Chapter 6

CONCLUSIONS AND PERSPECTIVES

In order to achieve the aims of this paper, numerical analysis of four connection systems with various connection forms, taking into consideration size differeces between bolt and bolt-hole (bolt clearance) of 0.1 mm and 2.0 mm, was performed to investigate their structural behaviors: connection stiffness of axial force (F) and two bending stiffness (My and Mz), respectively. At the same time, buckling analysis of 25 m and 50 m three-way grid shells was performed to determine the influence of different connection stiffness on buckling load based on various connection systems, in particular the influence of different bolt clearances on the buckling load of global grid. The conclusions of these analyses are summarized as follows;

- Finite element analysis of four connection systems revealed that different shapes or forms of connection may determine the varying stiffness of connection systems. Generally speaking, the connection systems, which have two shear planes, showed higher stiffness than those with one shear plane.

- On the other hand, the connection systems which were connected with an unsymmetrical beam end with one shear plane was not influenced as much by different bolt clearances as those using two shear planes because the structural mechanism is based on the shape of the joint assembly.

- Low connection stiffness in conjuction with initial geometrical imperfection leads membrane stress to change easily to bending stress, so that the critical point of grid shell occurred at a low failure load factor.

- The influence of different bolt clearances of connection systems in a grid shell depends mainly on the connection stiffness and rise-span ratio. The overall buckling load of both perfect and imperfect high-rise grid shell was shown by this research to be much more greatly influenced by different bolt clearances than in the case of low-rise. In the sense of practical design of grid shells or free-form grid spatial structures, it can be predicted that imperfectly-shaped high-rise grid shells can be sensitive with regards to the buckling load, displaying a large deviation in bending stiffness due to bolt clearances.

The main goals of this research have therefore been accomplished. Due to the results of this research, the structural influences of various connection systems, in particular different sizes of bolt clearance with various rise-span ratios on the buckling load can be predicted for the practical analysis and use in the design of the grid shells and the free-form grid spatial structures as well.

The above mentioned results, however, are not totally sufficient to define member buckling behavior in the whole failure mode. The behavior of all member elements should be further integrated and calculated and for that, more degrees of freedom should be converted into the element. Also, in order to consider more detailed parameters, it is required that nonlinear torsion curves based on different bolt clearances be investigated.

In chapter 4, the screw thread was assumed to be bolt clearance 0 mm. This is an alternative simulation. Even though more concrete geometries with a nonlinear contact element can require a long calculation time and a hard convergence procedure, the effort with detailed simulation´s geometry will be just as valuable for predicting exact values as a physical experiment.

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LIST OF SYMBOLS

Chapter 2

D	Diameter of steel ball
di	Diameter of bolt
ξ	Ratio between the inserted length of the bolt into the steel ball and the diameter of the bolt
η	Ratio between the diameter of the circumscribed circle of the sleeve and the diameter of the bolt
θ	The smaller intersecting angle between two bolts
sin	Sine
cot	Cotangent

Chapter 3

BP	Bilinear plastic behavior
E	Elastic modulus of steel
E_0	Elastic modulus of stainless steel
EPP	Elastic-perfectly plastic behavior
F	Total applied load
f	A factor of times the elastic modulus of the material
k	Spring stiffness
n	Coefficient of material strain hardening
P	Applied load
x-,y- and z-	Cartesian coordinate axis
ε	Direct strain of material
ε_{min}	Minimal principal strain under pure axial tension and combined tension and bending on the bolt
ε_{max}	Maximal strain under pure axial tension and under combined tension and bending on the bolt
$\varepsilon_{u,b}$	Ultimate strain on the bolt
$\varepsilon_{11,ave}$	Maximal average principal strain on the bolt
ε_{11}	1st principal strain
$\varepsilon_{y,av}$	Maximum average y-direction principal stran
δ_i	Amount of the interpenetration
δ	Global displacement at applied load level
μ	Coefficient of friction
σ	Direct stress of material
$\sigma_{0.2}$	0.2% proof stress (elastic yield)

Chapter 4

b	Depth of cross section
ε	Direct strain of material
ε_{11}	1st principal strain
h	Hight of cross section
$F_{a,R,k}$	Characteristic shear force
F_b	Bolt load
F_{be}	Applied load for bending moment
F_u	Ultimate load
L	Distance of bending test
M	Bending moment
ΔV	Deviation between bolt and bolt-hole (bolt clearance)
θ	Rotation of bending test
μ	Coefficient of friction
σ	Direct stress of material

Chapter 5

Asymm.	Asymmetrical load case
b	Depth of cross section
d	span of grid shell
f	rise of grid shell
f/d	rise span ratio
g	dead load
h	Hight of cross section
Imper.	Geometrical initial imperfection grid shell
L	Length of member
M_{yi}	Internal bending moment around y- axis from the elastic computation
M_{zi}	Internal bending moment around z- axis from the elastic computation
N_i	Internal axial force from elastic computation
$M_{y,pl,d}$	Limit state yield bending moment around y- axis at design load level
$M_{z,pl,d}$	Limit state yield bending moment around z- axis at design load level
$N_{pl,d}$	Limit state yield axial force at design load level
p	failure load factor
s	snow load
Vz	Displacement in the global z-direction
γ	self weight of steel
γ_g	self weight of glass
ΔV	Deviation between bolt and bolt-hole (bolt clearance)

ABSTRACT

Introduction

Free-form grid spatial structures and facades that follow the envelope surface of a complex-shaped skin, such as the DZ-Bank in Berlin (Frank O. Gehry), the British Museum in London (Norman Foster), the My Zeil in Frankfurt (Massimiliano Fuksas), have become a very interesting issue in modern architecture. There are several important factors in such single layer lattice dome and complex-shaped spatial structures, for instance, optimal form finding and strong material strength and so forth, but the optimal design and analysis of connection are significant points in free-form spatial structures, because such extraordinary geometries and its continuously changing curvature can be defined by the angles of the connections' geometries, and the stiffness of connection can determine the stability of the whole free-form structure. Therefore, it is very important to recognize that the appropriate analysis and connection design have to be performed, in order to design the reasonable global single layer spatial structure and free-form spatial structures.

General procedures

For the FEA of four connection systems, bending stiffness (My and Mz) and axial force (F) tests were performed. These analyses include the modeling of the bolt assembly, the contact stiffness and the influence of bolt clearances, which were considered using two parameters, such that ΔV=0.1mm and 2.0mm. Due to a specific function of COMBIN39 in ANSYS, the moment-rotation behaviors and load-displacement curves could be transferred to nonlinear spring elements in global grid shells with 25 m and 50 m span that have three different rise-span ratios (0.1, 0.2 and 0.3), to realize the nonlinear characteristics of the connection systems.

Results

Connection system having two shear planes showed higher stiffness than those with one shear plane. On the other hand, node connectors with one shear plane were not as influenced by differing bolt-holes as those with two shear planes due to shape-of-joint behaviour. Secondly, the low connection stiffness with initial geometrical imperfection easily leads membrane stress to bending stress, so that the critical point of the grid shell occurred with low load failure factor. The influence of bolt clearance depends mainly on the node stiffness and rise-span ratio. The overall structural behavior of an imperfect high-rise grid shell can be very sensitive, displaying a large deviation of bending stiffness due to bolt clearances.

KURZFASSUNG

Einführung

Die attraktive Formensprache von Freiformflächen hat dazu geführt, dass sie in den letzten Jahren zunehmend für Gebäudehüllen eingesetzt werden. Dies ist unter anderem in Projekten wie der DZ-Bank in Berlin, dem Westfield Shopping-Center in London oder bei „My Zeil“ in Frankfurt am Main zu beobachten.
Vor diesem Hintergrund beschäftigt sich das vorliegende Forschungsvorhaben mit dem Stabilitätsverhalten von frei geformten Stab- und Gitterschalen und untersucht dabei insbesondere den Einfluss der Knotensteifigkeit auf die Gesamtsystemsteifigkeit. Bis dato sind insbesondere noch keine systematischen, detaillierten Berechnungen zur Knotenausbildung, die auf Effekte wie Scher-Lochleibung und Lochspiel in Bezug auf die Gesamtstabilität von Kuppeln bzw. Schalen Rücksicht nehmen, unternommen worden. Diese Lücke soll mit der Forschungsarbeit nun geschlossen werden.

Ablauf der Untersuchungen

Zunächst werden grundsätzliche Knotensysteme, die in Gitterschalen und frei geformten Flächen zur Anwendung kommen, beschrieben (Kapitel 2). In der Zeitspanne der Entwicklung von traditionellen räumlichen Gitterstrukturen bis hin zu den aktuellen Freiformflächen sind sehr unterschiedliche Knotensysteme geschaffen worden. Diese habe jeweils charakteristische geometrische bzw. strukturelle Eigenschaften, die vergleichend untersucht und dargestellt werden.

In Kapitel 3 werden die Ergebnisse von experimentellen Biegeversuchen an zwei Knotensystemen mit denen aus einer Finite-Elemente-Analyse (FEA) verglichen, um die Methodik der numerischen Simulation abzustimmen und zu verifizieren. In den numerischen Analysen werden dabei detaillierte Kontaktmechanismen eingesetzt, um das genaue Kontaktverhalten zwischen Stab und Knoten bzw. Schrauben und Löchern in den Knoten zu simulieren.

Basierend auf den validierten Ergebnissen aus dem vorhergehenden Kapitel, können nun in Kapitel 4 mittels FEA zwei typische Biege- (My, Mz) und eine Zugbeanspruchung (F axial) zur Analyse von Knotensystemen simuliert werden. Hierzu werden drei Laschenknoten und ein Stirnflächenknoten, die verschiedene, aussagekräftige geometrische Charakteristika zeigen, herangezogen. Die Berechnungen erfolgen insbesondere für zwei unterschiedliche Lochspiele (ΔV) von 0.1 und 2.0 mm als geometrische Parameter, so dass sich verschiedene nichtlineare Knotensteifigkeiten abhängig vom Lochspiel und Knotentyp im Vergleich ergeben.

Kapitel 5 untersucht den Einfluss der Knotensteifigkeit auf das Stabilitätsverhalten von Gitterschalen bzw. Stabschalen. In der Literatur existiert bereits eine Reihe von numerischen Analysen, die Knicklasten für verschiedene Geometrien, d.h. für verschiedene Verhältnisse von Stich zu Spannweiten bei Kuppeln und Tonnenschalen, angeben und dabei den Einfluss von geometrischen Imperfektionen berücksichtigen. Was derzeit allerdings gänzlich fehlt, ist eine detaillierte Betrachtung der Knotenausbildung und ihrer Einflüsse auf die Gesamtsstabilität von Kuppeln bzw. Schalen. Dabei werden durch lokale Schwächungen im Knoten, wie zum Beispiel durch das Lochspiel der Schraubenverbindungen, die Traglasten erheblich herabgesetzt.
Um dies systematisch zu erfassen, werden zwei Kuppeln der Spannweiten 25m und 50m mit drei unterschiedlichen Verhältnissen von Stich zu Spannweite (jeweils f/l = 0.1, 0.2 und 0.3) untersucht. Durch die Sonderfunktion COMBIN39 (nichtlineare Feder) des FE-Programmes ANSYS (Version 11), können dabei vielfältige nichtlineare Knotensteifigkeiten, die jeweils unterschiedliche Lochspielversätze von 0.1 und 2.0 mm aufweisen, für jeden Knoten in der globalen Kuppel simuliert werden.

Ergebnisse und Ausblick

Die numerischen Analysen zeigen, dass verschiedene Knotenausbildungen oder Verbindungsarten in den Knoten unterschiedliche Steifigkeiten festlegen können.
Generell zeigen Knotensysteme, die zwei Scherflächen haben, eine höhere Steifigkeit als solche mit nur einer Scherfläche.
Allerdings ist der Einfluss unterschiedlichen Lochspiels auf das mechanisch-strukturelle Verhalten bei Knotensystemen mit einer Scherfläche (unsymmetrische Verbindungsform) geringer als bei einer Verbindung mit zwei Scherflächen (symmetrisch).

Hinsichtlich des Stabilitätsverhaltens einer Schale oder Kuppel erzeugen geringe Knotensteifigkeiten bei geometrischer Imperfektion sehr leicht einen erhöhten Biegespannungsanteil zusätzlich zu den Membranspannungen, so dass die Traglast wesentlich abnimmt.
Der Einfluss von unterschiedlichen Lochspielen in den Knoten kann bei globalen Strukturen hauptsächlich durch die Knotensteifigkeit im Zusammenhang mit dem Verhältnis von Stich zu Spannweite charakterisiert werden. Generell werden die Traglasten sowohl der perfekten als auch der imperfekten Modelle mit einem hohen Verhältnis von Stich zu Spannweite stärker von der Knotensteifigkeit beeinflusst als solche mit einer geringeren Stich-Spannweiten-Ratio.
Im Hinblick auf den praktischen Entwurf von Stabschalen oder frei geformten Gitterschalen muss daher berücksichtigt werden, dass die möglichen Traglasten bei einem hohen Verhältnis von Stich zu Spannweite durch die erhebliche Abweichung der Biegesteifigkeit infolge großen Lochspiels in den Schraubenverbindungen und durch die auch davon beeinflusste geometrische Imperfektion wesentlich abnehmen.

CURRICULUM VITAE

Name	Kyung Ju Hwang
Date and place of birth	29 October 1975, Daegu (Republic of Korea)
Nationality	Korean
School	1991-1994 Cheong-Gu High School
University	1994-2000 Architecture Study at Kyung-Il University (Republic of Korea)
	2001-2003 Kyungpook National University for Master of Engineering (Republic of Korea)
	2003-2009 Institute of Building Structures and Structural Design (ITKE), University of Stuttgart, Germany Dr.-Ing. (Scholarship of National Research Foundation of Korea)
Occupation	2006-2007 Teuffel Engineering Consultant, Stuttgart (Germany) Structural Engineer