World Academy of Science, Engineering and Technology
International Journal of Structural and Construction Engineering
Vol:7, No:1, 2013

Cost-Effective Design of Space Structures Joints: A Review

Mohammed I. Ali, Feng Fan, Peter N. Khakina, and Ma H.H

Abstract**—**In construction of any structure, the aesthetic and utility values should be considered in such a way as to make the structure cost-effective. Most structures are composed of elements and joints which are very critical in any skeletal space structure because they majorly determine the performance of the structure. In early times, most space structures were constructed using rigid joints which had the advantage of better performing structures as compared to pin-jointed structures but with the disadvantage of requiring all the construction work to be done on site. The discovery of semi-rigid joints now enables connections to be prefabricated and quickly assembled on site while maintaining good performance. In this paper, cost-effective is discussed basing on strength of connectors at the joints, buckling of joints and overall structure, and the effect of initial geometrical imperfections. Several existing joints are reviewed by classifying them into categories and discussing where they are most suited and how they perform structurally. Also, finite element modeling using ABAQUS is done to determine the buckling behavior. It is observed that some joints are more economical than others. The rise to span ratio and imperfections are also found to affect the buckling of the structures. Based on these, general principles that guide the design of cost-effective joints and structures are discussed.

Keywords**—**Buckling; Connectors; Joint stiffness; Eccentricity; Second moment of area; Semi-rigid joints.

I. Introduction

THE need for large unobstructed space has led to the increase of the use of space structures. The stability of these structures largely depends on the joints where the structural members are interconnected. The underlying criteria in the design of space structures includes the geometry of the nodes as well as the connection of the struts and the polyhedral units possible for each system because the structural issues can result in a rotation of nodes and lack of fit of members due to axial loads and residual stresses within the system [7]. Joints in space structures can be broadly classified as rigid, semi-rigid or pinned. According to Chilton [6], the stability of rigid jointed space frames depends on the bending resistance of the joints for its structural integrity, while space truss structures depend on their geometrical configuration to ensure stability. For example, in a three-dimensional pin-jointed space truss structure, it is a necessary condition for stability, that, $n = 3j – 6$, where n = number of bars in the structure j = number of joints in the structure 6 is the minimum number of support reactions. A semi-rigid joint is generally subjected to three different forces; tensile force, compression and bending moment [16]. Therefore in designing the joint, all this forces have to be considered. A pin-connected joint has a higher probability of failure as compared to the semi-rigid and rigid connections [10].

There exist over 250 different connectors. A question that comes to ones mind immediately is 'what is the difference between these many joints?' A close observation of the existing joints reveals that the joints can be classified in just a few categories. Most clients will prefer a cheaper connection. This raises another question; which is a more economical connector? The economy of a joint depends on how it is fabricated. The most important question is 'does the joint perform structurally as expected?' Some joints may be cheap but they do not perform as expected which makes them uneconomical. Also some joints may have good aesthetic value but low utility value which is still uneconomical. This paper discusses the existing joints by classifying them into categories according to where they are used, the materials that can be used to manufacture them, how they are manufactured, and how they perform structurally. Finite element (FE) modeling using ABAQUS is also done to determine the buckling behavior. With consideration of all factors, principles of designing a cost-effective joint are outlined.

Mohammed I. Ali. a) School of Civil Engineering, Harbin Institute of Technology, 2453 P.O. BOX 73, Huanghe Road, Harbin 150090, China ;(e-mail: missaali@yahoo.com.). b) Civil Engineering Department, Kordofan University, Sudan.
Feng Fan., School of Civil Engineering, Harbin Institute of Technology, 2453 P.O. BOX 73, Huanghe Road, Harbin 150090, China.
Peter N. Khakina, School of Civil Engineering, Harbin Institute of Technology, 2453 P.O. BOX 73, Huanghe Road, Harbin 150090, China.
Ma H.H School of Civil Engineering, Harbin Institute of Technology, 2453 P.O. BOX 73, Huanghe Road, Harbin 150090, China.

II. Design Consideration for Joints

A. Overview

According to Holmes and Martin [11], a good structural connection should be:

- Simple to manufacture and assemble
- Standardized for situations where the dimensions and loads are similar
- Manufactured from materials and components that are readily available
- Designed so that welding is generally confined to the workshop to ensure good quality and reduce costs
- Designed to avoid the use of temporary supports to the structure during its erection
- Detailed to resist corrosion and to be acceptable aesthetically and
- Low in cost and maintenance.

A cost-effective joint has to fulfill these requirements. Joints influence the economy of space frames because they may occupy up to 50% of the material required in the construction [19]. Therefore, the challenge that the designers for connectors face is how to make the joint simple but at the same time, effective. In most cases, elasto-plastic buckling of single-layer reticulated shells starts at the joints [9]. Then the local instability is followed by member buckling [12]. With the application of fractal geometry to grid and reticulated shells as in [22], and complex joints like that of connecting thirteen box-section members and transferring forces from rhombic section to rectangular section [13], critical examination of design of joints has become a necessity. Most designers use the experimental results to derive empirical design rules. However, there are some basic rules that have to be observed when designing a connector or joint. The connection stiffness, connection strength and connection ductility should be considered [5]. The rigidity of the joint increases the overall resistance of reticulated shells to external loads [14]-[21].

When using some forms of connectors, there is need to reinforce the connections so as to strengthen the structure against local instabilities [3]. This requires an increment in the material which ultimately affects the cost. Therefore it is important to design a joint which will not require reinforcement of the connection. The connectors have a thickness that induces an eccentricity between the nodes and these eccentricities may greatly reduce the resistance of the structure if the act as geometrical imperfections [8]. It is therefore important that in the design of the joint, eccentricity is avoided. It is also necessary to keep the buckling load in all the directions the same by ensuring that the second moment of area is constant in all directions.

A. Welded Joint Design

Welded connections may be in the form of Butt weld, Fillet weld or Plug and Slot weld. For thin plates, the Butt weld is of the complete penetration type while for thick plates it is the incomplete penetration type. According to American Institute of Steel Construction (2010) [1], the design strength of a weld is given by the lower of:

$$\phi F_{BM} A_{BM} \tag{1}$$

and

$$\phi F_w A_w \tag{2}$$

where FBM = Nominal strength of base metal
ABM = Cross-sectional area of base metal
Fw = Nominal strength of weld electrode
Aw = Effective cross-section area of the weld
Ø = Capacity factor

B. Bolted Joint Design

The five fundamental modes of failure of bolted connections are; bolt failure, bearing failure, tear-out failure, net section fracture and block shear failure. Each of these modes of failure is addressed in Australian Building Codes Board (1998) [2]. According to British Standard – BS 5950 (2001) [4], the shear capacity of bolted joint is:

$$P_s = p_s A_s \tag{3}$$

while the capacity in tension is:

$$P_{nom} = 0.8 p_t A_t \tag{4}$$

where ps = allowable stress in shear
pt = allowable stress in tension
As = shear area
At = tension area

For combined shear and tension:

$$\frac{F_s}{P_s} + \frac{F_t}{P_{nom}} \le 1.4 \tag{5}$$

where Fs = nominal strength in shear and
Ft = nominal strength in tension
responsible for obtaining any security clearances.

C. Categories of Joints in Space Structures

There exist very many different types of joints which have been classified into various categories. The joints are mainly manufactured by commercial companies. In this paper, the joints are classified into three broad categories; rigid, semi-rigid and pinned joints.

a) Rigid Joints

The advantage of rigidity is that it increases the overall resistance to external loads but the joints have the disadvantages of requiring highly skilled labor to work on the construction site. Traditionally, most early space structures used this type of joints but the trend is changing to semi-rigid joints.

b) Semi-Rigid Joints

These joints mainly consist of ball joints, members and connection mechanism using bolts alone or with nuts. According to Stephan [20] the classical node connector for double-layered structures is the ball node connector which can be complemented by the bowl node connector. For single-layer structures, the node connectors can be divided into two fundamental groups; splice connectors and end-face connectors. The advantages of semi-rigid joints include:

(a) It is possible to use tubular members which have a concentric profile and has the same second moment of area in all directions thus ensuring a constant buckling load in all directions.

(b) They can be used in a wider range of structures.

(c) They can be prefabricated in the industry and quickly assembled on site thus saving on time and making use of less-skilled labor.

The disadvantage of such joints is that if not well designed, they may turn out to be very complex and expensive as compared to other categories of joints. An example of such is the universal connector suitable for all types of structures by Konrad Wachsmann [18].

c) Pinned Joints

The members are connected to the joint so as to eliminate bending moments in some or all directions. The pinning concept is to design the splice plate by taking the center lines of the members either welded or bolted into it and aligning it to the Joint, thus making it pinned.

III. Finite Element Modeling

A. Test for Effect of Rise to Span (f/L) Ratio on Buckling

Space structures constructed of single-layer grids or shells may fail due to general buckling, local buckling at the joints or element buckling of the individual bars. Several single-layer reticulated spherical shells with rigid joints, diameter of steel pipes = 102 mm and with wall thickness of 6mm are modeled using ABAQUS while keeping the span (L) constant but varying the rise (f) to determine the buckling load. Fig. 1 shows the geometry of the shell. Fig. 2 shows the initial buckling load for different f/L ratios. It is observed that the buckling load increases with increase in f/L ratio up to f/L = 1/4, then is starts to reduce for shells with rigid joints.

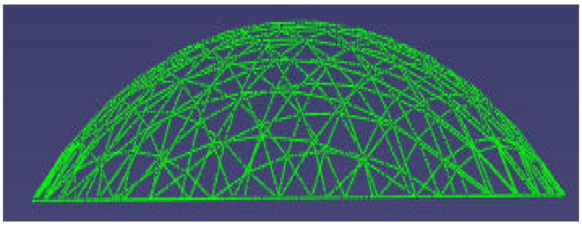

Fig. 1 Steel spherical shell: Span (L) = 30 m, rise (f) = 7.5 m

B. Effect of Initial Geometrical Imperfections on Buckling

To test the effect of the initial geometrical imperfection, a single-layer reticulated shell of L = 20 m, f = 2.5 m with diameter = 102 mm and wall thickness = 7 mm steel pipes was modeled using different initial geometrical imperfections. Fig. 3 shows the Load-deflection curves. It is observed that the initial buckling load is sensitive to initial geometrical imperfection because the load decreases with increase in the magnitude of the initial geometrical imperfection. Studies by Zhou [24] also showed the same trend when using timber. However, all the curves tend to meet at the post-buckling load which implies that the load is independent of imperfections.

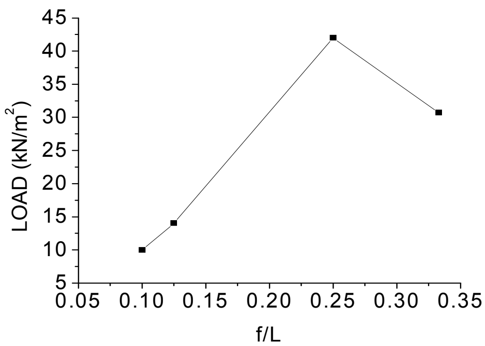

Fig. 2 Buckling loads of different f/L ratios

IV. Simplicity and Effectiveness of Joints

A. Review of the Existing Joints

The application of the samples of space structures joints systems to various types of structures is given in Table I. Flat structures mostly use plate and beam elements while curved structures mainly use shell elements. Temporary structures are those structures which are quickly assembled on site to serve a specific function which is not permanent. Table II gives the comparison of systems including their main characteristic.

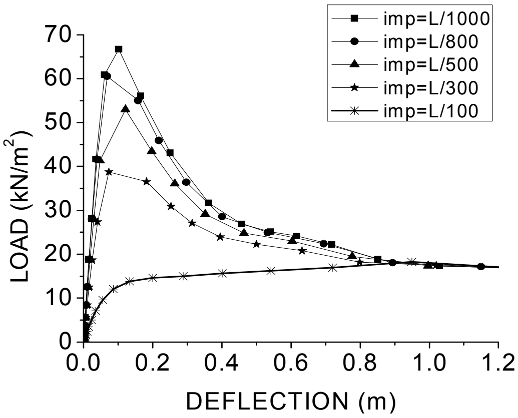

Fig. 3 Load-deflection curves: Span (L) = 20 m, diameter = 0.102 m, and wall thickness = 0.007 m

It is seen that steel is most commonly used. Aluminium has been included in the Triodetic system, while for the MERO system, steel is preferred through Aluminium is not ruled out. Plastic has been used also in MERO system. Different steel sections are widely used in most prefabrication systems due to the simplicity in connecting members, which lie in different angles at a single joint without eccentricity. The tubular steel sections make the connectors efficient in resisting the axial forces.

From the tables, it is seen that MERO system is the best system. It was developed by Dr. Ing. Max. Mengeringhausen in 1942. The MERO system is widely used for double-layered roof structures for both flat and curved surfaces [17]. As shown in Fig. 4, the joint addresses three different forces in the following ways

i. When the joint is subject to tensile force, the tensile force is transferred to the spherical ball through the interface between the cone and nut.

ii. When the joint is subject to compression force, the force is transferred to the spherical ball through the interface between the cone and sleeve.

iii. The bending moment causes the tensile and compressive force at the upper and under side of the joint which are addressed by the interface between the cone and the sleeve.

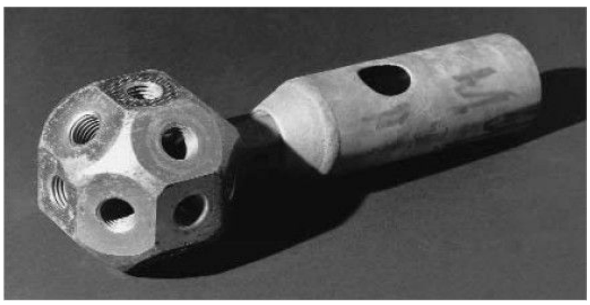

Fig. 4 1-Standard MERO KK node with 18 threaded holes and machined bearing surfaces at angles of 45°, 60° and 90°

In this system, welding is done in workshop and only bolting is necessary at the site and it is used with all types of structures. For structures of single or double curvature, systems like MERO, SPHEROBAT, SARTON, HEMTEC, SDC and Triodetic can only be used. The ORTZ, Harley, SEGM and SDC systems requires site welding and hence may prove to be difficult system when welding facilities are not available at the site and it also requires high skilled labor. Harley Systems was developed in Australia because it is relatively cheap as compared to nodal connectors. However the system is limited in resting buckling which requires other reinforcements. It also restricts its use to square-on-square and square-on-large square configurations. The system consists of chord members, web members and fasteners as shown in Fig. 5.

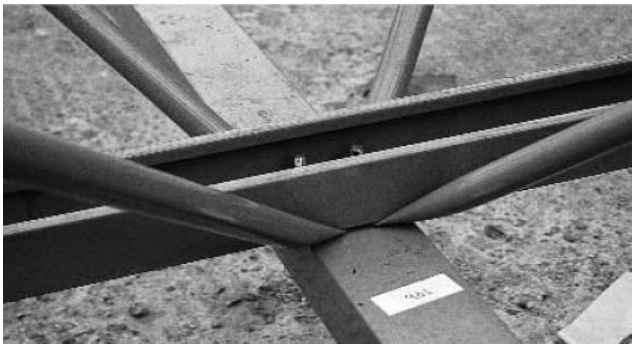

Fig. 5 Harley Type 80 node joint

B. General Principles for a Simple but Cost-Effective

Most stable joint systems are those that have a constant buckling load in all directions. Also to save on time and labor, prefabricated connectors are preferred. While considering all these, ultimately, the joint should be simple but strong enough to resist all the external loadings. These factors have led to a move from rigid joints to semi-rigid joints. Although many joints have been developed so far, MERO system and its modifications still remain the most popular.

TABLE I
APPLICATION OF THE JOINTS SYSTEMS

S.No	System	Flat structures	Curved structures	Temporary structures
1	MERO	●	●	●
2	SPHEROBAT	●	●	
3	SARTON	●	●	
4	NS Truss	●		
5	Unistrut	●		
6	HEMTEC	●	●	
7	Nodus	●		
8	NEWBAT	●		
9	Pyramitec	●		
10	ORTZ	●		
11	Harley	●		
12	SEGMO	●		
13	SDC	●	●	
14	Triodetic	●	●	

This is because the system makes use of tubular members which ensures constant buckling load in all directions. However, a lot of its modifications have come up so as to address the issue of interaction between the sleeve and the cone.

From the experiments done by [23], for an I-section member, local web buckling happens at the support where the web panel is under the actions of shear and localized support reaction and underneath a loading point, where the web panel is under the actions of moment, shear and a concentrated load. There is the tendency for the sleeve which is attached to the spherical ball to exhibit the same behavior.

Some modifications of the MERO system where the tubular cone is turned in a plate reduce the cross-sectional area which creates a weak point where failure of the joint may start. Also using a plate inside a tube reduces resistance to shear forces which has made it necessary to include packing material in the tube. This ultimately increases the volume of material in the connection which also increases the cost.

V. CONCLUSION

A good joint should satisfy equilibrium, deformation, compatibility and fracture conditions. Advances in space structures joints are towards semi-rigid joints because they tend to satisfy most of the conditions, use of less-skilled labor and save on time of construction. Many semi-rigid joints have been developed and their design rules are mainly based on experimental results. In this paper, an attempt has been made to bring out some requirements for a good semi-rigid joint which is strong to resist the external loads. It includes ensuring that the connector's parts are made to have uniform buckling load in all directions and making the joint simple but strong.

Joints in this paper have been classified as rigid, semi-rigid or pinned. They have been reviewed in terms of where they are applied, how they are manufactured, the material that can be used to manufacture the connectors and their structural performance. It is noted that the MERO system stands out to be the most applied joint in space structures but it is undergoing many modifications to function more effectively. It is important to design a simple cheap connector of a joint but it must also fulfill the structural requirements for it to be cost-effective. Joint size may be determined by the size of the structures. It is therefore also important to design a structure with a size which is cost-effective. For shells with rigid joints, $f/L = 1/4$ has the highest resistance to buckling. Studies by [15] show that for shell semi-rigid joints, $f/L = 1/3$ gives the highest resistance to buckling. These f/L ratios also give the highest bending stiffness making them the most economical. Further work can be done to determine the post-buckling load which is independent of initial geometrical imperfections so as to design joints based on this load to ensure maximum safety which is also a very important factor in the cost effectiveness of space structures.

TABLE II
COMPARISON OF THE SPACE STRUCTURES JOINTS

No	System	Materials	Structural configuration		Structural elements		Jointing system		
			Double layer Multi-layer	Single layer	Independent bars	Sub-assemblies	Weld	Bolted	Shape for bar
1	MERO	Steel/ Aluminium Plastic	●	●	●			●	○□□
2	SPHEROBAT	Steel	●	●	●			●	○
3	SARTON	Steel	●	●				●	○
4	NS Truss	Steel	●					●	○
5	Unistrut	Steel	●			●		●	[○
6	HEMTEC	Steel	●						○
7	Nodus	Steel	●			●	●	●	○□□
8	NEWBAT	Steel	●		●		●	●	○
9	Pyramitec	Steel	●			●		●	○
10	ORTZ	Steel	●				●		○
11	Harley	Steel	●				●		○
12	SEGMO	Steel	●	●	●		●		○
13	SDC	Steel	●	●	●		●		○
14	Triodetic	Steel/ Aluminium	●	●	●			slots	[○ ●

REFERENCES

[1] American Institute of Steel Construction, Specification for structural steel buildings, Chicago, 2010.

[2] Australian Building Codes Board, Steel structures, AS 4100, 1998.

[3] R. C.Battista, M. S. Pfeil and E. M.Batista, "Strengthening a reticulated spherical dome against local instabilities", J. Constr. Steel Res., 57, 15-28, 2001.

[4] British Standard – BS 5950, Structural use of steelwork in building - Part 1: Code of practice for design – Rolled and welded sections, 2001.

[5] J. Chen, and H. Chen, "Stability of steel structures theory and design," China Electric power press, Beijing, China, 2009.

[6] J. Chilton, Space grid structures, Architectural Press, Oxford, UK, 2000.

[7] S. Darvishani-Fikouhi, Honeycomb topologies; "Design rationalization of a free-form space frame structure," Dissertation, University College London, London, UK, 2009.

[8] C. Douthe, O. Baverel and J. F. Caron, "Form-finding of a grid shell in composite materials", J. IASS. 47, 53 – 62, 2006.

[9] F. Fan, Z. Cao and S. Shen, "Elasto-plastic stability of single-layer reticulated shells", Thin wall struct., 48, 827-836, 2010.

[10] M. Hansson and P. Ellegaard, "System reliability of timber trusses based on non-linear structural modeling", Mater. Struct., 39, 593-600, 2006.

[11] M. Holmes and H. L. Martin, "Analysis and design of structural connections: Reinforced concrete and steel," John Willey & sons, New York, USA, 1983.

[12] A. Ivan and M. Ivan, "Typical failure modes of some single layered reticulated shells", International Colloquium-Recent advances and new trends in structural design, Editura Orizonturi Universitare, Timişoara, Romania, p. 145-154, 2004.

[13] X. Liu, Q. Zhao, H. Liu and Z. Chen, "Innovations in design and construction of the new stadiums and gymnasiums for the 2008 Beijing Olympic games", J. IASS. 52(1), 39-52, 2011.

[14] A. López, I. Puente and M.A. Serna, "Analysis of Single Layer Latticed Domes: a new Beam-element", International IASS Symposium on Lightweight Structures in Civil Engineering. Warsaw, Poland, p. 639 – 644, 2002.

[15] H. H. Ma, F. Fan, and S. Z. Shen, "Numerical parametric investigation of single-layer latticed domes with semi-rigid joints", J. IASS., 49 (2), 99-110, 2008.

[16] H. Ma, F. Fan, Z. Cao, M. Cui and S. Shen, "Numerical simulations of semi-rigid joints in single-layer dome structures", J. IASS. 52 (1), 3-18, 2011.

[17] Z. S. Makowski, "Analysis, design and construction of braced domes" GRANADA, London, UK, 1984.

[18] Z.S. Makowski, "Development of jointing systems for modular prefabricated steel space structures", International IASS Symposium on Lightweight Structures in Civil Engineering, Warsaw, Poland, 2002, p. 17 – 41.

[19] Narayanan, S. "Space Structures: Principles and Practice," Multi- Science Publishing Co. Ltd., Brentwood, USA, 2006).

[20] S. Stephan, J. Sánchez-Alvarez and K. Knebel, "Reticulated structures on free-form surface, " MERO GmbH @ Co., Wurzburg, Germany, 2010.

[21] E. Tatsa and Y. Tene, "Buckling of reticulated shells with rigid joints", Acta Mech., 19, 77-88.

[22] M. A. Vyzantiadou, A.V. Avdelas and S. Zafiripoulos (2007), "The application of fractual geometry to the design of grid or reticulated shell structures", Comput. Aided Design, 1974, 39, 51-59.

[23] E. C. Zhu, Z. W. Guan, P. D. Rodd and D. J. Pope, "Buckling of oriented strand board webbed wood I-joists", J. Struct Eng., 2005, 131(10), 1629-1636.

[24] H. Z. Zhou, F. Fan, and E. C. Zhu, "Buckling of reticulated laminated veneer lumber shells in consideration of the creep", Eng. Struct., 2010, 32, 2912-2918.