INTEGRATED DESIGN METHODS FOR THE SIMULATION OF FIBRE-BASED STRUCTURES

ABSTRACT

The production of structural components based on fibre-reinforced polymers (FRP) for the building industry is still characterised by a classic downstream development process from design through engineering and down to fabrication. In the aerospace and automotive industry, the current technical developments in simulation and manufacturing processes have reached a highly advanced status. Nevertheless, these manufacturing and analysis processes are in most cases non-transferable or unsuitable for architectural and structural purposes. The goal of the research presented in this paper is to take advantage of the benefits of FRPs within the architectural domain – focusing on material efficiency, durability and light-weight construction - and to find solutions for the problem of transferability into the building scale. For the construction of a Pavilion built on the campus of the University of Stuttgart in 2012 [Fig. 1], process-specific tools with a high degree of accuracy embedded from the start were developed for the material analysis, optimisation and fabrication steps. In contrast to product prototyping, which forms the basis of industrial mass production, prototype here refers to the establishment of processes within the context of a post-industrial, customised fabrication paradigm.

Figure 1: ICD/ITKE Research Pavilion 2012

INTRODUCTION

Current applications of fibre composites in architecture

Polymers and fibre composites have been a fervid topic of discussion in the building industry since the early '50s, rapidly followed by a hiatus spanning almost 40 years due to economic and cultural reasons. During this period of relative silence, the composites scene has been primarily dominated by the aerospace and manufacturing industry, mainly triggered by the inherent advantages in weight reduction that such materials offer. The abundant resources invested since then have led to the development of refined products and extremely sophisticated modelling and simulation techniques that perfectly meet the requirements of engineers and manufacturers working in the aerospace field. After many years, polymers and composites are currently experiencing a second rise in popularity in the building industry, largely due to the ever pressing request for freeform surfaces and the pursuit of shape freedom on behalf of contemporary architects. In spite of this growing trend, the full potential of fibre-based materials has been tapped only in the rarest cases. The lack of proper knowledge of the material's properties, along with the absence of apt simulation techniques and building codes is still hindering the successful implementation of composites in architecture.

Current integrated CAE and CAD simulation techniques

A range of different integrated design tools and workflow methodologies have been developed in recent years. One common procedure is certainly the coupling of parametric geometry models and structural analysis. In the first instance it offers the designer the opportunity to evaluate the structural behaviour and performance at an early design stage (van de Weerd et al 2012). Subsequently however, more precise engineering models and detailed analysis are needed to draw a statement about the ultimate limit state and the serviceability of the structure (Fallbusch et al 2012). Contrary to this established procedure the authors pursue a different aim, namely the development of process-specific tools and solutions with a high degree of accuracy right from the start. For the successful simulation of strongly anisotropic materials as fibre reinforced polymers (FRP), a precise mechanical modelling is required. The simulation of the mechanical behaviour of fibre reinforced polymers in the building industry still represents a complete novelty, and in most cases its complexity is strongly reduced by adopting oversimplified models. This is due to the limited knowledge of the material's behaviour on behalf of engineers, but also to the lack of proper simulation tools. The accurate modelling of fibre structures, combined with the modelling of complex free-form surfaces, plays an important role in other fields as the automotive and aerospace industry and demands for specifically developed simulation methods depending on the problem. In addition to proper material simulation, a dedicated fabrication process has to be used for components or structures. Depending on the complexity of the production method, these processes can only be simulated through Finite Elements. This is already the norm in mechanical and building engineering, where simulation tools are required to assess and better evaluate the corresponding processes. In the latest developments in robotic fabrication in architecture the possibilities of process simulation by means of Finite Elements have been scarcely used.

In the current paper the authors will expose in detail the techniques and simulation methodologies elaborated for a recently built, entirely fibre based project, which also take into account peculiar aspects of its development and implementation. A unique piece of its kind, being the world's first architecture built entirely by a robotic carbon and glass fibre winding technique, the project required the development of custom tools for structural analysis and simulation of the fabrication process. Two aspects will be specifically covered in the paper, one being the simulation of the fabrication process that required extensive research to take into account the physical response of the fibre bundles, and the other the analysis of the mechanical behaviour of the fibre reinforced structure.

MATERIALITY

Characteristics of fibre reinforced polymers (FRP)

In contrast to metal, glass, timber and other conventional building materials, many fibre-based materials are suitable for moulding and shaping methods which enable the relatively simple production of components with complex shapes. This offers great design freedom but at the same time also risks of improper application, as in architecture an appropriate building culture with fibre-based materials is still not widely spread. Traditionally, structures are assembled from a limited number of materials with defined properties. When building with polymers, one of the major challenges is to choose the right solution from the vast range of raw materials and semi-finished products. The selection and control of the material components represent new and demanding responsibilities for architects and engineers (Knippers et al. 2010). If, for example, we compare glass and carbon fibres, then we discover that the tensile strengths of the fibres alone are roughly identical. However, the elastic modulus of carbon fibres is much higher compared to glass fibres. Therefore, owing to the limited extensibility of the polymer matrix, the strength of carbon fibre-reinforced polymers is higher than that of glass fibre-reinforced polymers. If the stress-strain curves of these two materials are compared to steel or aluminium the advantages become clear [Fig. 2]. The strength of the composite component depends on the interaction between fibres and polymer matrix. A fracture in a laminate is generally caused by cracks in the matrix, which in turn are caused by the maximum admissible strain in the polymer being exceeded. Using a polymer with a high maximum permissible strain therefore increases the strength of the entire composite component.

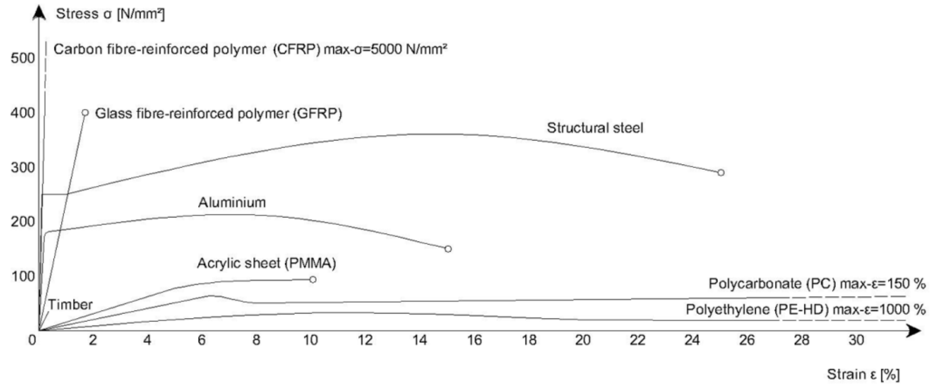

Figure 2: Stress-Strain Curves of different materials [Knippers et al. 2010]

Classical winding techniques are typically used in the manufacturing of pipes, vessels, tanks, and other rotationally symmetric hollow components. The advantages of this method are the high level of mechanisation and the exact, high density fibre arrangement. In composite wrapping, pretensioned rovings are wound around a rotating mandrel. The fibre reinforcement of the laminate is controlled by the rotary speed of the mandrel and the speed of winding fibres. One-off mandrels made from a soluble substance or, for larger series, reusable mandrels made from steel or aluminium are used depending on the batch size and the geometry of the component. To ease demoulding, mandrels are often slightly conical in shape, or made from folding segments.

Advanced fabrication method

The fabrication of complex geometries produced in FRP typically requires moulds or custom formwork. The material and time intensive fabrication process of these moulds is usually offset by high production runs. Consequently, an application of FRPs in architecture poses the inherent problem that it either requires moulds on an architectural scale or many unique moulds for a potentially single use (Fischer 2012). Minimising the mould requirement was therefore another central concern throughout the project and at the same time became one of its defining features. The requirement was met by prefabricating a linear steel frame as temporary support for the glass- and carbon fibres during fabrication [Fig. 3]. The fibres are spanning between defined anchor points on the frame, which control fibre position and allow for a continuously changing fibre orientation. In the robotic filament winding process, the industrial robot continuously lays resin-saturated glass and carbon fibres, thereby gradually building up a mould as previous layers harden and subsequent layers are placed. This specific setup favours double curved anticlastic surface geometries of negative Gaussian curvature as it naturally produces hyperbolic paraboloid surfaces consisting of straight lines (Schwinn et al 2012).

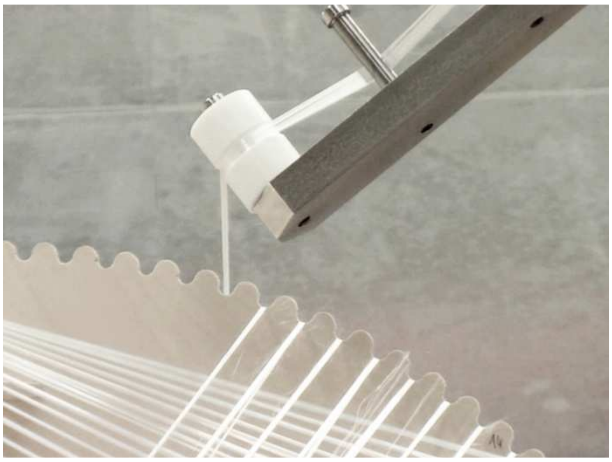

Figure 3: Filament winding process of the ICD/ITKE RP12

SIMULATION OF FABRICATION PROCESS

Because of the innovative manufacturing technique adopted for the production phase, it was necessary to simulate the entire fabrication process to take into account possible faults and misleading assumptions. As the resin soaked fibres do not possess any bending resistance whilst the epoxy is still in the process of drying out, successive layers of fibres wrapped on the previous ones have the effect of further deforming the system.

The end result is a compromise between the physical behaviour of the different fibre layers which simultaneously react to the external loading brought into the system by the pre-stressing of successively wrapped fibres and the geometrical constraints defined by the architectural project. The process of form-finding the final configuration of the system implied the simulation of the entire wrapping process to find the contact points [Fig. 4-A] between the already wrapped layers and the currently spun fibre in the first place, in order to update the global system with the new external loading and thus finding the newly achieved form. The deformations involved in the process, being of consistent magnitude (meaning that the deformation components of higher order may not be neglected), along with the contact element problem between the fibres, result in a highly complex problem that needs to be solved through advanced computational techniques to handle all the non-linear aspects involved in the calculation.

The methodology adopted for the calculation of the resulting geometry and the associated prestress map occurred in a two-step looping procedure. In the first step the geometric intersection between the tensioned fibres and the currently spun roving is resolved. This is achieved by finding the intersection points of the tensioned fibres with the plane defined by the two support points and the average point of the robotic arm’s spatial trace. The intersection points define the structural nodes of the next fibre which is then added to the global Finite Element model. In the second step the mechanical model is updated with the newly acquired information. The structural nodes are added to the associated fibres, defining the new set of contact points onto which the next forces will act upon. The modified cable elements are then coupled to the nodes of the new fibre added into the system, which in turn represents the fibre currently being tensioned onto the supporting structure. Having updated the mechanical model, the calculation process takes place. The latest laid fibre is assigned a pretensioning force which has the effect of deforming the system under the external load as the structural nodes are coupled together with the current geometric configuration. Due to the missing bending stiffness of the structure during the wrapping process, the considerable displacements of the fibres have to be taken into account by resorting to a non-linear calculation. In order to take into account possible sliding effects due to lateral forces which occur if the fibre does not lie on the geodesic line of the surface, the coupling between the structural nodes is modelled through spring elements with infinite axial stiffness and a threshold lateral stiffness which derives from the friction value between soaked fibres previously tested in the laboratory. The process is then looped by reimporting the newly found geometric configuration and the current stress distribution [Fig. 4-B] in the CAD program (Rhino3d), finding the new contact points and finally performing the mechanical calculation. The calculation step was performed in SOFiSTiK using the adequate formfinding strategy for membrane and cable nets, resulting in a straightforward and efficient implementation.

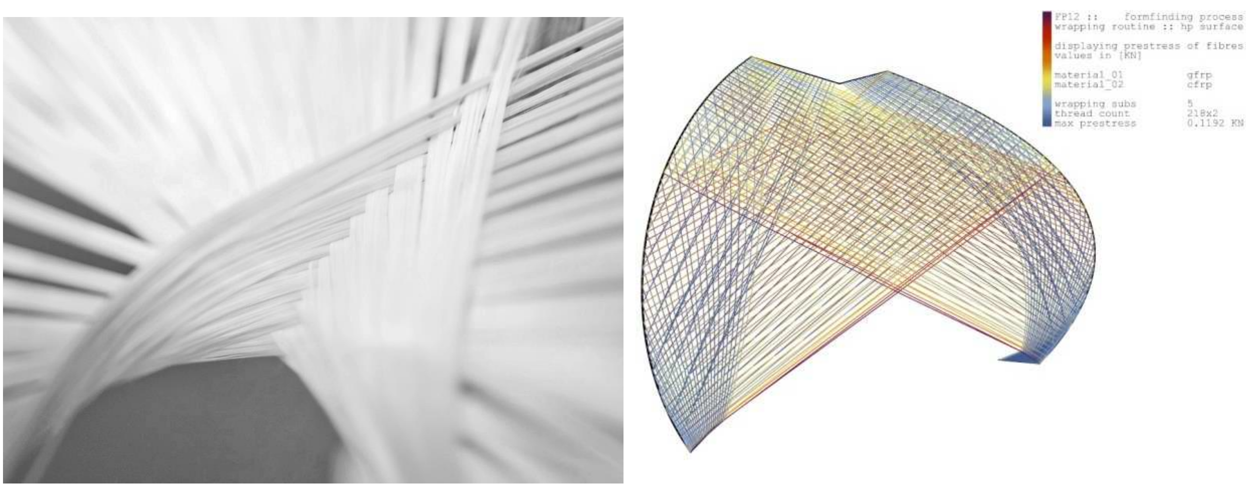

Figure 4: Close up of roving contact prototype [A]; Filament winding process simulation of the ICD/ITKE RP12 [B]

SIMULATION METHOD OF THE RECIPROCITY OF FIBRE MATERIALITY AND GEOMETRY

General

Fibre based composites are naturally anisotropic, meaning that the mechanical properties of the compound greatly vary according to the direction of loading, unlike steel for instance which is a totally isotropic material. This is obviously true as the fibres confer an inherent directionality to the material itself. This aspect invalidates classical material theory and the constitutive laws as known from elementary mechanics, posing non-trivial questions to the analyst dealing with the subject. On the other hand, by controlling key parameters it is possible to exploit such qualities in order to achieve a more efficient material configuration from a structural and mechanical point of view. Computationally this is achieved by assigning different stiffness values to the quads that make up the global Finite Element model. The pre-processing operation for the construction of the model is performed beforehand by analysing the directions of the fibres and their layering incidence on the constructed surface. Said values are subsequently transferred to the mechanical model by converting them to stiffness and direction parameters that characterise a quad or a cluster of quads. In such way it is possible to assess a quantitatively precise and realistic value of the local mechanical features of the fibre lay-up, which is then used to construct the model of the whole surface which undergoes further structural and mechanical analysis.

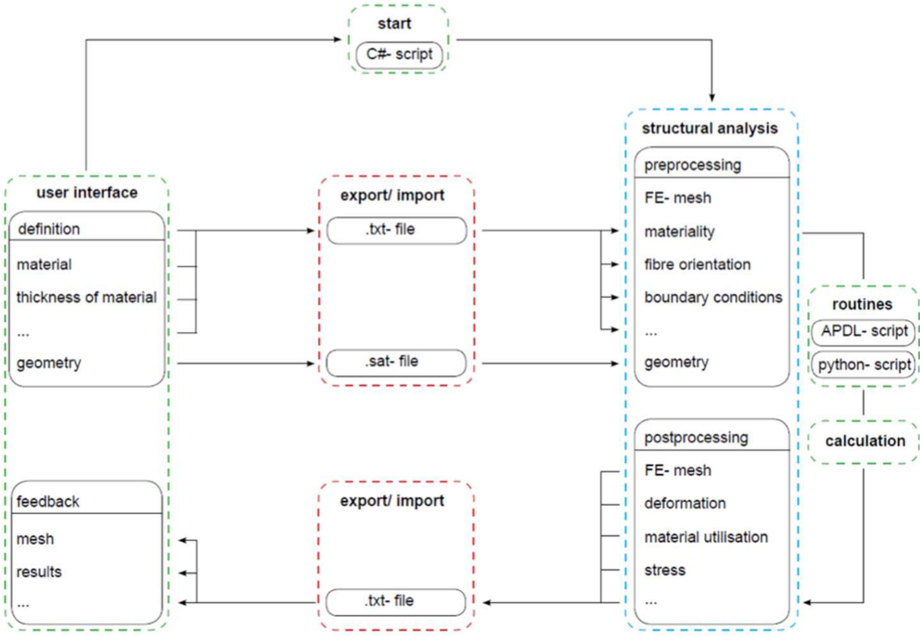

Figure 5: Coupling interface between Rhino/Grasshopper and ANSYS

Coupling interface

As the most stable format for importing geometries from Rhino3d into ANSYS the *.sat* file format was identified. Especially in the definition and numbering of nodes and structural areas, the coherence is strong and it allows for a rational creation of lists. In addition, areas previously processed in Rhino through Boolean operations are converted in such a way that the geometry is generated properly. This is for instance not the case for other formats as the *.iges* file format. Key parameters such as stiffness, strength properties, thickness, fibre lay-up and also fibre orientation are first defined in Grasshopper and then saved and stored in several *.txt* files [Fig. 5]. ANSYS Workbench (WB) is then started in batch mode through a custom written script. In WB it is possible to control and couple different simulation types, ranging from Structural to CFD, through the implemented Python programming language. However, the programming of the structural mechanic part is based on the ANSYS Parametric Design Language (APDL). This internal scripting language can be used to automate common tasks or even to build a fully parametric model. APDL encompasses a wide range of other features, such as if-then-else constructs, do-loops, and vector and matrix operations. Based on APDL, a complete parametric model was developed which was then complemented by the individual variables previously defined in the parametric model [Fig. 5]. For each Finite Element of the model, several loops are run which associate the multi-layered composite with the corresponding number of layers, material and thickness, and for each layer the fibre orientation is defined by a local coordinate system. The fibre orientation is mainly determined by the winding logic. Subsequently, the total anisotropic stiffness for each element is calculated adopting the Classical Laminate Theory and thereby abstracted. The results of the Finite Element analysis are finally exported to several *.txt* files, along with the complete FE mesh and the associated deformations, strains, etc. of individual nodes. The raw data is then processed within Grasshopper, the FE geometry reconstructed and the mechanical results displayed in the form of a colour graded mesh.

Implementation of FRP in the FE-Modeling

Only in rare cases fibre composites are exclusively loaded uniaxially, meaning that it could be possible to operate only on a single fibre direction. Due to the predominance of multi-axial stress cases, the designer must take into account different fibre orientations within one laminate. For the calculation it is not necessary to determine the material properties of the multi-layered composite, as those of the individual layers are sufficient. This allows to reduce the cases of material testing to a minimum and also to calculate the laminate properties of any layer combination. Following the laws of elasticity, the properties of the entire laminate can be determined by taking into account the stiffness of each individual layers:

$$\{\hat{n}\} = \{\hat{\sigma}\} \cdot t = \sum_{k=1}^{n} \{n\}_k = \sum_{k=1}^{n} \{\sigma\}_k \cdot t_k \qquad (1)$$

Where $\hat{n}$ = global axial force, $\hat{\sigma}$ = global axial stress, t = thickness, n = axial force of a single layer and σ = axial stress of a single layer. If $\{\sigma\}_k$ is replaced by $[\overline{E}]_k \cdot \{\varepsilon\}_k$ and by the geometric relationship:

$$\varepsilon_{xk} = \hat{\varepsilon}_{xk}$$
$$\varepsilon_{yk} = \hat{\varepsilon}_{yk}$$
$$\varepsilon_{xyk} = \hat{\varepsilon}_{xyk}$$

The following law of elasticity applies:

$$\begin{Bmatrix} \hat{n}_x \\ \hat{n}_y \\ \hat{n}_{xy} \end{Bmatrix} = \underbrace{\begin{matrix} \sum_{k=1}^{n} \overline{E}_{11k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{12k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{16k} \cdot t_k \\ \sum_{k=1}^{n} \overline{E}_{12k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{22k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{26k} \cdot t_k \\ \sum_{k=1}^{n} \overline{E}_{16k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{26k} \cdot t_k & \sum_{k=1}^{n} \overline{E}_{66k} \cdot t_k \end{matrix}}_{Stiffnessmatrix[A]} \cdot \begin{Bmatrix} \hat{\varepsilon}_x \\ \hat{\varepsilon}_y \\ \hat{\varepsilon}_{xy} \end{Bmatrix} \qquad (2)$$

This mechanical model is commonly referred as Classical Laminate Theory (CLT) [Schürmann 2007]. Conversely, having defined the properties of the multi-layered composite it is then possible in a second step to calculate the strain and stress of each single layer. The multi-layer composite is modelled with a shell element. The contribution of each layer to the overall stiffness and hence the resulting load bearing quota in respect to the total load, is a consequence of the rigidity and thickness of the single layers and must therefore always be taken into account [Fig. 6]. Mechanically there is a parallel connection between the stiffness of the single layers. Since the stiffness depends on the direction, the layers' stiffness can only be summed linearly if all the values refer to the same coordinate system. Therefore, the stiffness of the single layers must be conveniently oriented with a coordinate transformation. However, in the modelling of the Finite Elements the associated coordinate systems of the single layers must be first placed in the correct position.

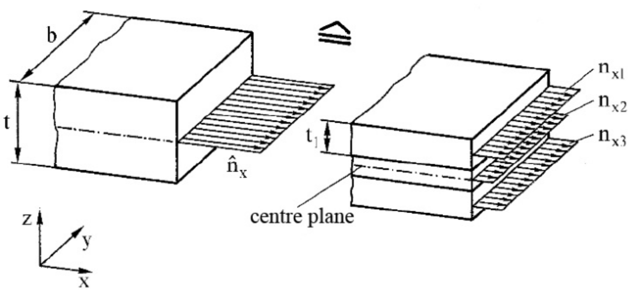

Figure 6: Force equivalence between internal force flow and sum of layer internal force

For fibre-based materials different failure theories are known, which also differ in their results. For the developed tools, the Tsai-Wu failure criterion and the Puck criterion have been applied [Puck 1996]. The latter will be presented in detail because of its great importance in the prediction of FRP behaviour. The fracture analysis of multi-layered composites always takes place at the level of the single layer. The calculated strains and stresses of the internal forces are calculated by the CLT on the single layer. Two basic types of fracture can be identified, the Fibre Failure Criteria (FFC) and the Inter-Fibre Failure Criteria (IFFC) [Schürmann 2007]. The FFC considers only the fibre stress in the longitudinal direction, presenting a formulation which is driven by a relatively simple criterion and is characterised by a planar fracture surface [Fig. 7-A]. In contrast, the fracture surface of the matrix is considerably more complex. Due to the influence of a spatial stress state derived from presence of both normal and shear stress, three failure modes are possible which are associated to the external loading [Fig. 7-B].

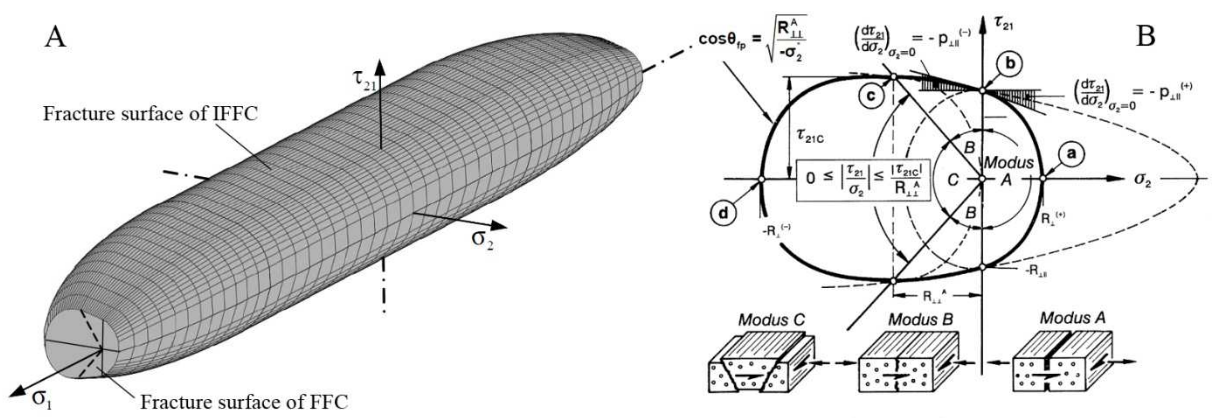

Figure 7: Fracture surface [A]; IFFC according to Puck for planar state of layer stress [B] (Puck 1996, p. 425, 433)

Because of the complex failure mechanism of FFC and IFFC, an accurate modelling of the fibre orientation of the single layers is extremely relevant together with the influence on the stiffness distribution. It should be noted that the failure of a laminate is not a single, isolated event, but rather an evolutionary process. The loading of a laminate can therefore be highly increased beyond the cracking start in one or more layers. This is primarily due the fact that a statically indeterminate system is prevailing at material level. By redistributing the load to adjacent layers, a load rise is still possible and it allows the engineer to increase the material utilisation. This behaviour was taken into account for the optimisation of the ICD/ITKE Research Pavilion 2012 to fully exploit the resistance of the material. The optimisation process in order to achieve a minimal use of material was, in addition to typical structural aspects, especially focused on the reduction of the fabrication time of the Pavilion itself.

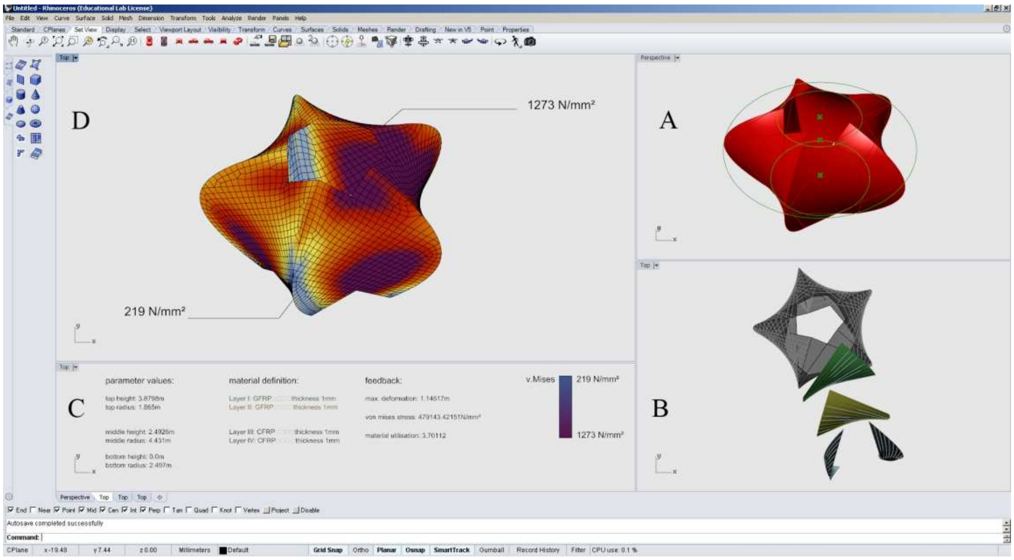

Figure 8: User interface in Rhino/Grasshopper, early design stage ICD/ITKE RP12

By the defined parametric geometry in Fig.8-A and the assignments of fibre arrangement and number of single layers to a section of the surface, the reciprocity between geometry and fibre orientation in the single layers is considered. This entails that by changing the geometrical parameters, the fibre orientation of the individual layers are also modified due to the changes in the winding logic [Fig.8-B]. After assigning the material properties and the thickness of the single layers, the boundary conditions and the applied loads in Grasshopper, a coordinate system is generated for each single layer of each element. The stiffness of each element is then calculated according to the CLT. Following the FE calculation, the internal forces of the element are recalculated, and the material utilisation is updated according to Puck’s criterion. In Fig.8-C and Fig.8-D, the deformation, material utilisation or stresses can be displayed depending on the local settings. In this way the user only needs to interact with the CAD interface, minimising the complexity of the analysis environment. The early integration of accurate structural analysis within the design process prevents the appearance of ill variations with a high degree of accuracy. The simple interface presents to engineers and architects the opportunity to design and analyse complex structures without possessing a deep knowledge of modelling and failure mechanism of FRP. By defining the parameter space of the geometry model, the best combination of shape and fibre arrangement could be found through an optimisation routine [Fig. 9].

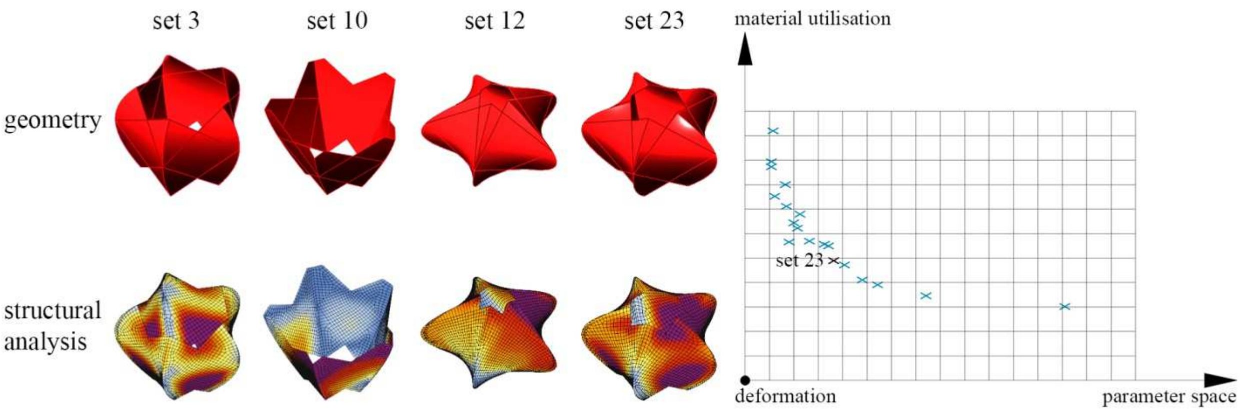

Figure 9: optimisation of shape and fibre arrangement

CONCLUSIONS

The possibility of retrieving in such detail vital parameters for the assessment of the structural response, has offered the engineers and architects involved in the project powerful means to actively design the very same component by drawing fundamental decisions on the thickness of the lay-up and the running direction of the fibres since the very early design stage. This total integration of architectural aspects and mechanical feedback has enabled the planning and fabrication of highly customised components that completely meet the structural requirements of the project, allowing for a complete optimisation not only of the shape and geometry of the element itself but within the local material properties of the element too.

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