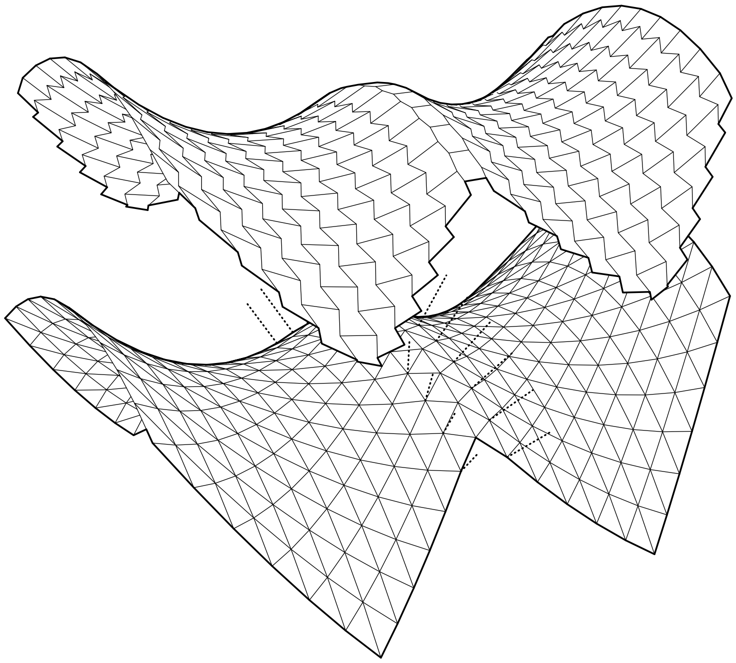

Figure 7.21: Example of a mesh (bottom) and a polyhedron generated with VNPI using this mesh (top). Dotted lines indicate explicitly defined normal directions.

7.8 Catmull-Clark subdivision

As triangles are always planar, modelling triangulated meshes is much easier than modelling trivalent polyhedra. Wang et al. show that Loop subdivision of a mesh can result in a triangulated surface that can be used to construct a valid trivalent polyhedron [139], thus showing that subdivision has the potential to be used as a design method for trivalent polyhedra. However, as shown in Fig. 7.22 (left), not all input meshes result in valid geometry when intersecting planes that are defined using vertex normals.

The size of triangles in the coarse mesh is reflected in the size of the final segments and thus needs to be controlled during the modelling process. Predicting the regularity of the resulting polyhedron requires trial and error and/or experience; the result

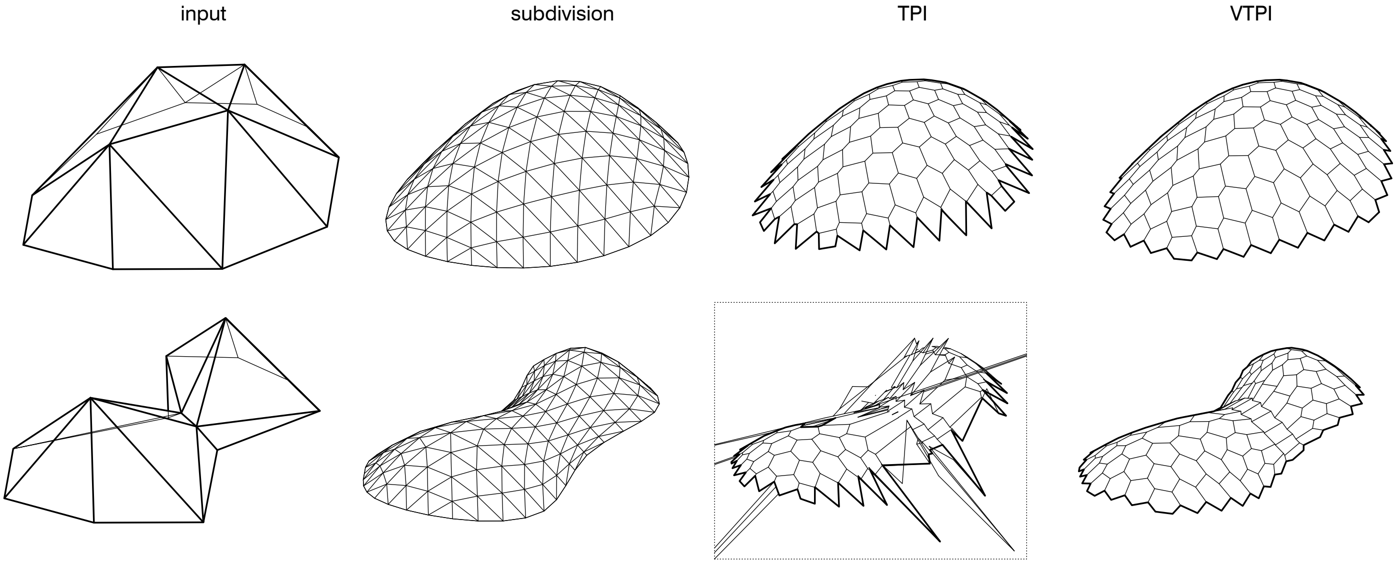

Figure 7.22: Starting with a coarse triangle mesh (left), Loop subdivision generates a smoother surface (center left). Using vertex locations, vertex normals, and connectivity information from this triangle mesh, a polyhedron can be constructed using TPI (center right) or VTPI (right).

depends both on the regularity of the coarse mesh and on the curvature anisotropy. When using TPI, the resulting geometry can be generated in a few milliseconds, which is fast enough to enable a workflow in which the polyhedral geometry is updated after every change in the control mesh, so that a designer can adjust the mesh geometry until the resulting polyhedron is valid.

Another approach is to use VTPI to create a polyhedron, with the triangulated mesh as input. The results of this procedure are much more robust than those using TPI, as illustrated by the example in Fig. 7.22 (right). However, as this process is computationally much more demanding, a very efficient implementation or significantly faster computer hardware would be required to be able to use this method interactively.

When using subdivision modelling in architecture, quad-based geometry combined with Catmull-Clark subdivision [26] is often used. The resulting geometry is not trivalent, which can be resolved by either projecting a triangle grid on the mesh, or constructing a triangle grid using every other point in the subdivided mesh.

7.9 Local manual editing with automatic connectivity updates

As discussed in Section 6.6, local modifications to polyhedral geometry can be carried out manually in a few simple steps. However, when having to carry out these steps for various versions of a design, comparing alternatives or experimenting with the adjustment of multiple segments can be cumbersome. This section discusses a faster workflow to effectuate small adjustments to existing polyhedral geometry.

In an existing polyhedron, connectivity between segments is defined. Some changes (such as moving a segment up or down by a small amount) can be made without affecting connectivity; for such changes, the polyhedron can be reconstructed using the existing connectivity graph and the planes that the segments lie on. Slightly larger changes may lead to invalid intersections and thus require an update to the connectivity graph. When modifying a single segment, the number of affected segments is small and as a result, detecting and resolving connectivity issues can be carried out automatically. In case the changes resulting from moving or rotating a segment lead to an invalid solution that is too complex to conveniently resolve in an automated manner, the change can be broken up into a series of smaller movements, which leads

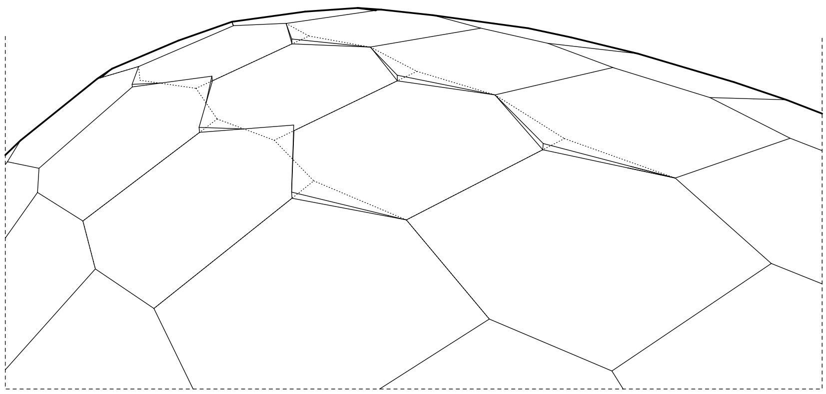

Figure 7.23: Adjusting an existing segmentation pattern by moving a vertex without adjusting the segments' planes results in stepping at joints.

to less intrusive connectivity issues that can be expected to be automatically resolvable.

When implementing this process, the result is a digital design tool in which segments of a polyhedron can be conveniently moved or rotated individually.

7.10 Controlled deviations

Chapter 6 and the previous sections in this chapter focus on the design of trivalent polyhedra: shapes that consist of perfectly flat segments that are infinitely thin and in which three segments come together in a single point. In reality, plate shells have a thickness, which means that planes do not necessarily have to exactly meet at joint surfaces: when accepting the occurrence of a certain amount of stepping at the joints, one can modify the joint pattern without adjusting the planes defining the bottom surfaces of plates (see Fig. 7.23).

Depending on joint detailing and the size of steps between plates, stepping may or may not be visually noticeable. Visible stepping could be considered undesirable from an aesthetic point of view, but it can also be considered a design feature, as exemplified by the Block Research Group's Armadillo shell [20]. The gained design freedom in the segmentation pattern expands the design space of plate shells, allowing greater geometric freedom and allowing the adjustment of joint patterns in structurally weak areas or in areas where plate shapes lead to inefficient material use.

When adjusting a segmentation pattern this way, the intersection line between three edge planes no longer is a single line: typically, each pair of two edge planes has a different intersection line. Geometrically, this inexactness can be resolved in two ways: one can fill the volume between the three intersection lines, or one can twist the edge planes to make them meet in a single intersection line (see Fig. 7.24). The latter solution is easier to keep airtight, but adds complexity to the joint machining process. However, if finger joints are used, creating a twist in the joint surface can be included in the joint milling process, meaning that no additional fabrication steps are necessary. With either solution, the top edge of some plates may need to be milled off to create a more continuous top surface. The impact on the geometry of the thermal insulation needs to be considered as well, as the geometric complications that occur in the plates will also occur in this layer.

The relation between the amount that a point is moved and the resulting stepping depends on surface curvature: where the angle between plates is close to 180°, moving points results in minimal stepping, whereas at smaller angles, stronger stepping occurs. An example of how far corner points can be moved for various stepping heights is shown in Fig. 7.25.

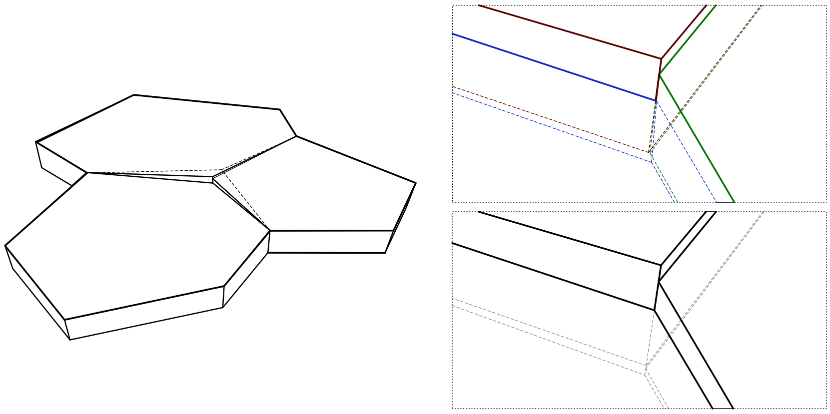

Figure 7.24: Corner details with planar joints intersecting in three non-collinear intersection lines (top right) and twisted joint faces intersecting in a single line (bottom right).

7.11 Conclusion

This chapter discussed various contributions to design methods for trivalent polyhedral geometry. The wide range of presented approaches results from a search for a method that is intuitive, flexible, reliable and suitable for any input geometry. No such universal method has been found, but the proposed methods improve upon existing methods by making design processes more interactive, increasing the design space, making the process of modifying designs less tedious, and increasing the control a designer has.

A complication in the design of plate shell geometry is the lack of reliable plane intersection methods for anticlastic surfaces: existing methods only work reliably when the spacing of tangent planes matches surface curvature. The proposed plane intersection method for anticlastic surfaces (see Section 7.1) is a major improvement over other plane intersection methods for anticlastic surfaces, as it leads to valid results for a vastly larger range of input geometry. This can greatly improve the robustness of plate shell design methods when applied to anticlastic surfaces, including

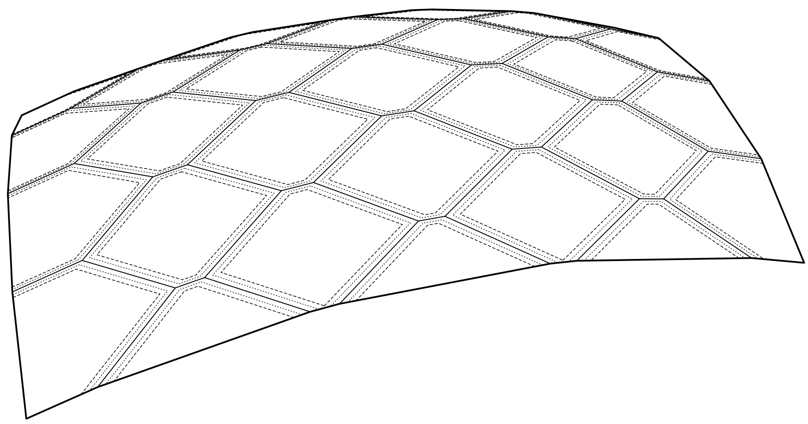

Figure 7.25: Areas in which edges in a plate shell can be freely moved with a resulting maximum stepping height of 1 cm (dotted line) and 2 cm (dashed line). The plates in this figure are approximately 2.5 m long.

but not limited to agent-based algorithms that rely on valid plate geometry. In addition to being more robust than existing plane intersection methods for anticlastic surfaces, the method results in fairer and visually more coherent segment shapes.

Table 7.2 shows a comparison between several design methods for plate shells. The *curvature sensitivity* property indicates to what extent the curvature conditions (in particular curvature anisotropy) affect the validity of the resulting polyhedral geometry. The *transition sensitivity* property indicates to what extent the validity of the polyhedral geometry is affected by the presence of parabolic lines. The *design space* property indicates the variety of designs that can be created with the method, and the *design control* property indicates how much control the designer has over the resulting geometry. The values in the table are a qualitative assessment by the author, as due to the differences between input types, no objective quantitative comparison can be carried out.

Method	**Input type**	**Curvature sensitivity**	**Transition sensitivity**	**Design space**	**Design control**
agents + TPI	NURBS surface	very high	very high	large	medium
agents + CAGM	NURBS surface	low	very high	large	medium
interactive agents + CAGM	NURBS surface	low	very high	large	high
planar hexagonal meshing (Li)	NURBS surface	low	high	medium	low
coordinate power fields (Pluta)	NURBS surface or mesh	low	low	large	low
agent-based + iterative slicing	NURBS surface	very low	–	small	medium
meridian placement	NURBS surface	medium	medium	medium	low
incremental plate placement	curves	medium	low	medium	medium
interactive edge propagation	lines/curves	high	high	large	high
pentagon placement relaxation	connectivity graph	low	low	medium	low
Catmull - Clark subdivision	mesh	high	high	large	high
vertex normal plane intersection	mesh	high	high	large	high

Table 7.2: Comparison of design methods for plate shell geometry.

Looking at further contributions to design methods for polyhedral geometry in more detail, Section 7.2 discusses an interactive agent-based design method in which the designer can make geometric modifications to which the agent system reacts virtually instantaneously. This turns a mostly autonomous computational process into an interactive tool, where the designer develops a feel for agent behaviour instead of just visually observing such behaviour. Additionally, edge-based behaviours are discussed; such behaviours can be used to improve plate shell geometry, but also to adjust joint geometry to local structural conditions.

Section 7.3 discusses how plate shells can be designed based on a 2D projection only. This can either be done using straightforward geometric reconstruction only or in combination with 2D spring relaxation. This design method makes it possible to study the effects of segmentation patterns on surface curvature, instead of the other way around.

For some design tasks, simpler parametric tools can lead to good solutions that would be hard to achieve with agent-based tools. Section 7.4 discusses a parametric model that can be used to construct controlled segmentations by placing plates on section curves of a surface. Section 7.5 discusses how similarly controlled polyhedra can be generated based on control curves and/or numeric input instead of a design surface. Instead of defining only tangent planes or conversely defining the complete geometry of segments, the strategy in this method is to design a segment plane and only a few strategic points or edges while leaving other edges temporarily undefined. A similar strategy is employed in a method to locally define edge geometry, as discussed in Section 7.5.2.

Section 7.6 discusses a design method that combines the placement of pentagons in a hexagon-dominant structure with spring relaxation. While there may not be any direct practical applications to this method due to limited direct control over the output, the method results in geometric configurations that could inspire novel plate shell designs.

Sections 7.8 and 7.7 discuss how mesh modelling can be used in plate shell design. In the former section, planes are defined by the vertex normals of 3D connectivity graphs; instead of a combination of a design surface and a connectivity graph, a single mesh fulfils both functions. In the latter section, subdivision is used to define plane placement, after which TPI or VTPI are used to find a valid segmentation.

Section 7.9 discusses digital tools that can simplify the process of making local changes to a polyhedral design.

Section 7.10 discusses deviating from perfect polyhedral geometry: so far, all geometric design methods discussed here are based on polyhedral shapes consisting of segments with no thickness that intersect each other at exact lines and points. However, actual plate shells do have a thickness, and particularly when angles between plates are shallow, moving edges from their geometrically calculated position would only result in minimal deviations between the bottom surfaces of plates. When accepting even just a couple of millimetres of deviations between plates, substantial freedom in the segmentation design can be gained.

A general observation on the design methods discussed in this chapter is that insight into surface curvature and geometric properties of polyhedra is necessary in order to effectively use the tools. By extension, plate shells can be most effectively designed when the designer has a global design strategy to deal with curvature. Depending on this strategy and the design intent, a suitable design method can be chosen.

8

Conclusion

This dissertation set out to investigate topics relevant to the design and fabrication of timber plate shells, in order to evaluate how suitable such plate shells are for applications as roof structures. In particular, the suitability of timber plate shells for vertical extension projects in the existing building stock has been assessed. Furthermore, architectural design considerations have been outlined and contributions have been made to computational design methods for plate shells.

The first plate shells were constructed in the 1970s in shapes based on regular subdivisions of spheres. More recently, the design of plate shells has become relevant again thanks to advances in computational design and digitally controlled fabrication, making it possible to create structures consisting of plates with unique geometry without inducing high additional costs, thus allowing a vastly expanded range of architectural applications.

Using wood for plate shells has been made possible by the availability of engineered timber plate materials such as LVL and CLT, which have become readily available on the market in large dimensions around the turn of the 21th century. The combination of computational design and digitally controlled fabrication with the availability of large timber plate materials results in the potential to create very light timber shells. However, only few timber plate shells have been constructed so far.

Timber structures strongly contribute to sustainable construction, as wood is a renewable resource that acts as carbon storage. Timber plate shells expand the range of structural typologies and as such contribute to the application potential of timber in the construction sector. Due to their structural efficiency, timber plate shells are particularly suited to applications where low weight is important.

Vertical densification (the addition of building volume on top of existing buildings) is a sustainable response to ongoing urbanization, and is an application where low weight is advantageous. Structural solutions for vertical densification projects need to be geometrically adaptable to existing structural and geometric conditions, and (based on common dimensions in the existing building stock) need to be able to span up to 15 m for residential buildings or up to 20 m for commercial buildings.

8.1 Evaluation of timber plate shell properties

Two types of timber plates were introduced and analysed in Chapters 3 and 4. The first plate type aims for simplicity and low cost and consists of solid plates of a single layer of CLT, connected with crossing screws. The second plate type aims for minimal weight and consists of hollow components that are glued together out of multiple LVL elements and that are connected to each other using finger joints and bolts.

Each of these systems has advantages and drawbacks: the CLT plates are easier to fabricate, are more resistant to fire and insulate sound better, but are heavier. The hollow components are lighter and allow disassembly and reassembly, but are not very resistant to fire. While both systems can fulfil criteria posed by building code for a large range of applications, hollow components can thus only be used for applications where fireproofing is less of a concern, unless sprinkler systems are used. Both plate types are lightweight, have a favourable environmental impact and allow fast on-site assembly. High prefabrication accuracy is required to ensure that all components fit together well, which is important for structural performance, air tightness, sound insulation, moisture tightness, and fireproofing.

Acoustically, there are no specific drawbacks to plate shells so long as focusing of echoes at ear level is avoided. Daylight can be let in through glazed façades, through openings within plates, or through larger openings in the shell. Electric cables can be integrated into hollow components relatively easily, but due to their size and due to the more complex joints at the edges of plates, ventilation channels cannot be easily integrated within the plates. The placement of such channels should instead be taken into account as part of the global design strategy. As with other roof construction systems, thermal insulation and roofing need to be added as additional layers on top of the timber structure.

A span of 23 m has already been demonstrated in the BUGA Wood Pavilion, and even larger spans can be realized using thicker plates. For the vast majority of existing buildings, the distance between the front and back façades is smaller than this, so timber plate shells can span virtually any distance necessary for vertical densification applications.

Because timber plate shells consist of more elements and are more complex to fabricate than CLT slabs, plate shells are more expensive than roofs consisting of flat CLT slabs when applied to short spans. But given appropriate support conditions and sufficient height, timber plate shells are very material efficient at longer spans; for larger spans, the resulting material savings can be larger than the additional fabrication costs compared to CLT slabs. Exact cost comparisons need to consider additional costs resulting from more complex geometry of the thermal insulation and waterproofing layers and can only be made on a project-specific basis. Logically, actual costs depend on the market situation and the willingness of contractors to work with novel construction types that require high accuracy.

8.2 Architectural design of timber plate shells

Architectural design considerations were discussed in Chapter 5, starting with the structural impact of design decisions. Thrust forces are a primary concern and the structural efficiency of plate shells largely depends on the available support conditions. Strategies to resolve thrust forces (for example within existing floor planes or walls, or by using tension cables within the space) should thus be included in the design concept. As with continuous shell structures, a higher rise of plate shells leads to higher structural efficiency. Segmentation patterns affect where forces act on the supporting geometry and also affect structural performance: short edges can result in stress concentrations and collinear edges can compromise stiffness, resulting in large deformations.

Connecting double-curved structures to an underlying orthogonal support structure is inherently challenging, as intersections between synclastic structures and a horizontal or vertical plane are curves, not straight lines. The same is true of anticlastic surfaces that are not ruled surfaces. One way to resolve this issue is by letting shells come down in column-like configurations; another is to extend walls to the exact height needed to connect to a plate shell. Yet another possibility is designing plate shells so that the supported edges of the structure are approximately collinear, but such designs feature limited surface curvature, which negatively affects structural performance.

Two options to fulfil thermal insulation requirements are preformatted rigid thermal insulation plates, and soft thermal materials in combination with battens. Using battens requires more labour on site but can simplify the attachment of additional layers that may be added for aesthetic reasons (for example, thin timber plates). For waterproofing, using materials that allow stretching (such as EPDM) minimizes the number of joints in the waterproofing layer, saving costs and decreasing the chances of leaking.

Plate shells have a unique architectural character, in which the segmentation pattern can be perceived from the interior and in which the structural system forms the enclosure of the space. Segmentation patterns are linked to surface curvature and in some designs, segmentation patterns are visibly linked to the global design geometry.

Plate shells can be used to construct a variety of typologies featuring double curvature, ranging from spherical shells to designs featuring kinks and openings. Such shapes are difficult to construct using other construction methods. Kinks or discontinuous global geometry can be used as a design feature to control room height, to create large daylight openings, and to integrate technical installations (such as HVAC channels).

8.3 Design methods for plate shells

Chapters 6 and 7 discuss a wide range of geometric design methods, as well as geometric considerations relating segmentation patterns to surface curvature. Contributions include a novel segmentation method for anticlastic surfaces and extensions to agent-based design tools.

Various geometric design methods use tangent planes generated on a base surface (typically a NURBS surface). How suitable a base surface is for segmentation can be evaluated using various curvature visualization methods. Of particular interest are principal curvature directions and curvature anisotropy; visualization methods combining these two properties are proposed.

Plate shells can also be constructed without using a base surface, in an incremental way (row by row) or starting from a two-dimensional projection. This can lead to more regular segmentation patterns than those generated on a base surface, especially around curvature transitions.

An ideal computational design method for plate shells should be robust, flexible, intuitive and fast. Despite the multitude of geometric design methods that were evaluated and introduced, no single method has been identified that fulfils all these criteria. Therefore, a designer needs to select the right design tool, which is only possible with some insight in the geometric intricacies of plate shells discussed in Chapter 6. The global geometry design and the segmentation design should not be treated as two subsequent steps, but should be developed in parallel.

8.4 General conclusion

Timber plate shells are a lightweight and sustainable construction system that is suitable for applications as a roof construction system for vertical densification projects. Plate shells are most economical at longer spans (starting at around 10 meters), provided that hinged supports are available or the supports can be structurally connected horizontally.

To effectively design plate shells, custom digital design tools and insight into the effect of surface curvature on segmentation patterns are necessary. While improvements to design tools are proposed, various tools have been used to create the plate shells shown in this dissertation, with the choice of design tool depending on the specific design task. Unfortunately, this suggests that with currently existing tools, designing plate shells remains a rather difficult task.

A further challenge is that contractors would need to be willing to fabricate and build plate shells. In addition to plate shells being a construction type that most contractors are unfamiliar with, plate shells also require higher fabrication accuracy than is the norm in the construction sector, not only to be able to assemble the plates but also to achieve high structural performance and sufficient fire resistance – although this latter topic should still be investigated more deeply using physical tests.

Despite these design and fabrication challenges, timber plate shells are a construction system that merits wider application: timber plate shells can not only be extremely light, sustainable, and economical, they also form a unique addition to the vocabulary of timber architecture.

9
Glossary

This section aims to clarify the meaning and use of terms that some readers may be unfamiliar with, of terms that may be ambiguous, and of terms that have different meanings in different contexts. All of the following definitions are intended to describe the meaning of the terms within the context of this dissertation and are not intended as formal or universal definitions.

In this dissertation, the terms polyhedron, segment and edge are used when referring to geometric principles. The terms plate shell, plate and joint are used when referring to structures.

agent
An entity within a software program that reacts to its context (for example by moving or changing its associated geometric or non-geometric properties), including (but not necessarily limited to) interactions with other agents.

anticlastic
Surface curvature that has opposing signs in the two principal curvature directions (also called negative Gaussian curvature).

conjugate curve network
A grid-like set of curves that follow principal curvature directions on a surface.

curvature of a polyhedron
The curvature of a smooth surface that a polyhedron approximates.

curvature anisotropy
The proportion between the curvature in the two principal curvature directions at a point on a surface. Curvature on a sphere is isotropic (equal in all directions), whereas curvature on a cylinder is infinitely anisotropic.

curvature lines
Curves on a surface that follow the principal curvature directions of the surface (also called lines of curvature).

Delaunay triangulation
A shape consisting of triangles that have been generated between points in such a way that for each triangle, the smallest sphere that is defined by the vertices of that triangle does not enclose any of the other vertices.

design method
The process of creating a design, using a specific process and specific design tools. In the context of this dissertation, this means that two processes that use different tools to achieve a similar result are considered two different design methods.

design tool

A piece of software that systematically carries out steps (typically geometric operations) on input provided by a designer, resulting in a design (or partial design) as output.

edge

A straight line segment that forms part of the boundary of a segment in a polyhedron, or a straight line between two vertices in a mesh.

fairness

The aesthetic appeal of a shape (such as a polyhedral segment), based on geometric properties such as proportions between edges, proportions between angles and the proportion between edge length and surface area.

hexavalent

A property of a polyhedron indicating that at each corner, six segments come together.

mesh

A digital representation of a three-dimensional shape, defined by vertices (points in space), edges (lines between vertices) and faces (flat surfaces between lines).

morphospace

The range of designs (or geometric possibilities) that can be realized within a system while meeting specific constraints (such as available material sizes or fabrication limitations).

normal

The vector that is perpendicular to a plane or perpendicular to a surface at a specific point.

NURBS model

A digital representation of a three-dimensional shape in which curves (straight or curved) and surfaces (flat, curved or double-curved) are defined mathematically using control points.

parabolic line
The curve that forms the boundary between synclastic and anticlastic areas of a surface.

plate shell
A structure consisting of planar elements that predominantly transfer loads through shear forces and compression.

plate
A polygonal building element or component that is part of a plate shell.

principal directions
The direction in which the curvature at a point on a surface is strongest and the direction perpendicular to this.

polyhedron
A three-dimensional shape consisting of planar segments with straight edges.

segmented shell
A shell structure that has been constructed by joining multiple components together on-site (instead of creating one continuous structure). Plate shells are an example of segmented shells.

segment
A planar element that is part of polyhedral geometry.

segmentation
A polyhedral approximation of a double-curved surface.

synclastic
Surface curvature that has equal signs in the two principal curvature directions (also called positive Gaussian curvature).

tetravalent
A property of a polyhedron indicating that at each corner, four segments come together.

trivalent

A property of a polyhedron indicating that at each corner, three segments come together.

umbilical region

The region around a point on a surface where the surface curvature is isotropic and thus approximates a sphere.

valid polyhedron

A polyhedron without any holes or self-intersecting segments.

vertical densification

Increasing the amount of usable floor space in a building by adding one or more additional floors on top of the existing building, or by modifying the roof shape of the building.

A

Appendix A: BUGA Wood Pavilion

This appendix shows drawings (scale 1:200) and photographs of the BUGA Wood Pavilion in Heilbronn.

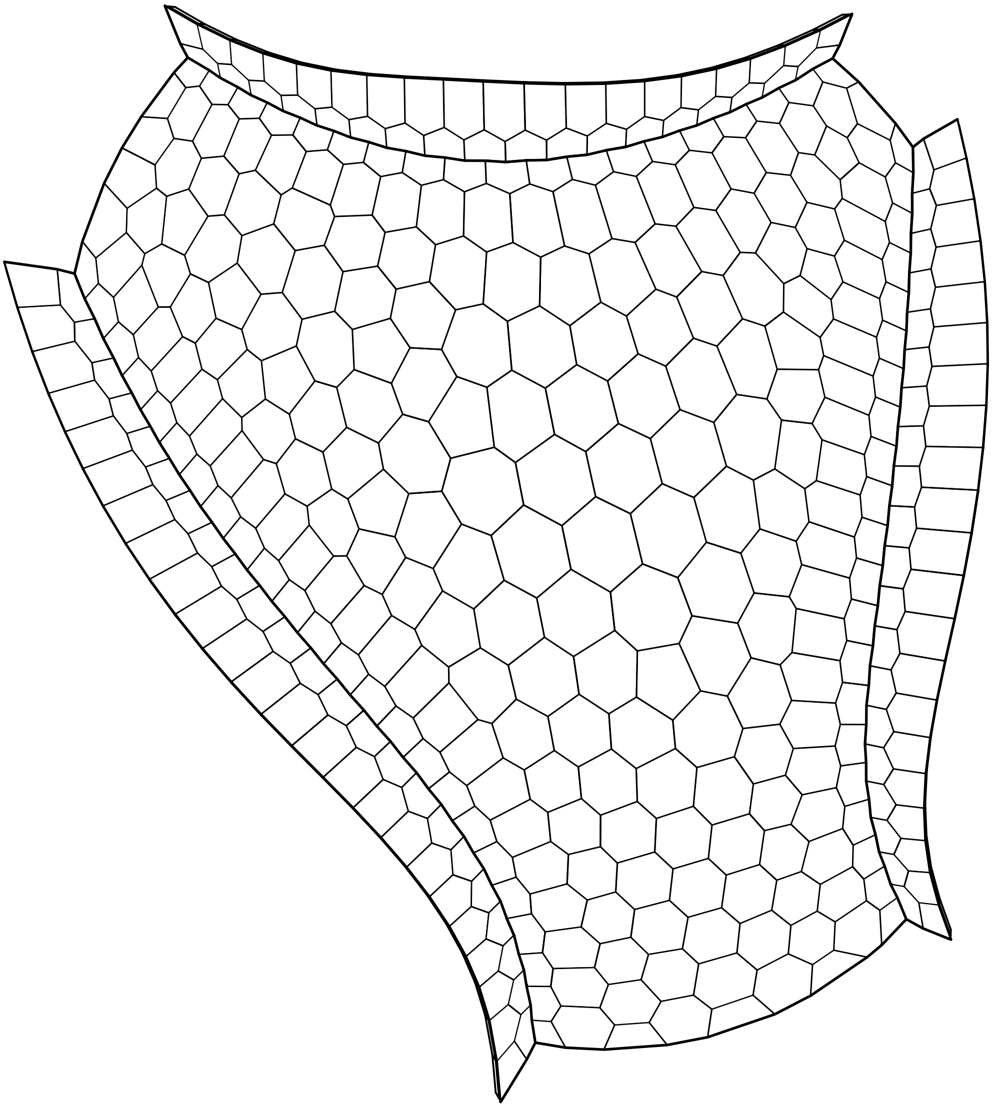

Figure A.1: Top view, scale 1:200. Image source: ICD/ITKE, University of Stuttgart

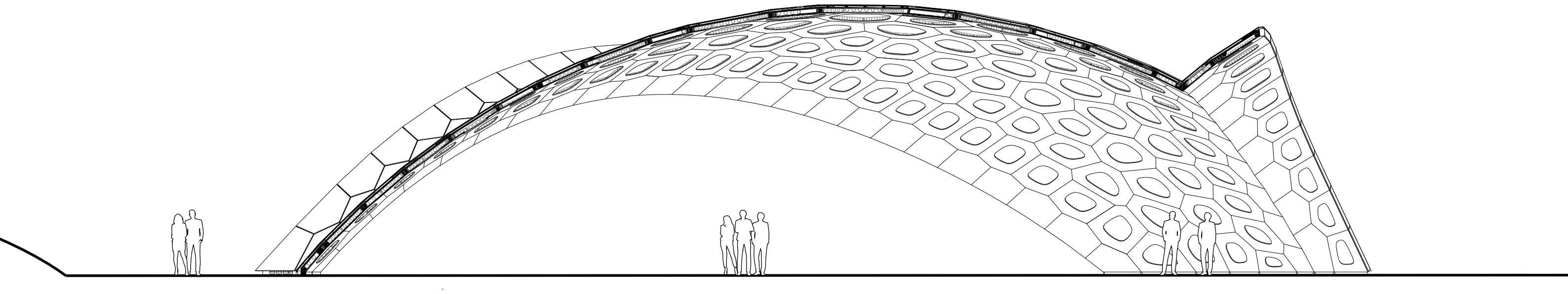

Figure A.2: Section, scale 1:200. Image source: ICD/ITKE, University of Stuttgart

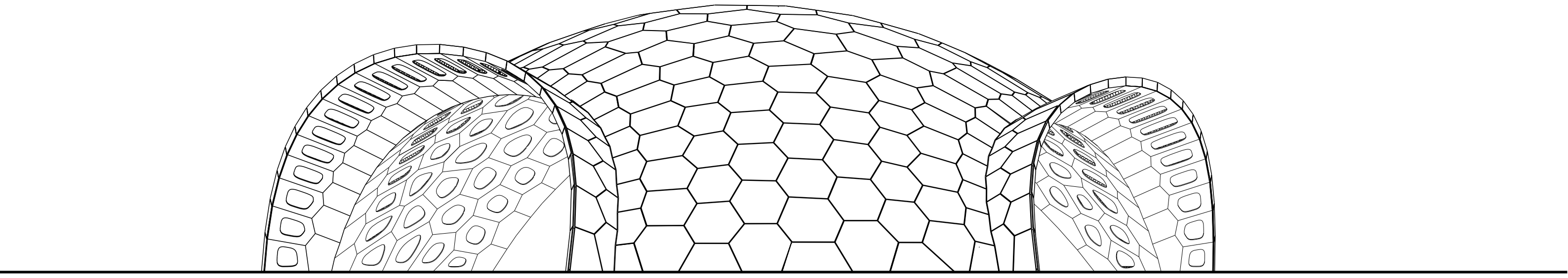

Figure A.3: View from south, scale 1:200. Image source: ICD/ITKE, University of Stuttgart

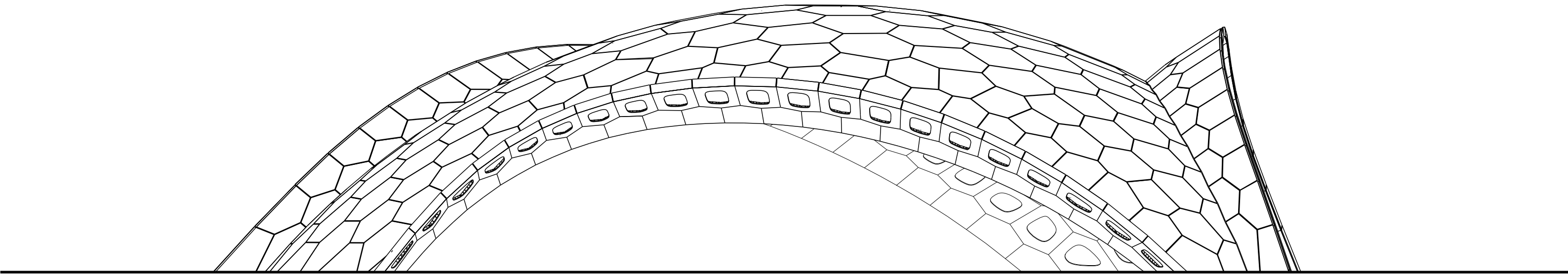

Figure A.4: View from east, scale 1:200. Image source: ICD/ITKE, University of Stuttgart

Figure A.5: Multi-robot fabrication setup for the BUGA Wood Pavilion. Image source: ICD/ITKE, University of Stuttgart

Figure A.6: The BUGA Wood Pavilion. Image source: ICD/ITKE, University of Stuttgart

Figure A.7: Detail of the BUGA Wood Pavilion. Image source: ICD/ITKE, University of Stuttgart

B

Appendix B: FEM Setup

This appendix contains an example of relevant sections of the Sofistik setup for the Finite Element Analysis used for structural comparisons in this dissertation.

```
+prog aqua urs:1  $ standard + material

HEAD
NORM 'DIN' 'en1992-2004' CAT 'AN' UNIT 5
MAT NO 160 E 4400000 GAM 5  $ e modulus: 50 % of C16 mean value in strongest direction
END

+prog sofimshc urs:2
HEAD
#define THICKNESS=0.16[m]
#define FIXLEFT=PP
#define FIXRIGHT=PZ
#define FACTOR=1.0
#define CXCM=$(factor)*444.55   // bending
#define CXCP=$(factor)*2277.53  // shear
#define CYCP=$(factor)*22681.01  // compression/tension
#define CZCP=$(factor)*10318.99   // out of plane shear
SYST 3d GDIR NEGZ GDIV 10000
CTRL MESH 2
CTRL HMIN 0.15


// geometry data
// points and springs (for 61 edges)

$ edge 1
SPT NO 1 X 2.202488 Y 1.251102 Z 3.495945 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPT NO 2 X 0.000000 Y 1.251102 Z 1.816341 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPT NO 3 X 2.082102 Y 1.251102 Z 3.404140 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPTS REF 4 TYPE CX CM $(CXCM) GRP 1
SPTS REF 4 TYPE CX CP $(CXCP) GRP 2
SPTS REF 4 TYPE CY CP $(CYCP) GRP 3
SPTS REF 4 TYPE CZ CP $(CZCP) GRP 4
SPT NO 4 X 2.082102 Y 1.251102 Z 3.404140 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPT NO 5 X 2.000364 Y 1.251102 Z 3.341807 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPTS REF 6 TYPE CX CM $(CXCM) GRP 1
SPTS REF 6 TYPE CX CP $(CXCP) GRP 2
SPTS REF 6 TYPE CY CP $(CYCP) GRP 3
SPTS REF 6 TYPE CZ CP $(CZCP) GRP 4
SPT NO 6 X 2.000364 Y 1.251102 Z 3.341807 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPT NO 7 X 1.918626 Y 1.251102 Z 3.279474 SX -0.795167 SY 0.000000 SZ -0.606390 NX -
0.510139 NY -0.540611 NZ 0.668952 TITL 1 XFLG PLA
SPTS REF 8 TYPE CX CM $(CXCM) GRP 1
SPTS REF 8 TYPE CX CP $(CXCP) GRP 2
SPTS REF 8 TYPE CY CP $(CYCP) GRP 3
SPTS REF 8 TYPE CZ CP $(CZCP) GRP 4
[...]

// joint lines
SLN NR 1 NPA 1 NPE 3 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 2 NPA 3 NPE 5 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 3 NPA 5 NPE 7 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 4 NPA 7 NPE 9 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 5 NPA 9 NPE 11 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 6 NPA 11 NPE 13 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 7 NPA 13 NPE 15 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 8 NPA 15 NPE 17 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 9 NPA 17 NPE 19 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 10 NPA 19 NPE 21 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 11 NPA 21 NPE 23 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 12 NPA 23 NPE 73 GRP 1 BEZ 1 XFLG PLA   $ edge 1
SLN NR 13 NPA 73 NPE 71 GRP 1 BEZ 4 XFLG PLA   $ edge 4
SLN NR 14 NPA 71 NPE 25 GRP 1 BEZ 3 XFLG PLA  FIX $(FIXLEFT)  $ edge 3
SLN NR 15 NPA 25 NPE 27 GRP 1 BEZ 2 XFLG PLA   $ edge 2
[...]
```

```
// structural areas

// plate 1
SAR NO 1 GRP 1 MNO 160 NRA 7 QREF CENT DRX 0.00000 DRY -0.63453 DRZ -0.77290 T 0.16[m]
MCTL REGM NX -0.43557 NY -0.69573 NZ 0.57117
SARB TYPE OUT NL 1,2,3,4,5,6,7,8,9,10,11
SARB TYPE OUT NL 12,13,14,15,16,17,18,19,20,21
SARB TYPE OUT NL 22,23,24,25,26,27,28,29,30,31
SARB TYPE OUT NL 32,33,34,35,36,37,38,39,40,41
SARB TYPE OUT NL 42,43,44,45,46,47,48
[...]

END  $ end mesh definition

+prog sofiload urs:3  $ load definitions
HEAD
LC NO 1 DLZ 0.0 TITL 'G'
QUAD FROM GRP TO 1 TYPE pg p 1
QUAD FROM GRP TO 2 TYPE pg p 1
[...]

LC NO 2 DLZ 0.0 TITL 'G2'
QUAD FROM GRP TO 1 TYPE pzz p -0.11
QUAD FROM GRP TO 2 TYPE pzz p -0.11
[...]

LC NO 3 DLZ 0.0 TITL 'S'
QUAD FROM GRP TO 1 TYPE pzp p -0.68
QUAD FROM GRP TO 2 TYPE pzp p -0.68
[...]
END

+prog ASE urs:4
HEAD
CTRL SOLV 4
CTRL CORE 8
CTRL ITER 3 V2 1
SYST PROB LINE TOL 0.01 ITER 400
LC 100 DLZ 1.0 TITL loads $ self load
LCC 1 FACT 1.0
LCC 2 FACT 1.0
LCC 3 FACT 1.0
END
```

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Curriculum Vitae

Abel Groenewolt is an architect and educator with a fascination for geometry, programming and digital design methods. After having received his MSc degree at Eindhoven University of Technology, he worked at K2S Architects and at Sarc Architects in Helsinki as well as in his own practice, completing projects in Finland and the Netherlands. He has employed computational methods in various design projects and developed multiple custom design tools. Through post-graduate studies at ETH Zurich, he further explored the potential of programming within the context of architecture.

Before joining the Institute for Computational Design and Construction as a research associate in 2015, Abel worked at the chair of Architecture and Building Systems at ETH Zurich, developing and employing computational design tools to analyze and optimize various energy-related building systems. He also worked as a plugin developer for Design to Production.

At the ICD, his research focused on the application of industrial robots in timber construction, as well as on the development of digitally assisted design processes for timber plate shells.

Since 2018, Abel is based in Brussels, where at the time of writing he combines a role as architect and computational designer at Ney+Partners with a position as visiting professor at the architecture faculty of KU Leuven.