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Investigation and Numerical Analysis of Node Connectors in Free-Form Spatial Structures

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Abstract

The recent completions of free-form spatial structures provide us a very attractive form. To realize such an extraordinary shape, it is absolutely necessary that the connector systems have to be investigated the characteristics of the systems and analyzed with a practicable method. In this context, this research consists of not only literature research but also numerical analysis with selected connector systems, which was adopted in real free-form spatial structures. For numerical analysis, especially, finite element analysis (FEA) is performed with a various test parameter using a commercial program ANSYS. Consequently, the general characteristics of node connectors the moment-rotation-curves are presented by considering a large deformation effect as well as a multi-linear material properties.

Keywords : Free-Form Spatial Structures, Node connector, Bending test, Moment-Rotation-curves, Bolt clearance

1. Intorduction

The Complex-shaped or free-form spatial structures and fassades 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 New Fair in Milan (Massimiliano Fuksas) and Whitecity in London (Buchan Group International), has become a very interesting issue in modern architecture.[6),7)]

There are several important factors in such complex-shaped structures, for instance, optimal form finding and so on, but the optimal design and analysis of connector are a significant points in free-form spatial structures, because such extraordinary geometries and its continuously changing curvature can be defined by the angles of the connectors' geometries. Therefore, it is very important to recognize that the appropriate analysis and connector design have to be performed, in order to design the reasonable global free-form spatial structures. The node connectors that were adopted in realizing the completions of current free-form spatial structures have very various forms so that people cannot compare with the same way. In other words, because they have specific geometries of connector, the characteristics of each connector should be absolutely considered for not only appropriate analysis but also optimal design a global structures. Several experimental and analytical works have already been reported for spatial frame structures. However, it is not enough to be presented that the specific characteristics of various connector systems be investigated, because they were just applied on approximate values of connector, such as relative inertial moment, related to beam element and so on. Moreover, to estimate the ultimate strength of connector system, it is absolutely needed to obtain more advanced analysis that is performed by semi-rigid effect with

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pretension behaviors as well as a detailed geometry of connector.

In this research, the author will examine on analysis of node connectors for free-form spatial structures with more advanced approaches.

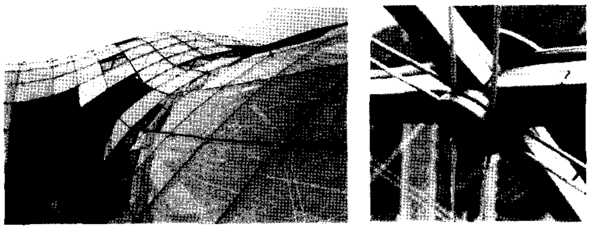
2. Characteristics of Connector in Free-Form Spatial Structures

Node connectors for free-form spatial structures, namely single layer surface structures can be divided in two fundamental groups, splice connectors and end-face connectors. From several sources, generally, most of the splice connectors require geometrical and structural optimization of the free-form structure, while the end-face connectors are geometrically more flexible and usually do not require a structural optimization.[7]

2.1 Splice Connectors

A common characteristic of such connecter system is that the connector surface between the center of connector and the end of elements are connected through splice plates in the longitudinal axis of the member by shear-stressed bolts or welding.

Shown in <Fig. 1> to 3 are, the splice connectors SBP-1, SBP-3 and HEFI-1, that the characteristic of this connector system can be easily observed. In 1989 Schlaich Bergermann & Partner, Stuttgart, Germany, designed the SBP-1 and used in Courtyard Skylight of Museum of Hamburg History. The node connector SBP1 consists of two flat plates that are connected by a single central bolt. End of element member is connected with the horizontal splice plates by two or more pre-tensioned bolts. The horizontal angle between the element members can be adjusted through the central bolt. Vertical angles can be accommodated

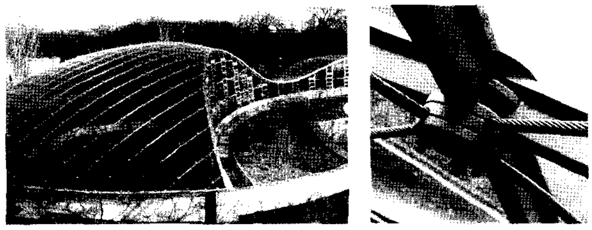


〈Fig. 1〉 Hamburg history museum and splice connector SBP-1

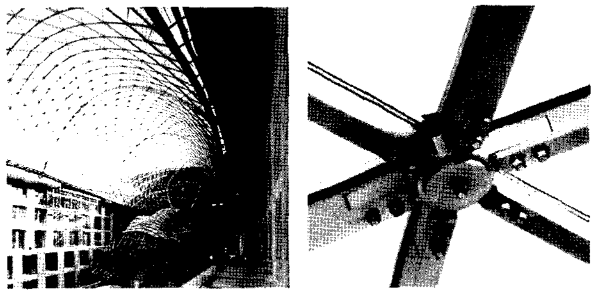
by folding the splices plates. Twist angles can be adjusted only the in very limited range of imperfections.[7]

<Fig. 2> shows one of the splice connector HEFI-1, which was introduced in 1999 by Helmut Fischer GmbH, Germany. The node connector consists of two flat splices with a circle groove and four holds. In order that the member element can be put into the grooves of the two disc, the end of member element have been chamfered with computer numerical machines (CNC). The discs and the member element are connected by bolts.

The splice connector HEFI-1 was adopted for the Hippopotami House of the zoological garden in Berlin and the courtyard roof of Friedrichstrasse No. 1991-1992 in Berlin. To design the inner court roof



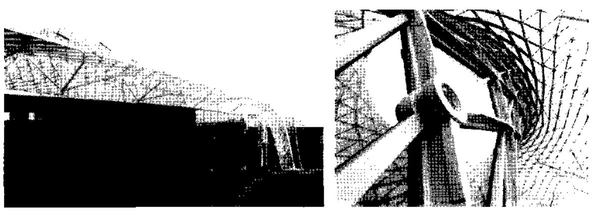
〈Fig. 2〉 Hippopotami House of the zoological garden in Berlin and splice connector HEFI-1



〈Fig. 3〉 DZ-Bank in Berlin and splice connector SBP-3 of the DZ-Bank in Berlin, Schlaich Bergermann & Partner developed the splice connector system SBP-3. The node connector consists of a solid plate with 6 horizontal finger splice plates. The end of member element was fabricated as a fork fittings, which can be connected to finger splice plates of the node by two or more bolts in double shear.[5,7]

2.2 End-Face Connector

The characteristics of the End-Face Connector, the second connector type of this research, is that the connect surface between the node and the end-face of the connected member is transverse to the longitudinal axis of the element member with pretension bolts or welding.[8] There are, of course, many end-face connecters, which are used in free form spatial structures, but the author would like to mention only one connector system MERO-4, because this connector system can represent almost the significant characteristics of another end-face connector system. <Fig. 4> shows an end-face connector, MERO-4. This node connector was designed and adopted by MERO in the roofs over the Central Axis and the Service Center of the New Fair in Milan, Italy. The node connector mainly consists of two dish nodes, one is at the top chord and the other is for the bottom chord at the end of each member. The node connector and element member are connected by two screw thread and bolts.(Fig. 4) <Table 1> summarizes the applicability and transferability of various node connectors for single layer free-form spatial structures.



〈Fig. 4〉 the New Fair in Milan and end-face connector MERO-4

3. Experimental Model

3.1 Comparing the real loading test and numerical analysis

Due to the data of real experiment, as the first step, the results of the loading tests of node

〈Table 1〉 Applicability of node connectors for free-form structures[7]

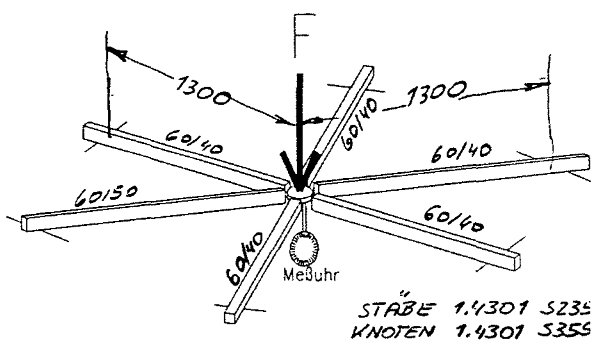
Node Connector		Transferability of Internal Force		Applicability	
Model	Connect-ion	Normal forces	Bending moments	Free-Form Structure Type	
SBP-1	Bolted splice	+	O	Geom. Optim.	Struc. Optim.
HEFI-1	Bolted splice	++	++	Geom. Optim.	Struc. Optim
SBP-3	Bolted splice	++	++	Geom. Non-Optim.	Struc. Non-Optim.
MERO-4	Bolted end-Face	++	++	Geom. Non-Optim.	Struc. Non-Optim.
	Welded end-Face	+++	+++	Struc. Non-Optim.	Struc. Non-Optim.
Notation		O Limited applicability + Adequate applicability ++ Good applicability +++ Excellent applicability		Geom. Optim. : Geometrically Optimized Surface Geom. Non-Optim. : Geometrically Non-Optimized Surface Struc. Optim. : Structurally Optimized Surfaces Sruct. Non-Optim. : Structurally Non-Optimized Surfaces	

〈Table 2〉 FE-parameters for in the numerical analysis

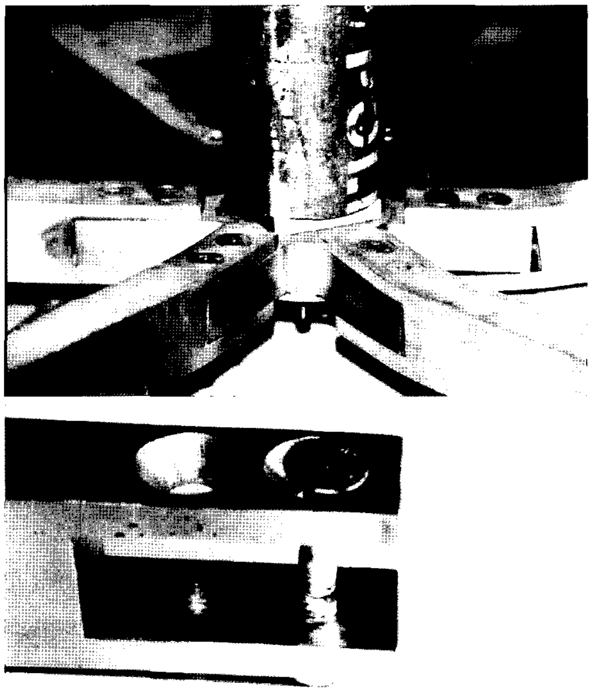
	Parameter
Material	E = 200000 [N/mm^2] ν = 0.3 p = 7.90 kg/dm^3
Mesh	1×1 [mm] (Bolt : M12×2) 2×2[mm](Beam element 40×60 [mm])
Elements Nr.	16292 (PLANE82) 596 (CONTA 175)
Friction coefficient	μ = 0.2
Bolt clearance	0.4 mm

connector SBP-3 is performed with numerical analysis, in order to compare the real loading test and numerical analysis. This connector was applied in glass free-form roof spatial structure for DZ-Bank in Berlin (by Frank O. Gehry). (Fig. 3)

In terms of material property, bolts and beam elements are composed of stainless steel. The element type used is the 8-node 2D plane stress element, which is defined by eight nodes having two degrees of freedom at each node: translations in the nodal x and y direction.(PLANE 82). To consider the pre-stressed bolt, 35 N/mm^2 was applied both on upper and below surface of bolt's head. Moreover, the contact between the two plates, the node connector and end of beam element, was modeled by the node-to-surface CONTAC175 ANSYS element, which may be used to present contact and slide between two



〈Fig. 5〉 Test set-up for load bearing capacity of SBP-3



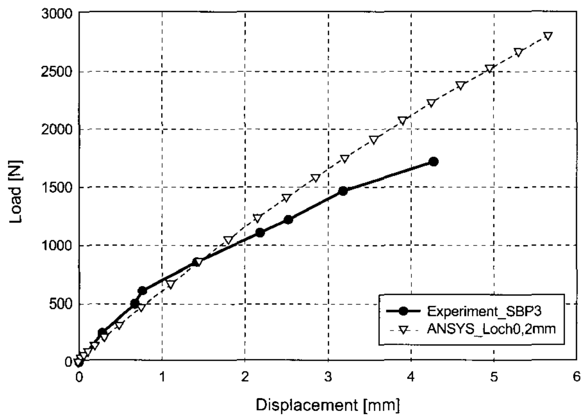
〈Fig. 6〉 Deformed configuration of the real specimen

surfaces (or between a node and surface, or between a line and a surface) in 2-D or 3-D. Friction coefficient(μ=0.2) was additnitionally considered in the contact elements.(Table 2)[9]

As only one-half of the front elevation of the experimental test is modeled, the center line of the node connector is an axis of symmetry. Node along this line axis cannot move in the horizontal plane, but may move vertically. Roller boundary conditions preventing horizontal moving are applied at the end of beam element. The beam member is supported on a roller support, a distance 1300 mm from

center line of node connector to the boundary condition. Two load step are performed to apply the loads, namely, the application of pre-stress and the application of the loads, and Fig .8 shows the test results. Even though the FE result matches not perfect with the experimental result, the numerical result provides quit a credible result to real one. In this FE result, it increases almost linear form, because the numerical test

⟨Fig. 7⟩ Von Mises Stress of FE model

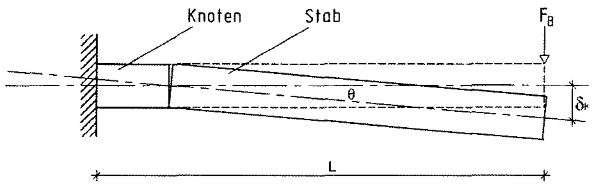


⟨Fig. 8⟩ Load and displacement curves: experimental and numerical result

was considered only elastic modulus of material. Moreover, the bolt clearance was applied with 0.4mm, but it is not sure with real test, because the author could not receive the exact bolt clearance value. Due to this tight bolt clearance 0.4mm, the load was continued to soar over the experimental result. However, the curve shows obviously the semi-rigid behaviour, and Fig. 6 and 7 show that the maximum stress of FE analysis almost consistent with the deformations of real specimens.

3.2 Bending Test

Through the chapter two the characteristics of four node connector systems have been researched, especially related to geometrical aspect. Based on the above research, three splice connecter types and one end-face connector were selected as an 2D experimental model with finite element analysis (FEA), in order to research the moment capacities of various connector system. Except for the bolt clearance 2.0 mm, he material properties and another conditions are almost same as the test in



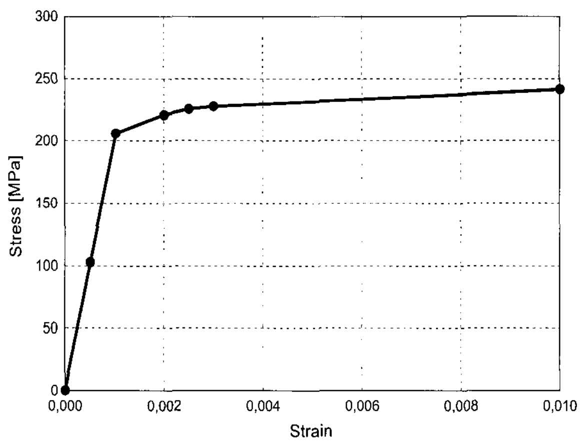
$\tan\theta = \delta k/L \approx \theta$ für $|\theta| \ll 1$

$M = F_B \cdot L$

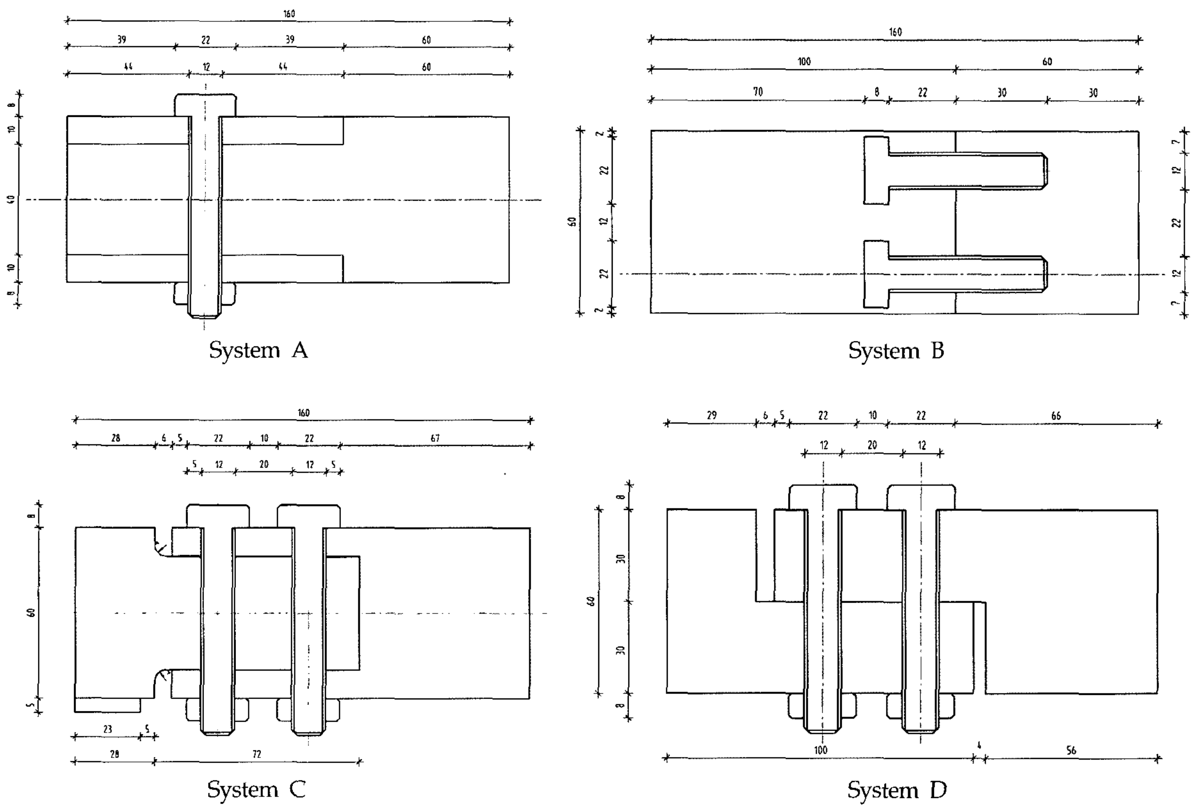
⟨Fig. 9⟩ Cantilever test set-up and definition for moment-rotation behaviour[10]

⟨Table 3⟩ FE parameters of bending test.

	Parameter
Material	E = 200000 [N/mm^2]
	ν = 0.3
	p = 7.90 kg/dm^3
Mesh	1×1 [mm] (Bolt)
	2×2 [mm] (Beam element)
Elements Nr.	9554 (PLANE82)
	596 (CONTA 175)
Friction coefficient	μ = 0.2
Bolt clearance	0.4 mm (System B-Thread bolt)
	2.0 mm (System A,C,D)



⟨Fig. 10⟩ Multi-linear stress-strain curve

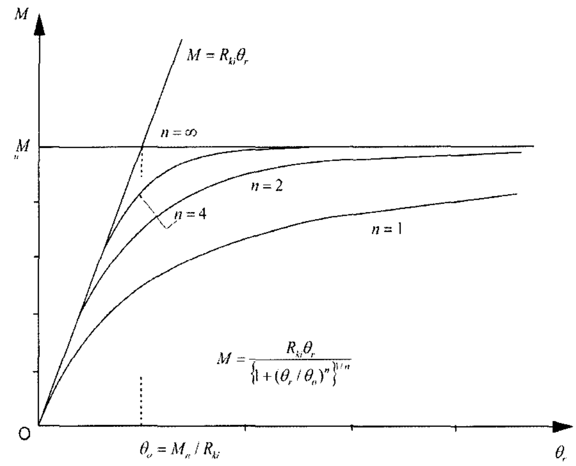


〈Fig. 11〉 The connector models for bending test

the chapter 3.1.(Table 3) In the sense of bolt clearance, the system B was applied by 0.4mm, because this system consists of thread bolt. Even though the author should have considered originally to more exact geometry for such as a thread bolt, the bolt geometry was simplified, because it will be very sophisticated and difficult to be applied with more detailed contact element with friction coefficient.

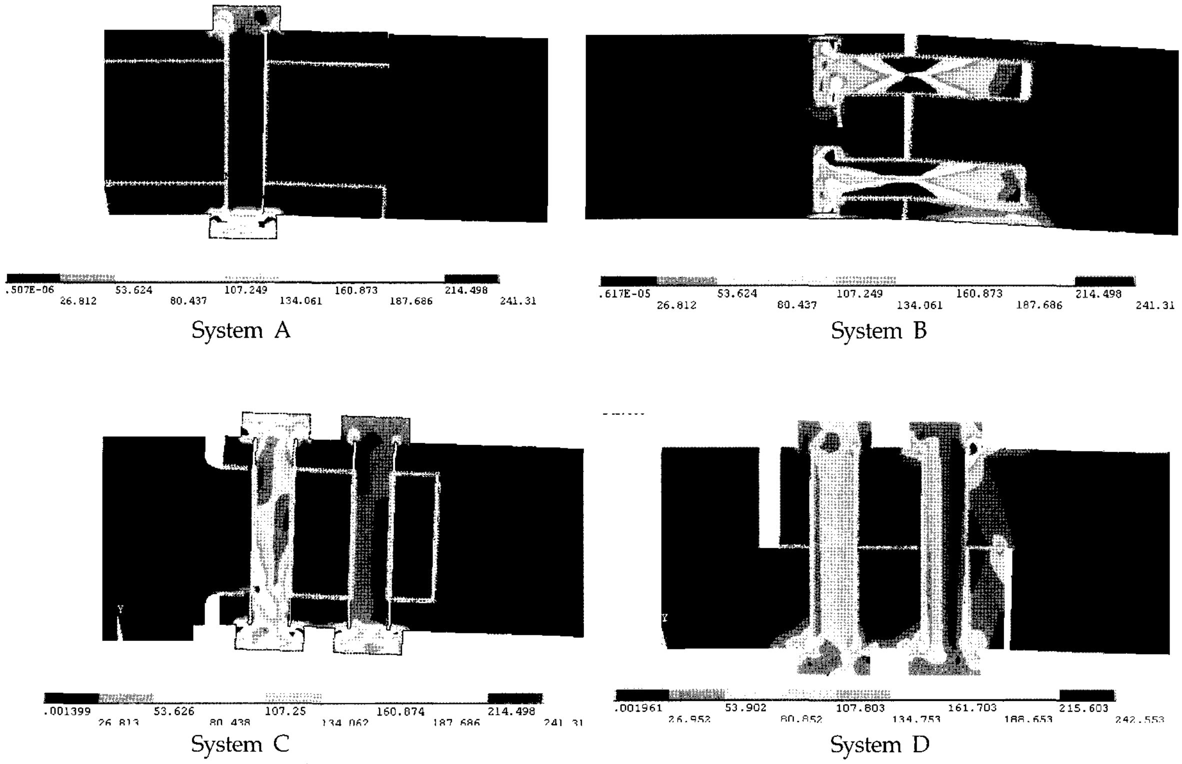
3.2.1 Results of analysis

The following analysis will cover the initial mechanical investigation of connector, especially the process of mechanical behaviour for the moment-rotation characteristics. To evaluate the connection behaviour, the three-parameter power model was used.(Fig. 12) This model was originally developed for the moment-rotation(M-θr relationship) characteristics of steel beam-to-column connections.

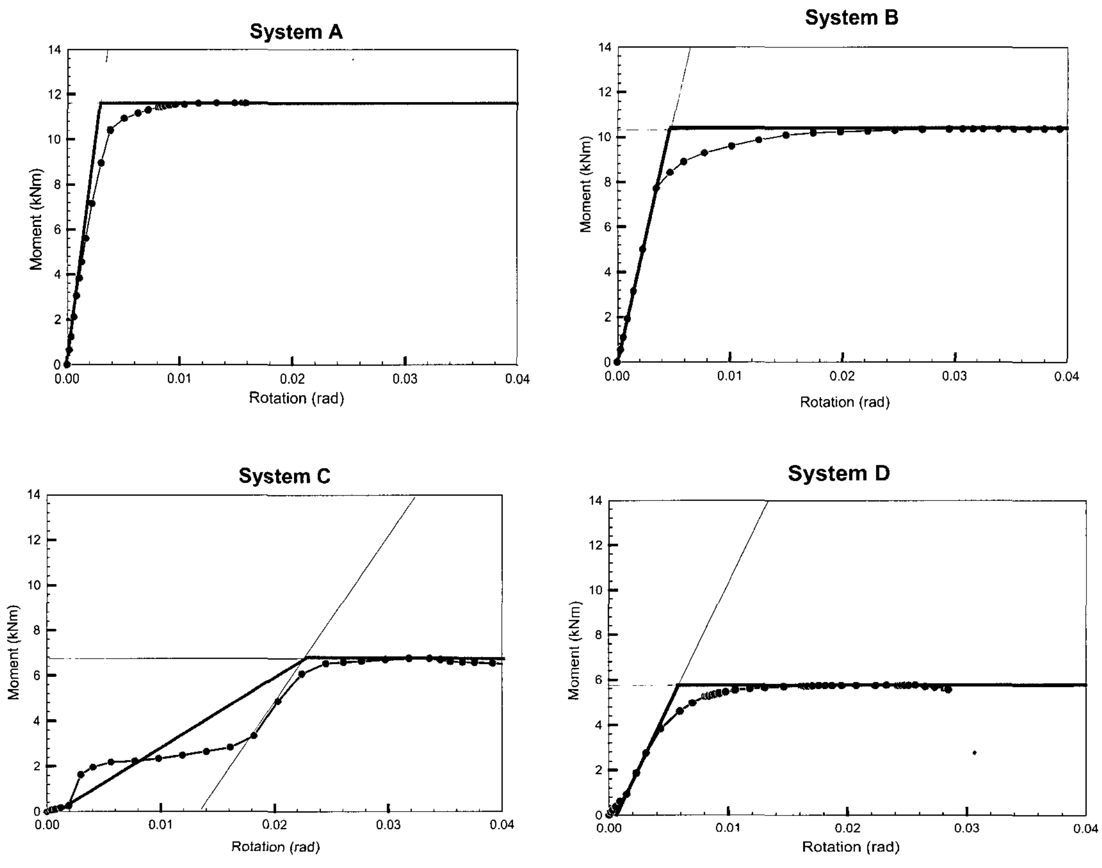


〈Fig. 12〉 Three-parameter power model[3)]

However, there are not yet appropriate model of the moment-rotation relationship only for connection model in free-form grid shell structures. Moreover, in this analysis procedure, the initial connection stiffness and ultimate moment capacity of the connection are determined by a simple analytical



〈Fig. 13〉 Von Mies Stresses of bending tests



〈Fig. 14〉. Moment-Rotation-Curves of bending tests

〈Table 4〉 The results of bending tests

	RB (kNm/rad)	My (kNm)	θs (radius)	θs (radius)
System A	3758.1	11.52084	0.00306	0
System B	2259.2	10.30000	0.00460	0
System C	293.31	6.74609	0.0230	0.001913
System D	1046.1	5.72000	0.0066	0.000565

RB : bending stiffness
My : yield bending moment
θy : roatation angle at yielding
θs : looseness of connector

model.[3)]

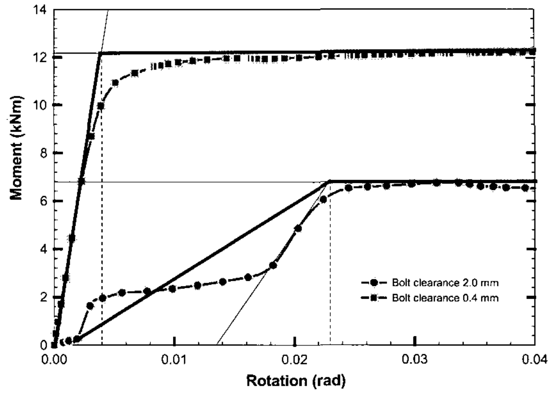
$$M = \frac{R_{ki}\theta_r}{\left[1+(\theta_r/\theta_o)^n\right]^{1/n}} \quad (1)$$

Mu = unltimate moment capacity
n = shape parameter
Rki = initial connection stiffness
θ0 = reference plastic rotation

As shown in Fig. 13 and 14, the moment and rotation of the beam element relative to the node connector is determined from the displaced shape of the connection, and node connector's stiffness were succeefully estimated. Fig. 13 shows various maximum stress very obviously.

Of course, all connection can not be compared with the same conditions, because they have very different geometric conditions. However, the connecter systems, which node connectors are jointed as close as possible with the end part of beam element, such as system A and B, show a high stiffness, because the closed connection prevents the connector's stiffness from looseness of bending stiffness. In terms of accomodation of local geometriy, for instance horizontal, vertical and twist angle, the system C and D can be effective, due to their geometries between node connector and the end of beam element.

Most of all, the system C shows very interesting rotation behaviour. The end of beam element of system C consists of fork-shaped. It means that upper and lower part of element move almost simultaneously when tensile and compression apply. Therefore, the bolt clearance 2.0 mm decreases significantly connector's stiffness.



〈Fig. 15〉 Moment-rotation relationships of system C with the bolt clearance 0.4 mm and 2.0 mm

〈Table. 5〉 Comparing of bolt clearances in the system C

Bolt clearance (mm)	RB (kNm/rad)	My (kNm)	θy (radius)	θs (radius)
0.4	2796.04	12.0230	0.0043	0
2.0	293.31	6.74609	0.0230	0.001913

In order to investigate the influence of bolt clearance, the bending test of system C was performed again with the bolt clearance 0.4 mm. Fig. 15. shows the moment-rotation relationship with system C, and as the author has expected, there are significant difference between the bolt clearance 2.0 mm and 0.4 mm. Due to the closed distance bestween bolt body and node connector, the stiffness soared from the beginning, if the bending moment started, and in case of bolt clearance 2.0 mm, the connecting stiffness is almost ten times higher than bolt clearance 0.4 mm. (Fig. 15 and Table 5)

4. Conclusions

In terms of node connector in free-form single layer spatial structure, the four node connectors were investigated relative to geometry's characteristic and applicability, and based on the investigation of connector, the two-dimensional moment-rotation analysis was successfully performed to estimate the stiffness of each connector. According to the design of connector, the applicabilities of node connectors are very different. Thus, it will be very a efficient way to design, if the designer would consider the local characteristics of connectors, because the local node connectors have very different geometry's characteristics that might probably exert significant influence on the global free-form spatial single layer structures. In the cases of bending analysis, the node connectors, which are connected as close as possible, presented normally a high stiffness. Most of all, the node connector with the fork-shaped end of beam element, namely, system C was heavily influenced by the bolt clearance.

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