Survey of Existing Studies on the Strength and Deformation of Spherical Joints in Steel Space Trusses

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ABSTRACT

In order to accurately predict the behavior of space trusses, it is necessary not only to account for the actual framing members, but also to be able to predict the response of the joints holding these members together. Moreover, to design the joint, one must consider not only the qualitative variables describing the joint, but also the stress distributions and deformations within the joint, under assumed design loads. In this paper, a survey of existing studies on the strength and deformation of spherical joints in steel space trusses is given. Remarks on the limitations of such studies are made and a need for a greater in-depth treatment in such studies is suggested.

INTRODUCTION

Space frame structures are well known in the building construction industry. Such structures are formed of a number of truss members which are joined at their ends to form a three-dimensional array.[4] This enables the construction of domes, arches, and flat roofs which cover large areas without the need for intermediate supports.

To achieve the construction of space trusses, it is necessary that joints be introduced which firmly connect the individual members to one another, accommodating at the same time the spatial network of these members, to result in a single integrated structural entity.[5] The different space joint systems that fulfill this objective can be grouped into three basic categories:

1. Systems in which the members are directly attached to each other;
2. Systems that use special connectors; and
3. Systems designed for the job at hand.

Presently, space joint systems that use special connectors in the form of spherical balls with connections for attachment of the truss members, predominate in space joint solutions. Examples include the German MERO System;[6] the American Unistrut System;[7] and the Japanese Tomoe Unitruss System.[8] A new spherical joint type in this category is currently being developed in the Civil Engineering Department of Wayne State University.[9,10] This joint consists of a hollow sphere containing a number of internal, preferably hollow spheres. All these spheres are in contact with each other, the objective being to produce a light, but structurally rigid, node. The spaces between the internal spheres can be filled, with foam for example, to improve its damping characteristics.

A spherical joint in a space truss will therefore be defined here as a space joint having at least one spherical connector, usually referred to severally as: spherical node,[11] spherical ball,[12] or simply as a node.[13] The spherical node enables an easy realization of the three-dimensional character of the space truss,[6] since by its geometry it can receive the truss members being connected to it from any angle in a three-dimensional space.

A spherical joint, like any other good space joint, must satisfy a number of requirements:

1. Structural
2. Geometric
3. Aesthetic
4. Economic

The structural requirements cover the following:

(a) Stiffness
(b) Strength
(c) Dynamic Characteristics

The geometric requirement demands that the size be large enough to connect several truss members and provide enough room for making connections. Usually, it is difficult to formalize aesthetic requirements, which can be described in general as those regarding the appearance of the spherical joint.

Economy demands that the spherical joint be cheap and easy to construct and yet meet its functional requirements.

STRENGTH AND DEFORMATION OF SPHERICAL JOINTS

In the United States the AISC Committee for the Design, Fabrication and Erection of Structural Steel for Buildings

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recommends specifications for joint analysis and design using steel material. The task committee on lightweight alloys of the American Society of Civil Engineers prepares recommendations for structural use of aluminum material. While these specifications have provided for a safe design and analysis of structural joints, the specifications, however, deal primarily with planar constructions. Though joints serve similar purposes in such constructions and space trusses—that of load transfer, their role in the later type of structure is more important because, usually, more members are connected to them. Further, members are located in a three-dimensional space; therefore the load transfer mechanism is more complex. Recognizing this inadequacy of the AISC Specification to provide for the safe design and analysis of spherical space joints, the Task Committee on Latticed Structures of the Committee on Special Structures of the Committee on Metals of the Structural Division of ASCE gave summaries of current approaches to be used in dealing with latticed structures.[14] However, the observation of the Committee that much of the design application knowledge for space joints is "proprietary and not published," serves to emphasize the dearth of knowledge in spherical space joint design and analysis.

A typical spherical space joint consists of many members connected to it. Consequently, failure of any such joint will lead to the failure of several members of the space truss. Reported cases of spherical joint failure in actual space trusses[15] have generally been:

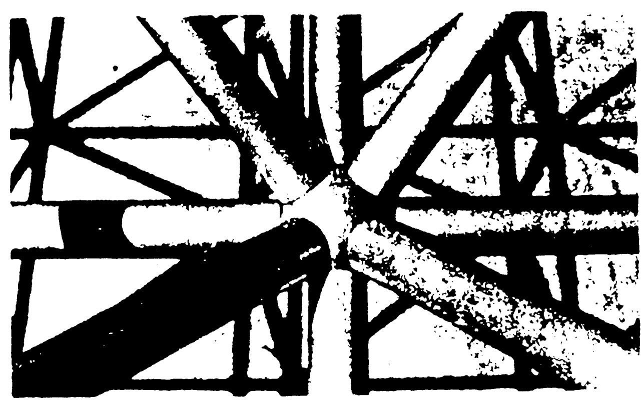
(a) Crushing of the spherical nodes at the points of attachment of bar members;
(b) High stress concentrations at edges of node holes leading to yielding and large rotations of bar members;
(c) High stress concentrations at point of attachment of bar members leading to cracks at these points;
(d) "Ovalization" at node openings. Structurally inefficient spherical space joints and, or failure of such joints are due primarily to this lack of knowledge of the complex stress distributions and deformations within such joints.

ASSESSMENT OF THE EXISTING INFORMATION ON STRENGTH AND DEFORMATION

The development of concepts of spherical space joints is still more an art than a science. A few investigators, however, have started to develop a methodology for structural shaping and design of such joints.[1,2] An attempt is even being made to develop analytical procedures for predicting the structural response and reliability of these joints under assumed design loads.[3] Perhaps the earliest effort at such an analytical solution is the one done by Bijlaard.[16] However, analytic methods are limited to structures with simplified boundary conditions. Most of the published investigations on the strength of and deformations within spherical joints are experimental, devoted to a particular spherical space joint system, with no attempt at a generalization of the results. Among the most extensive experimental tests conducted to investigate the strength of spherical joints is the one done by Kubodera et al.[17] The test was done to investigate the ultimate strength of a cast steel hollow spherical node used by the Japanese Tomoegumi Iron Works. However, the experimental models used by them to represent the state of stress of the node considered only uniaxial and biaxial stress state. A spherical node in a space truss accommodates many members, as shown in Fig. 1. The node is therefore subjected to multiaxial forces. The safety of such a node must therefore be studied, taking into consideration the multiaxial stress conditions combining these multiaxial forces.

Figure 2 shows the load deformation relations obtained by them for both uniaxial (labelled A) and biaxial (labelled B) load tests. Both test results show larger ultimate strength of the spherical node than the design load under these test models.

Hisanitsu et al.[18] conducted stress-strain measurements and ultimate strength tests on a monoblock spherical shell



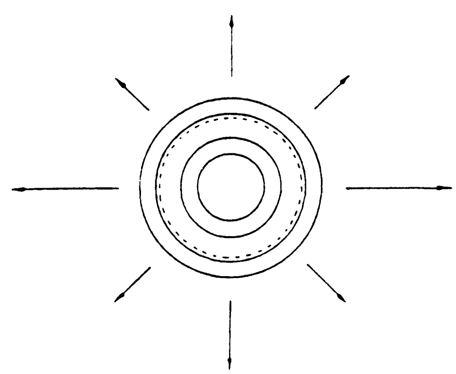


Fig. 1. A typical spherical node of a space structure.

Table 1. List of Test Pieces for Node Load Bearing Tests			
Loading Position	**Type of load**	**Node Size**	**Total**
Chord member joint	Compression Tensile Compression	N190,N210(2),N250(2),N290(2) N210 N250 N290 (at different joint angles) N250	7 3 5
Diagonal member joint	Compression Tensile	N190,N210(2),N250(2),N290(2) N210 N250 N290	7 3
Chord member joint	Compression-tensile Compression-compression	N250 N250	1 1
Diagonal member joint	Compression-tensile	N250	1

joint. These load tests and strain measurements are shown in Figs. 3a, b.

The relation between the branch pipe flange deflection L_f or the outside diametral variation L_h of the spherical shell and the load from the branch pipe is shown in Figs. 4a, b. Figures 5a, b show the stress distributions into the latitudinal and longitudinal directions inside and outside the spherical shell block.

Casting the shell block integrally to the main pipes alters the stiffness characteristics of the shell node and again, individual load tests do not represent the actual loading condition and load interactions on the spherical shell block.

A rigidity and load-bearing test has also been carried out by Nakano et al.[19] on the spherical nodes of the NS space joint system shown in Fig. 6.

Also investigated was the effect of node material on the bearing capacity of the node. Both uniaxial and biaxial load

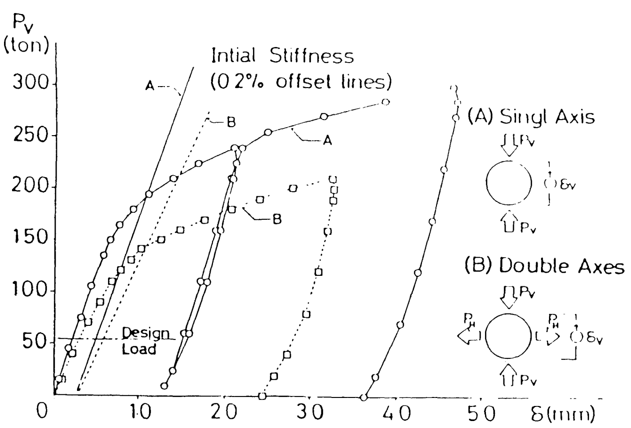


Fig. 2. Load-deformation curves for a uniaxial (A) load test and biaxial (B) load test.

tests were made. A summary of the load positions, the type of load, and node size is given in Table 1.

The load exerted by a chord member was determined by using the entire node body as a test piece and applying a load onto its equatorial plane. The load exerted by a diagonal member was determined using test pieces prepared by welding together the lower halves of two nodes cut from their equatorial plane as shown in Fig. 7. The load-deformation curves for the different node materials are shown in Fig. 8 and Fig. 9 shows the yield load in node-loading tests at chord members versus node thickness.

This yielded the relation:

$$P_y = At^B$$

where A and B are constants.

This experimental model again simplifies the multiaxial load condition of a typical spherical node to uniaxial and biaxial load conditions. The test pieces especially prepared do not reflect the actual load conditions of these pieces in the complete shell node.

Other tests include those of the Federal Institute for testing materials in Berlin, who carried out extensive tests to investigate the strength of the solid steel node used in the Züblin space truss system.[11] Series of tests have also been conducted on the mine-type spherical shell joints.[20] These uniaxial and biaxial test models were done to investigate the ultimate strength of the spherical node used in the joint. A summary of the described experimental tests is shown in Table 2.

CONCLUSIONS AND FUTURE RESEARCH NEEDS

The need for a greater in-depth study of the strength and deformation of spherical joints in steel space trusses is threefold. One is the obvious need for a safe design and analysis

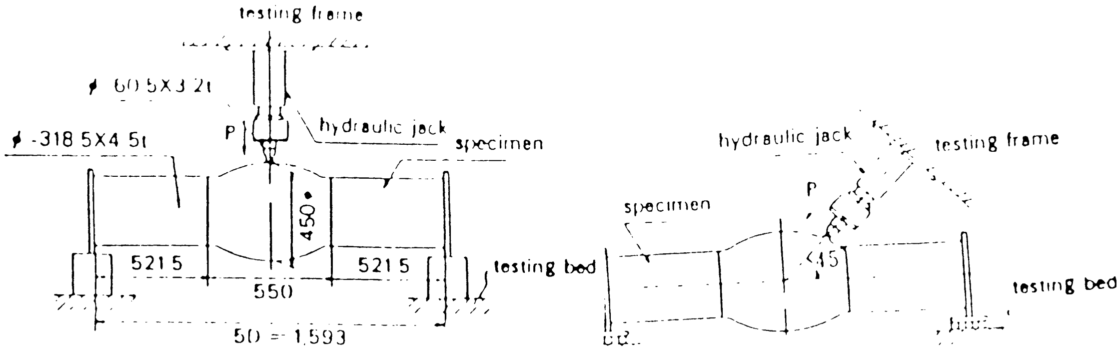


Figure 3a.

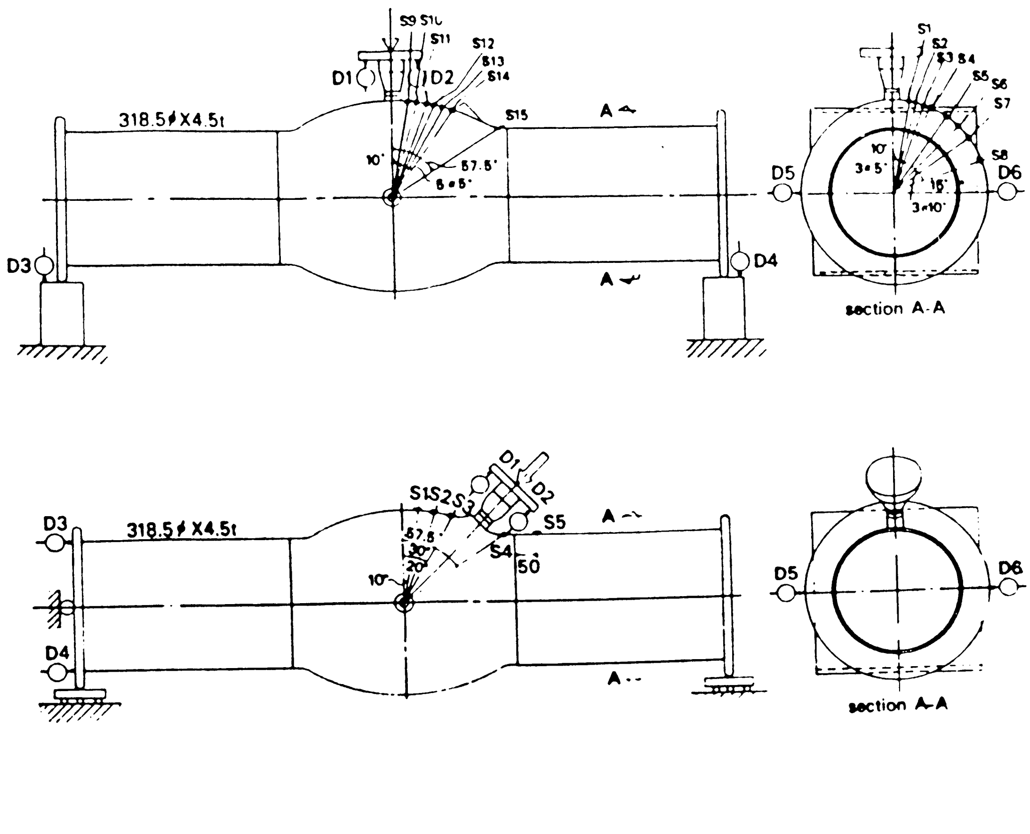


Fig. 3b. Strain measurements.

Table 2. Summary of Experimental Tests				
Ref.	**Name/Title**	**Objective**	**Result**	**Remarks**
11	Federal Institute for Testing Materials, Berlin, W. Germany, "Züblin Space Truss System."	Establish the strength of the solid steel node and thus confirm its safety.		
17	I. Kubodera, H. Koto, H. Ishizu, "Experimental Study on Strength and Stiffness of Nodes in New Space Frames."	1) Establish the ultimate strength of the hollow spherical node. 2) Establish the ultimate strength and bending capacity of the connector bolt. 3) Non-destructive testing of the prototype space frame; all through static loads.	1) High ultimate strength of the spherical node was confirmed. 2) High node ductility was confirmed.	1) Simplified stress state of node. 2) No stress distribution. 3) No effect of node thickness on the ultimate strength.
18	T. Kanno, N. Hisanitsu, S. Sakmoto, and T. Miyamura, "Cast Steel of Spherical Shell Joints of Off-Shore Space Structures."	Investigate the stress distribution and deformation of the spherical shell joint in order to establish designing procedures for such joints.	1) Maximum stresses occurred in the vicinities of the connection points. 2) Cracks occurred also at these points. 3) Joint failure was due to localized buckling near the connection points. 4) High yield strength of spherical shell was confirmed.	1) Shell stiffness is changed by the monolithic attachment to main pipes. 2) Individual load test fails to show the force interaction of the several branch pipes on the shell.
19	D. Nakano, M. Iwata, A. Kadono, and T. Ohba, "A Study of Tubular Steel Space Truss System. Development of NS Space Truss	Establish the load bearing capacity and rigidity of the spherical nodes used in the NS space truss system and thus confirm their safety.	1) High load bearing capacity was confirmed. 2) High ductility of the node material was established. 3) Thickness influenced load bearing capacity and rigidity.	1) Simplified stress state of the node. 2) Load state of test pieces changed during preparation to suit test condition.

of such joint types and thus the confirmation of their structural adequacy in steel space truss applications. The other goal is to develop design and analysis methodology of spherical joints in steel space trusses through an improved understanding of the stress distributions and deformations of such joint types. Such studies can be formalized as a basis for future spherical joint design and analysis code provisions regarding joints in steel space trusses. The third but less obvious goal will be an advancement of the science of the space truss joint design and of the analysis of multiplying perforated shells under load.

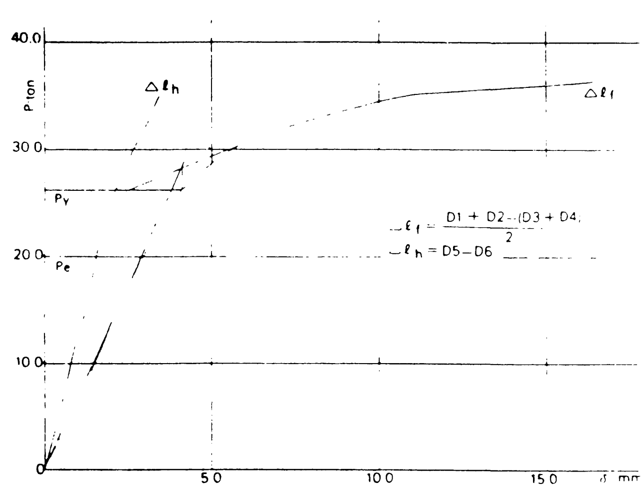


Fig. 4a. Load-deflection curves (Type I).

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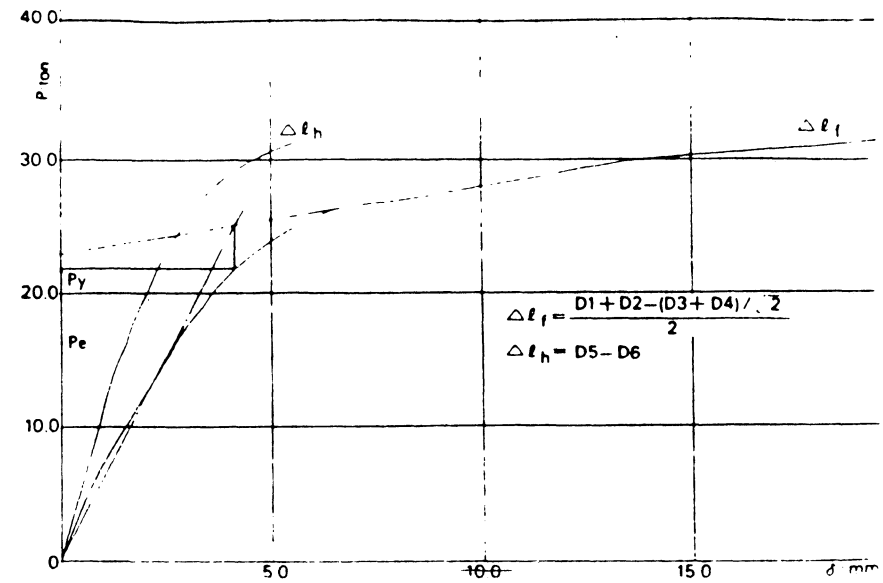

Fig. 4b. Load-deflection curves (Type II).

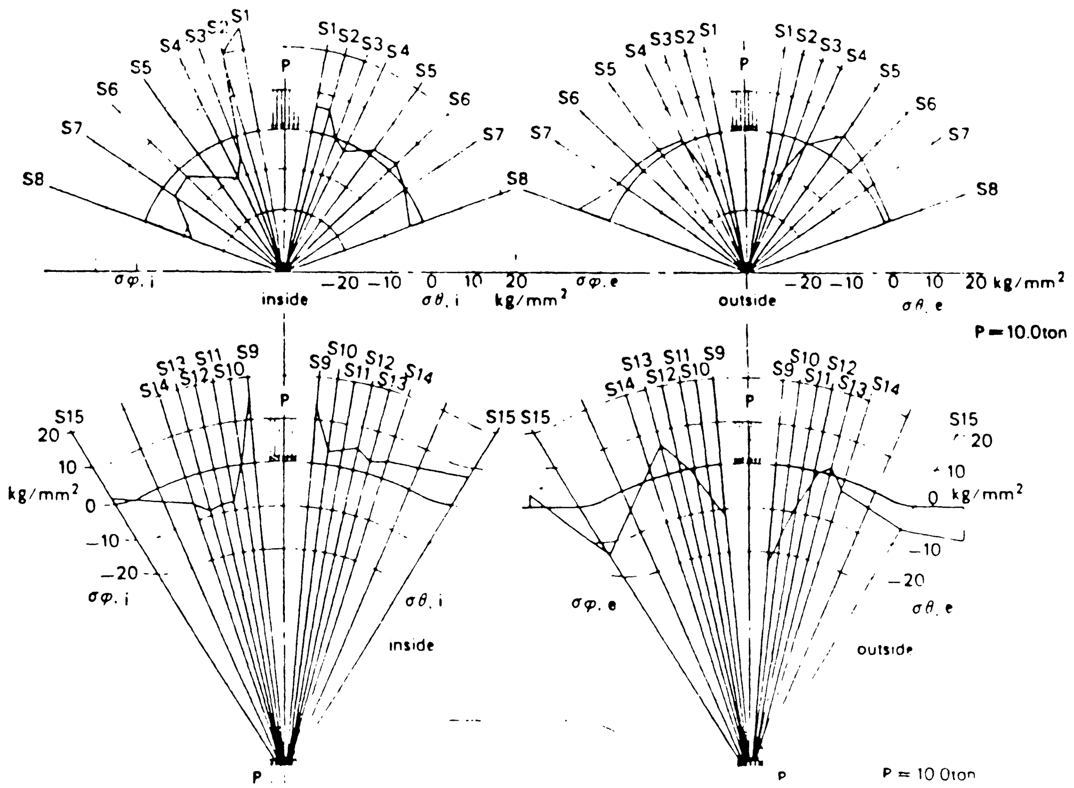

Fig. 5a. Stress distribution of spherical shell (Type I).

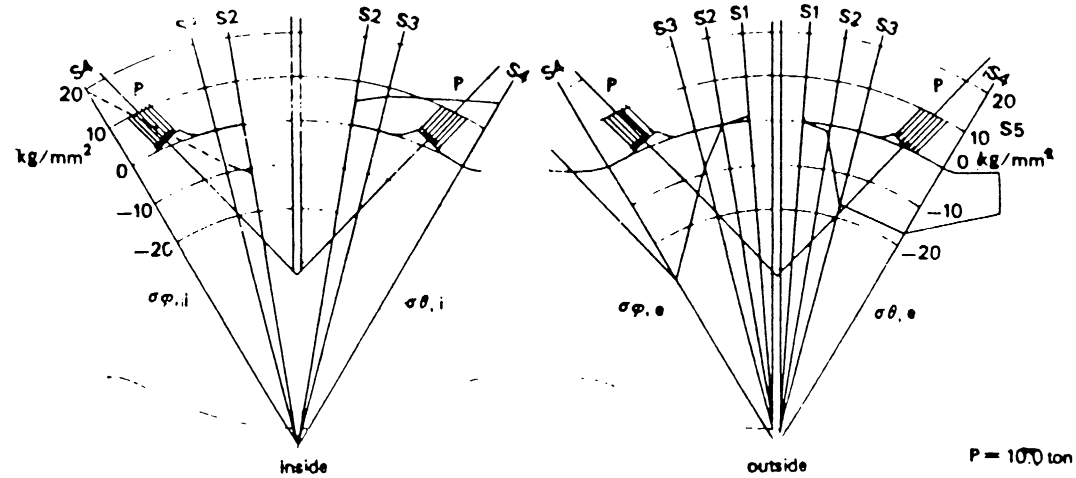

Fig. 5b. Stress distribution of spherical shell (Type II).

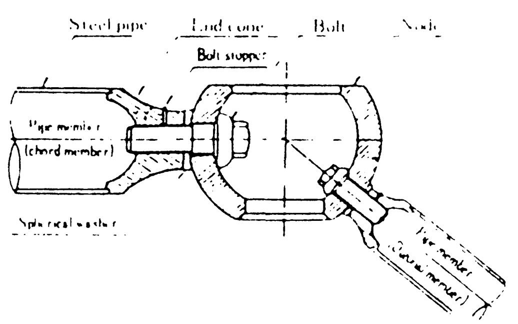

Fig. 6. Joint of NS Space Truss.

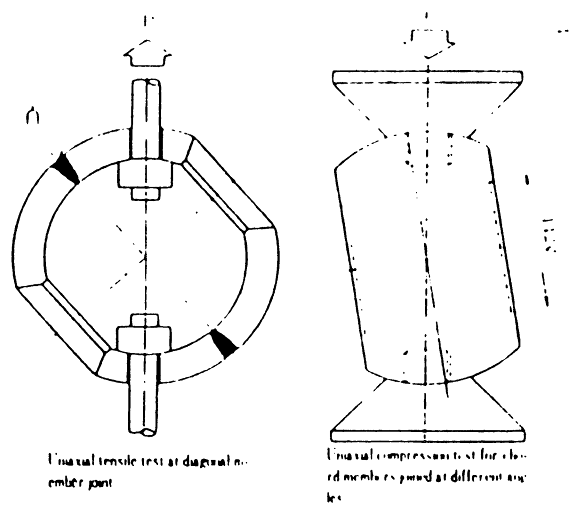

Fig. 7. Node uniaxial loading tests.

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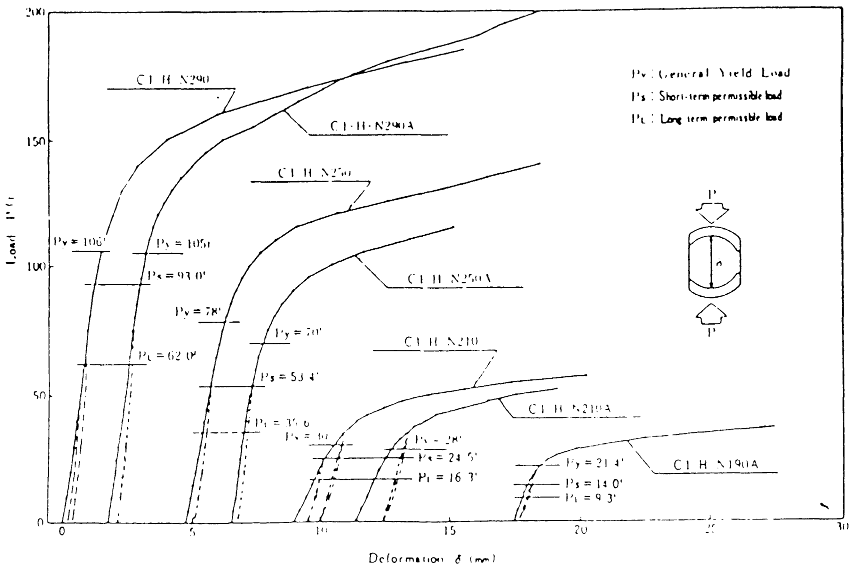

Fig. 8. Load/deformation curve for node uniaxial compression test at cord member joint.

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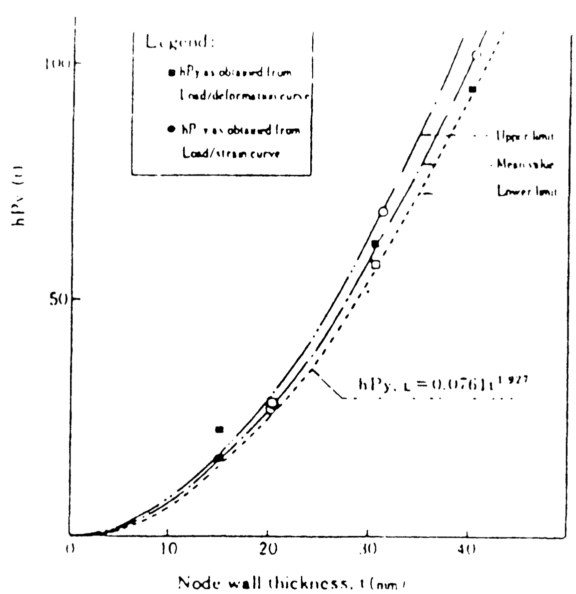

Fig. 9. Yield load, P_y *in node loading test at chord member joint.*

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