Investigation of Spherical Nodes Applied To Tubular Space Structure

Dante D.G. Sicuso

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ABSTRACT

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The material presented in this technical report covers the results of an experimental investigation aimed at determining the strength of a spherical joint which was proposed for connecting tubular members of a double-layer grid structure, designed as a flat roof construction, covering a gymnasium for the C.E.G.E.P. du Vieux Montreal.

The experimental joints were designed and fabricated in such a manner as to simulate a typical joint configuration which exist in the top and bottom layers of the structure. The joints were made from low carbon structural steel plates, shaped into two hemispheres and welded together to form a hollow sphere. In the experiment, the spherical joints were placed in a special test frame that was designed to simulate the load variation within the same plane as that of the actual structure.

The experimental investigation demonstrated a satisfactory performance of the loaded joints and resulted in test loads which were in excess of those predicted by the allowable stress method of design.

Since only a few tests were conducted, the above mentioned observations should not be considered as final conclusion on the behavior of these joints. Nevertheless, the author considers that the above results are consistent with the structural performance of these joints, particularly with respect to large plastic reserves of such structures.

ACKNOWLEDGEMENTS

Acknowledgement is made to Dominion Bridge-Sulzer Inc., Lachine, which is responsible for the supply of the space frame structure for this project without which the experimental investigation would not have been possible.

The writer also wishes to express his appreciation to:

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- his dear parents for their support and encouragement during the course of his studies.

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LIST OF SYMBOLS

Unless otherwise defined in the text, the list of the symbols used are as follows:-

A	=	Area
CSA	=	Canadian Standards Association
DCRP	=	Direct Current Reverse Polarity
DCSP	=	Direct Current Straight Polarity
Ft	=	Allowable unit stress in tension
Fy	=	Specified minimum yield point
I.D.	=	Inside Diameter of Tubular Section
ksi	=	Kips per square inch
O.D.	=	Outside Diameter of Tubular Section
P	=	Axial Load
psi	=	Pounds per square inch

CHAPTER 1

INTRODUCTION

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INTRODUCTION

1.1 General

While space structures are not new in concept, an increasing interest in them has become very noticeable during recent years. The basic objective is to obtain greater structural efficiency and potential cost saving through prefabrication and standardization of component parts. They also provide the economic answer to many design requirement such as covering large areas without using interior columns.

Many space structures have been designed and constructed using a variety of configurations and jointing methods. The most important economic consideration in the design of space frames is that of determining how the joints are to be fabricated.

There are numerous possibilities of joint details. The choice of joint or connector depends on the following considerations:

1. Types of members.

2. Sizes of members.

3. Geometric relationship of members.

4. Connection techniques such as welding, bolting or the use of special connectors.

5. Desired appearance.

6. Load capability.

A connector is the most important part of any fabricated system and the final commercial success relies directly on its effectiveness and simplicity. Several patented connectors have been developed for use in joining tubular sections, but the author has found that the premiums which have to be paid for most of these patented devices do not justify their use.

1.2 Previous Work

Many different types of connectors have been proposed for space structures, some have been used in practice, but only a few have survived the test of time. Some designers have made the mistake of trying to produce a universal connector suitable for all types of structures. As a rule, such attempts have produced connectors which have been unnecessarily complex, too sophisticated and consisting of too many parts.

Table 1.1[5] gives a list of systems dealt with in the past, including their main characteristics. This list is by no means exhaustive, but is restricted to systems for which adequate documentation can be obtained.

Table 1.1 Summary of Principal Features of Various Latticed Space Structures

	Name of System	Country	Dates of Introduction and First Employment	Materials	Sections of Members	Brief Details of Connections to Nodes
1	Mero	Germany	1940 - 1950	Steel/ Aluminium	○ □ ▯	The bars have truncated conical or pyramidal end fittings, which connect to spherical nodes by a central bolt with tightening sleeve
2	Space Deck	Great Britain	1950 - 1960	Steel	L ○ •	Lines of welded inverted pyramids. The squares of the upper layer are interconnected by bolts. The tubular sections of the lower layer are connected to the apices of the pyramids by sleeves with left-and right-hand threads
3	Triodetic	Canada	1950 - 1960	Aluminium/ Steel	○]	The ends of the bars, flattened and serrated, are driven into matching slots in the cylindrical nodes
4	Unistrut	U.S.A.	1950 - 1960	Steel	[[	Pressed-steel connectors with holes for bolting ends of bars
5	Oktaplatte	Germany	1950 - 1960	Steel	○	Hollow steel spheres and tubular sections are connected by fillet welds
6	Unibat	France/ Great Britain	1960 - 1970	Steel	I ○	Lines of inverted pyramids interconnecting by corners. Lower layer in tubular sections
7	Nodus	Great Britain	1960 - 1970	Steel	○ □ ▯	Nodes consisting of two hemispheric shells, with slots to take the bars

On close examination of the table, the reader will observe the following: -

a) A large proportion of these three-dimensional or space structures was designed and built before 1960, prior to the advent of electronic computers in design offices - a rather surprising fact.

b) Steel is the material most commonly used. Aluminum has been included as a standard material under the "Triodetic" system, while for the "Mero" system, steel is preferred although aluminum is not ruled out.

c) Nearly all available steel sections have been considered for fabricating the components of space frames, but the tubular section is mostly used.

The documentation on the above systems gives little information about how the components of the connectors are fabricated. This is understandable since in spite of the protection by patents most fabricators hold the view that when their initial patents expire they may yet be granted long term protection by virtue of their improved methods of fabrication. Nevertheless the reader will notice in Figures 1.1[5] to 1.6[5] inclusive, the relative size of the nodes and the desire to maintain some degree of simplicity in the joint details of the space truss members.

Figure 1.1 Mero Node

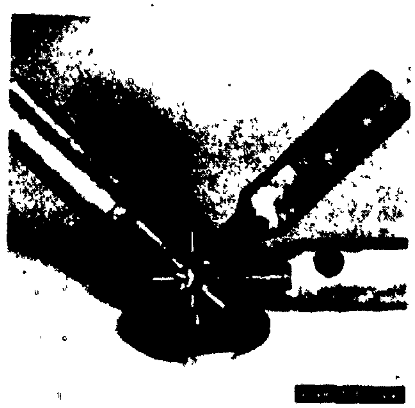

Figure 1.2 Section of Mero Node

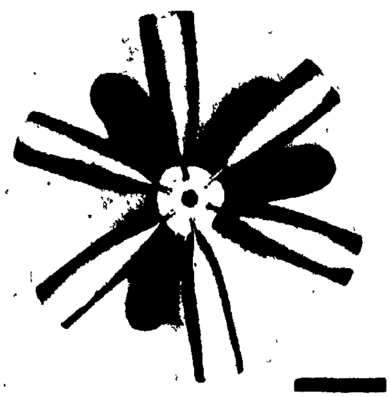

Figure 1.3 Trodetic Node

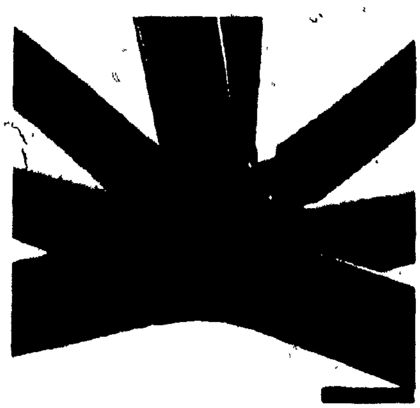

Figure 1.4 Nodus Node

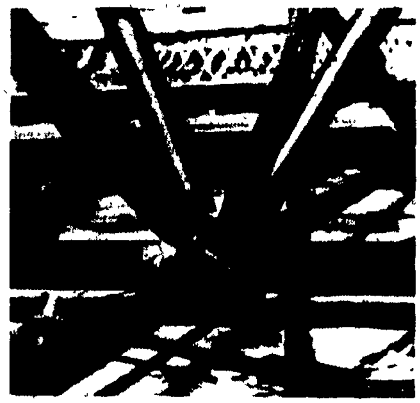

Figure 1.5 Oktaplatte Node

Figure 1.6 Oktaplatte Nodes and Diaphragm

1.3 Scope

For the space frame structure described in this paper, a direct connection between the tubular sections by using a hollow sphere was decided to be the best solution. This concept taken after the German "Oktaplatte" system, shown in Figure 1.5, was introduced to the market by the Mannessmann company, after acquiring the patent rights from H. König. The main element of this system is a hollow sphere made by welding together two semi-spherical shells, reinforced by a diaphragm sandwiched between them, as illustrated in Figure 1.6. The only difference with the nodes used for this project is that the hollow spheres were manufactured without a diaphragm.

The objective of the investigation described in this report was to: -

(1) determine the behavior of a hollow spherical node under different load combinations and to ascertain whether the joint test results would substantiate the actual design loads;

(2) verify the plate thickness required for each semi-spherical shells;

(3) provide design aids for designers and engineers.

CHAPTER 2

FLAT ROOF OF TUBULAR SPACE STRUCTURE

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FLAT ROOF OF TUBULAR SPACE STRUCTURE

2.1 Introduction

A space structure may be defined as a three-dimensional assembly of elements resisting loads which can be applied at any point, inclined at any angle to the surface of the structure and acting in any direction. There are many types of space structures. These take the general form of simple monolithic grid, double layer grid, and coplanar system (folded or curved structures).

The historical development of grids has been well documented by Makowski[8]. When lattice construction is used to obtain a flat surface, the familiar terminology to describe the structure is a grid. A grid framework can be described as a continuous monolithic plane system usually symmetrically tied together by a series of longitudinal and transverse members to resist all applied forces acting normal to the system's plane.

Since the load in a grid system is carried by bending, the bending stiffness is increased most efficiently by going to a double-layer system. In these systems the ends of the members are usually considered pinned so that a large three-dimensional space truss results. These three-dimensional planar systems are designed in many geometric patterns and have many names describing them.

2.2 Description of Structure

The space frame outlined in this paper is essentially a series of three-dimensional trusses in the form of a double-layer grid system. The height of the double-layer grids (i.e. the distance between the top and bottom layers) is 8 ft. The roof system is a staggered panel point space truss formed by offsetting the top and bottom chords by half a module in plan. The triangular grid on the top and bottom layers is formed of modular isosceles triangles 7 ft. 10 1/2 in. high with a base of 10 ft. 6 in. The joints of the top and bottom chords of each trusses are interconnected by diagonal bracings with such a distribution that the result is a series of irregular tetrahedra repeated close to each other. The reader will notice, with the help of the key diagram in Figure 2.1, the grid arrangement of members in Figure 2.2.

Designed as a flat roof structure, it consists of 3643 round Hollow Structural Sections (HSS) and 783 spherical joints to cover an area of 27,800 square feet. Measuring 135 ft. 8 in. by 204 ft. 9 in. with no internal columns, the structure weighs 171 tons or 12.3 pounds per square foot and has a 8 in. camber in the short span direction, as illustrated in Figures 2.3 and 2.4. The perimeter of the space frame was enclosed by a welded facia frame measuring 5 ft. 5 in. in width by 27 ft. high, as shown in Figure 2.5. The structural roofing is provided by 3 in. 22 ga. galvanized acoustic deck.

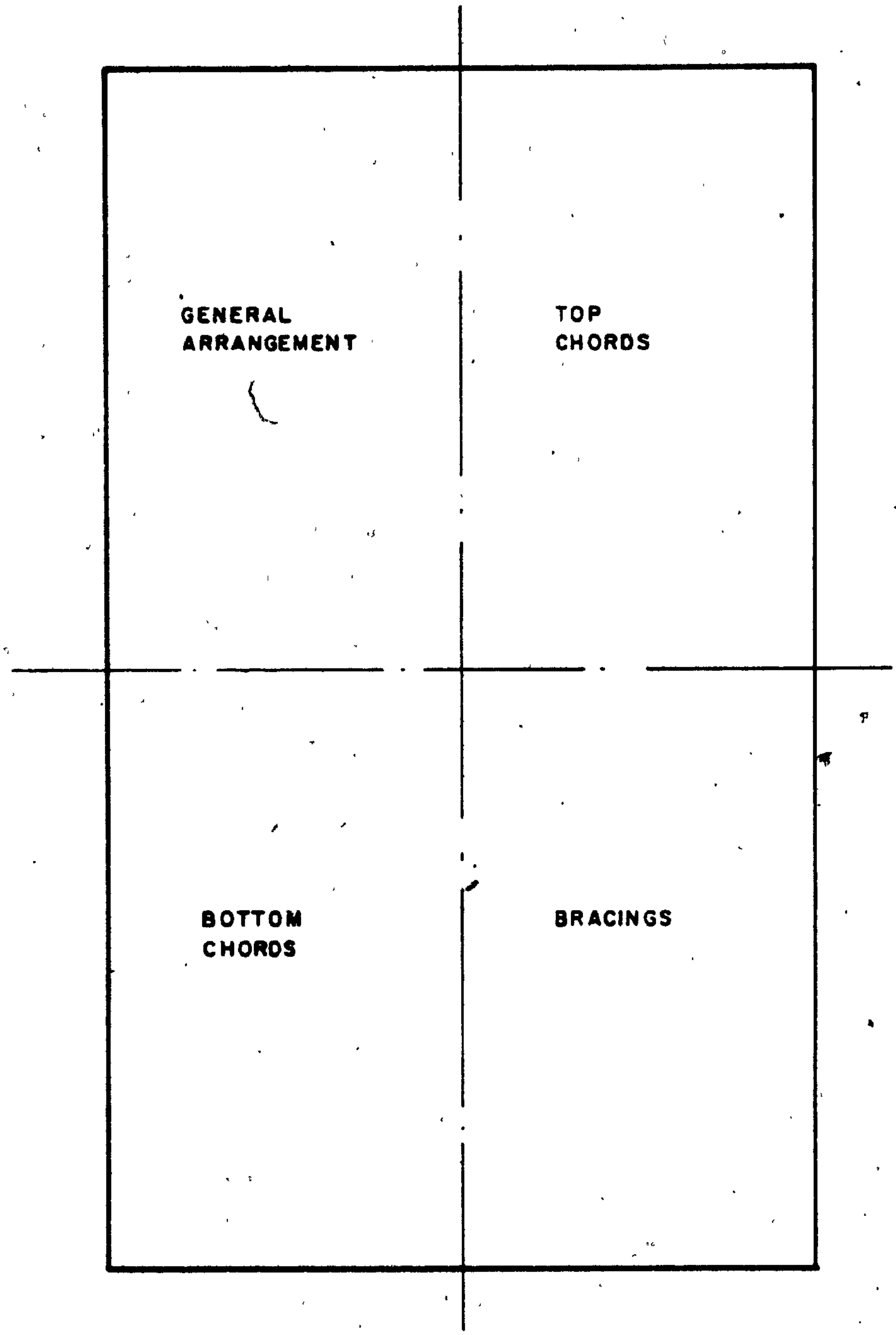
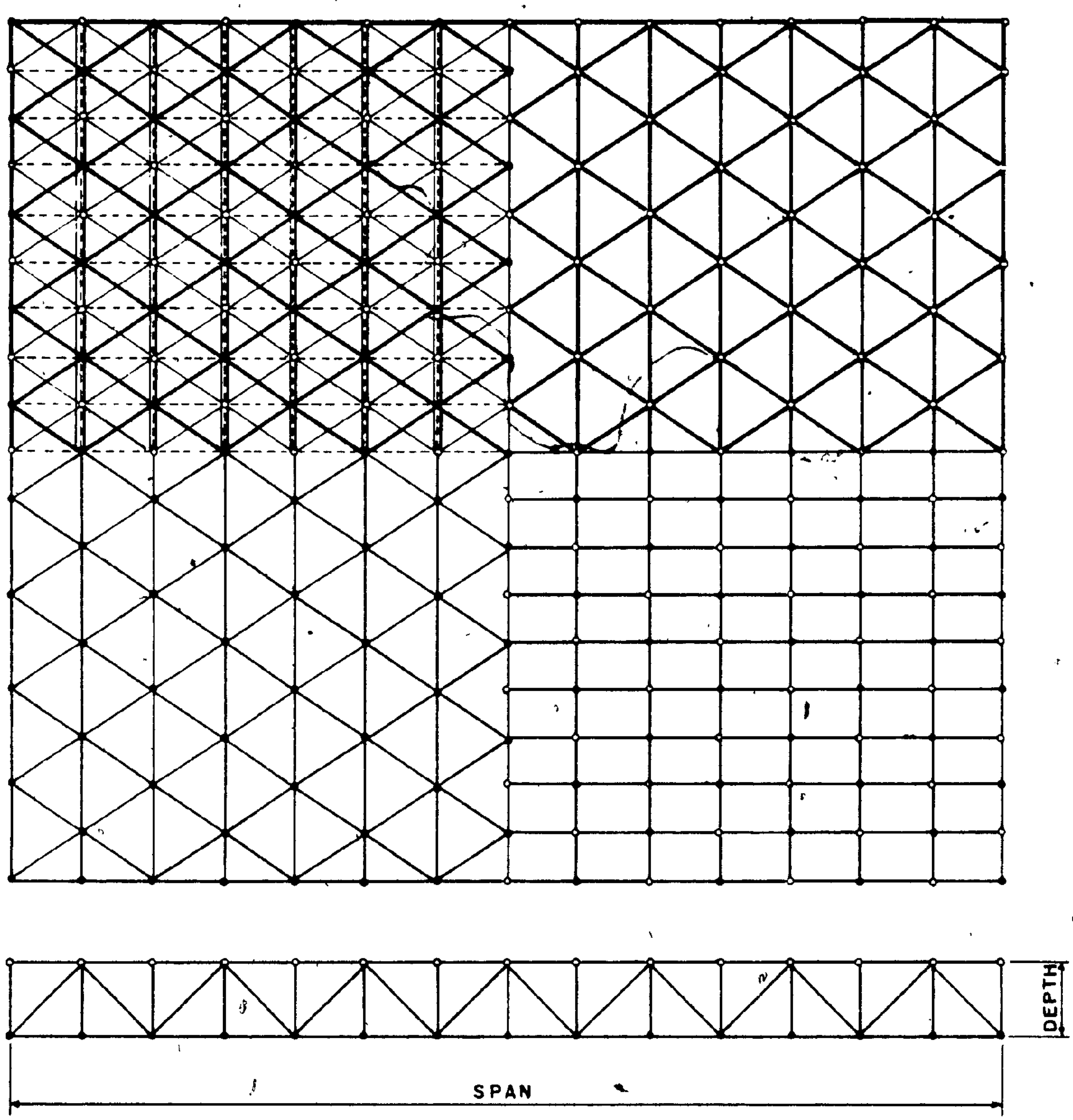


Figure 2.1 Key Diagram



EDGE ELEVATION

Figure 2.2 Grid Arrangement of Members

Figure 2.3 View of Space Frame Partially Erected

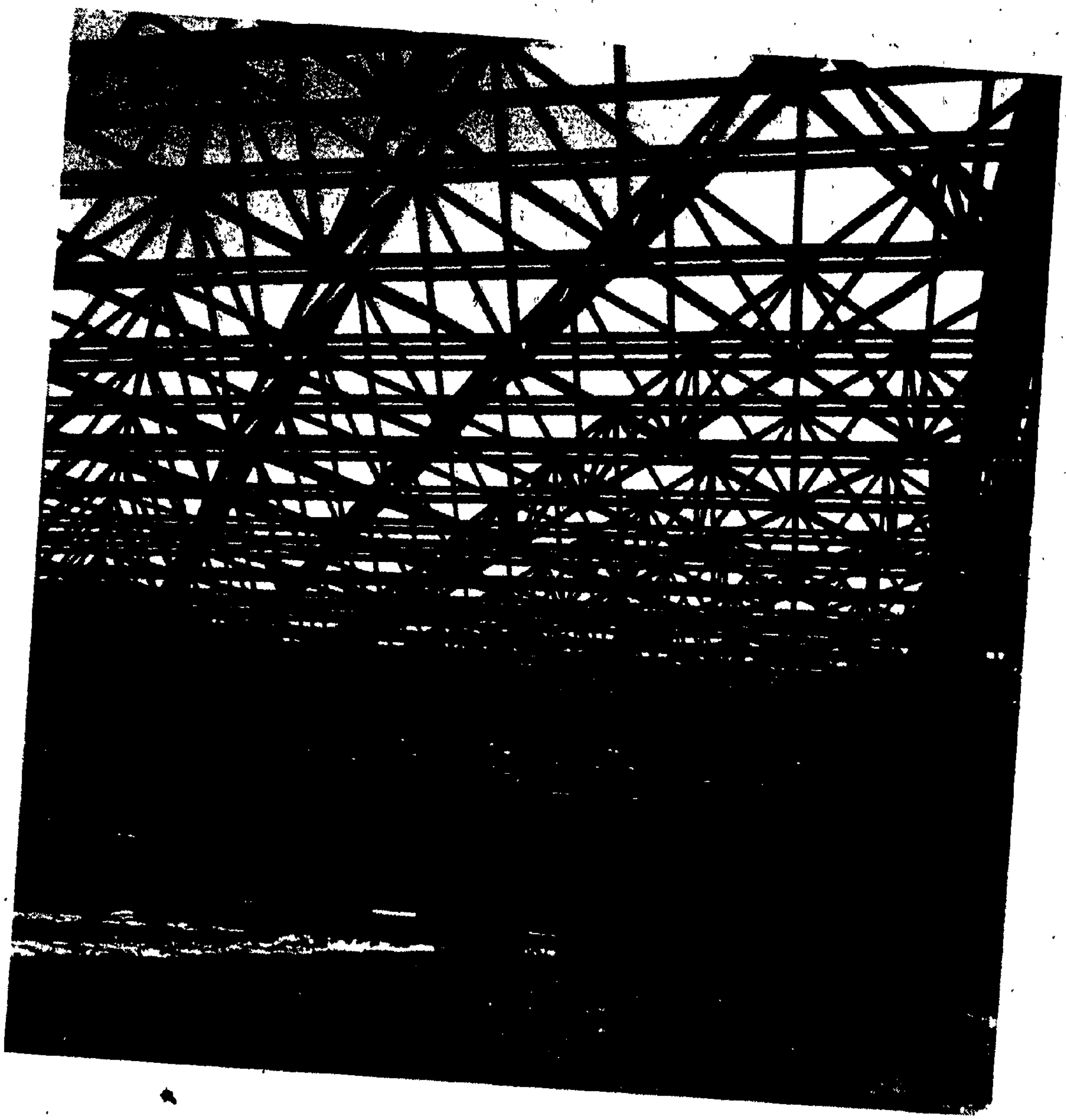


Figure 2.4 View of Erected Space Frame

Figure 2.5 View of Facia Frame

2.2.1 Nature of Members

As in the case of a plane truss, loads from the roof deck and suspended elements are transferred to the upper joints by means of continuous roof purlins, 4I7.7 spaced 7 ft. 10 1/2 in. on centres, welded on top of the spheres.

The connections between the nodes were affected by means of Hollow Structural Sections (HSS) of variable diameters and wall thicknesses, as shown in Table 2.1. The tubular sections for the top chord ranged between 5 9/16" O.D. X 0.3750" and 0.?580" wall thickness for the longitudinal members and 4 1/2" O.D. X 0.3125" and 0.1875" wall thickness for the diagonal members. The bottom chord members ranged between 4 1/2" O.D. X 0.3125" and 0.1875" wall thickness for the longitudinal members and 4 1/2" O.D. X 0.1875" wall thickness for the diagonal members. The diagonal members between the top and bottom grid interconnecting the joints of the top and bottom chords was 3 1/2" O.D. X 0.1875" and 2 3/8" O.D. X 0.1875" wall thickness was used for the truss vertical web members on the periphery. The top and bottom nodes at the ends of each truss were tied transversely parallel to the grid and perpendicular to the trusses with a 2 3/8" O.D. X 0.1875" wall thickness.

The material employed was Grade 50 conforming to CSA Standard G40.17-1969 "Cold-Formed Welded or Seamless Hollow Structural Section" for the 5 9/16" O.D. and to CSA Standard G40.16-1969 "Hot-Formed Welded or Seamless Hollow Structural Section" for the remainder. The HSS

TABLE 2.1 DESIGNATION OF TUBULAR MEMBERS

Members	Longitudinal		Diagonals	
	Actual O.D. (in.)	Wall Thickness (in.)	Actual O.D. (in.)	Wall Thickness (in.)
Top Chord	5 9/16	0.2580	4 1/2	0.1875
		0.3750		0.3125
Bottom Chord	4 1/2	0.1875	4 1/2	0.1875
		0.3125		
Bracing			3 1/2	0.1875
				0.3125
Transverse Ties			2 3/8	0.1875

supplied by "Stelco" are now produced in Class H - Grade 50 conforming to CSA Standard G40.20-M which are stress relieved. Residual stresses in the Class H product are relatively small and give superior structural performance. The largest section used was capable of resisting a maximum compressive axial load of 130 kips.

2.2.2 Joint and Support Detail

Theoretically the members should have spherical (ball-and-sockets) hinges at their ends - a most difficult condition to realize in practice.

Of all things which affect the joint details the most important is that of appearance and therefore the best detail is usually the one which has the best appearance. In general, welded joints which do not use connection devices seem to best satisfy the requirement of appearance.

The geometric relationship between members played an important role in the selection of the diameter of the spherical node. In addition the selection required special study of angles of intersection and accessibility for welding. To accommodate the framing of ten tubular members (six on the horizontal grid plane and four diagonals between the top and bottom grid) of different diameters framing at a joint, a 12 in. diameter hollow sphere was used at all the nodes. A typical bottom chord joint is shown in Figure 2.6. The spheres were fabricated from CSA G40.12 material having a yield of 44 ksi. (Now replaced by CSA G40.21-44W or G40.21M-300W metric version).

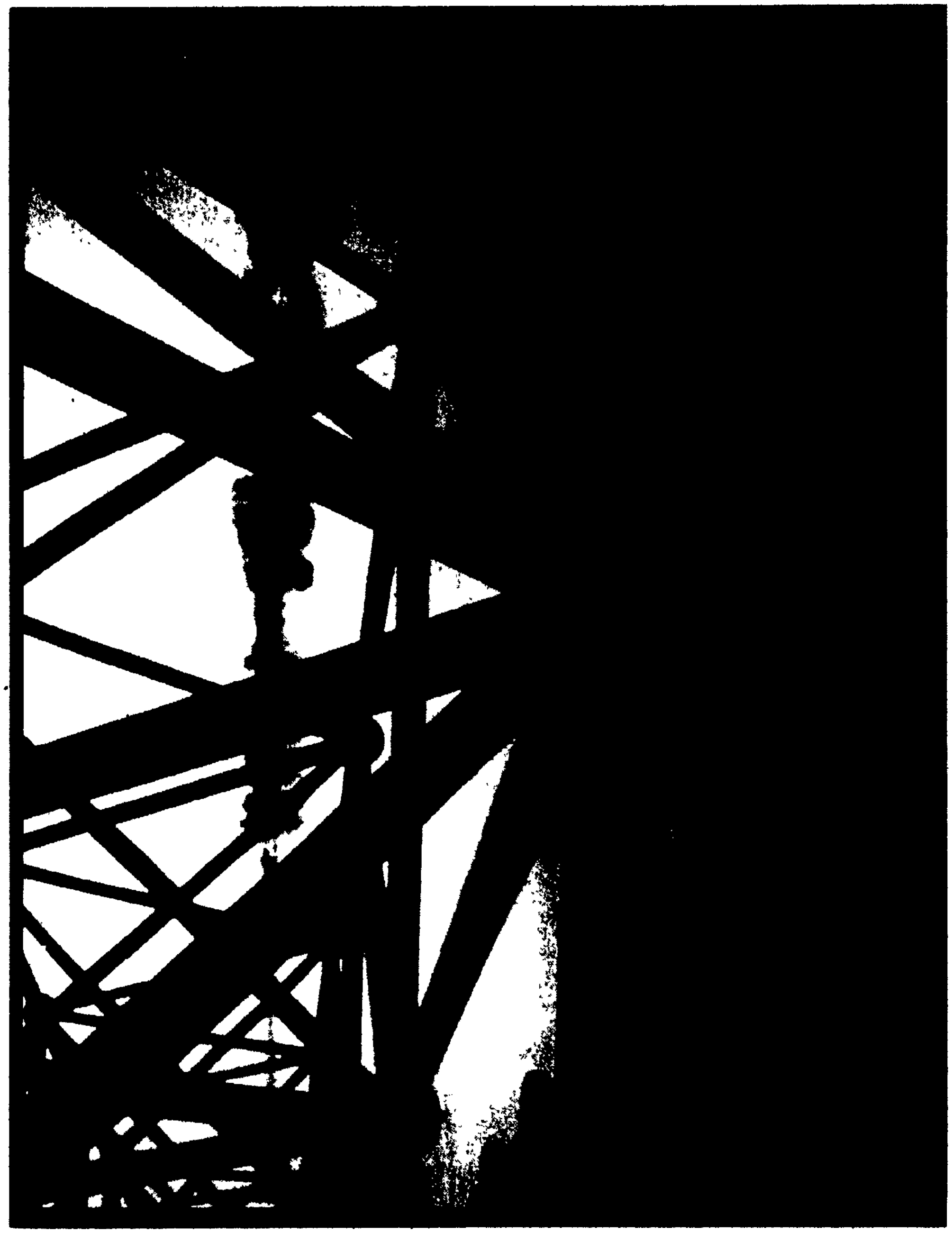


Figure 2.6 Typical Bottom Chord Joint

The number and location of supports used is principally a function of the plan requirements and the stress levels in the members as determined from the analysis of the structure. The support system consisted of a total of 78 steel base plates embedded in a peripheral concrete wall foundation to receive the load by means steel-reinforced elastomeric bearing pads (Grade 50, durometer), as shown in Figure 2.7. The supports at the four corners of the space frame where fixed bearing type to resist expected lateral, longitudinal and uplift forces; these supports did not have any elastomeric pads, as shown in Figure 2.8. The remainder of the supports supplied at each node on the foundation were expansion bearing type, free to move only in the direction perpendicular to the peripheral foundation wall.

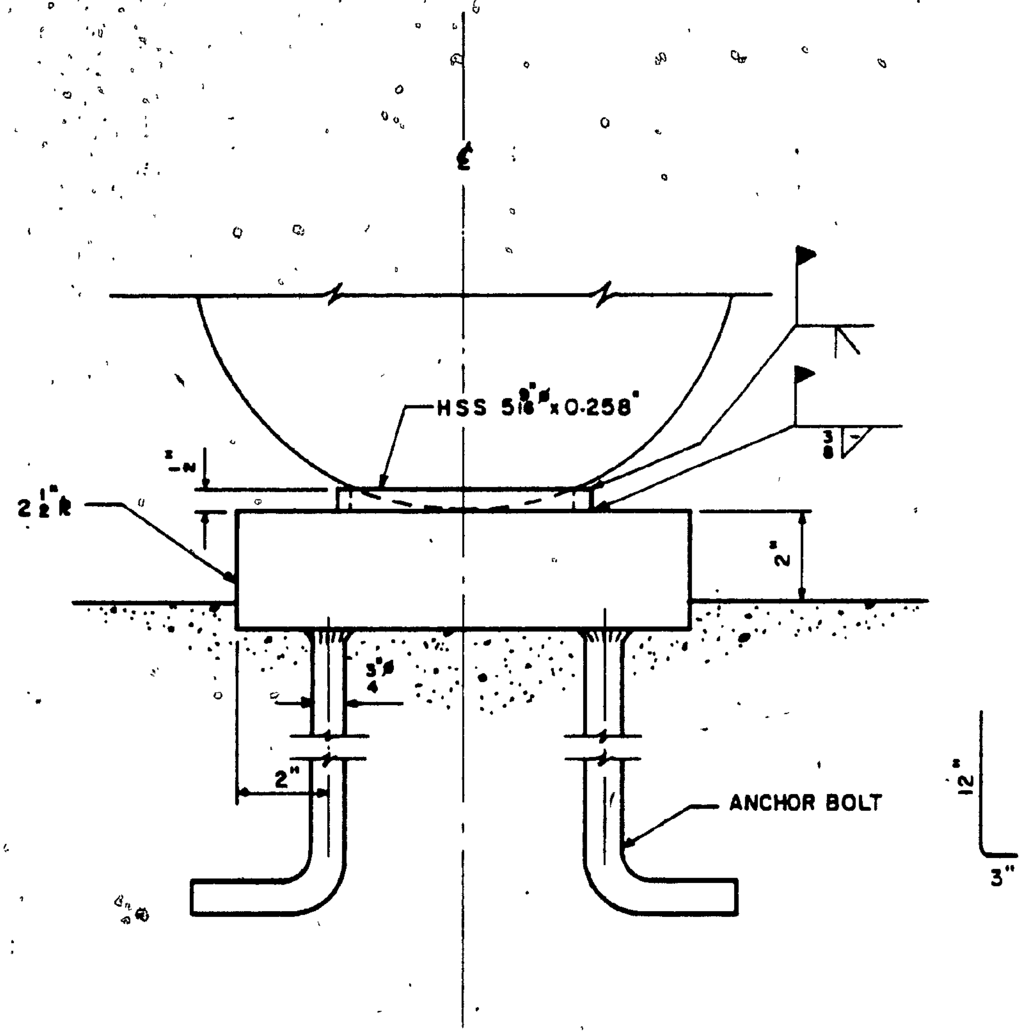


Figure 2.7 Fixed Bearing

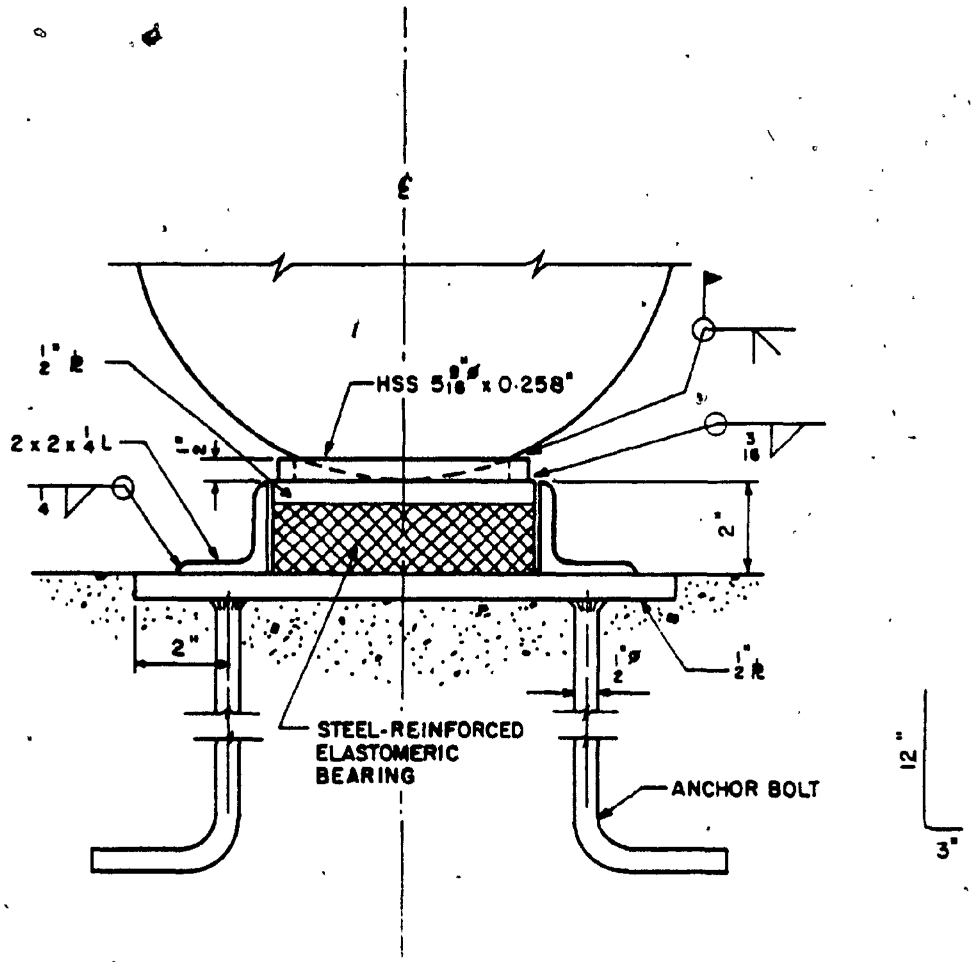


Figure 2.8 Expansion Bearing

CHAPTER 3

FABRICATION OF HOLLOW SPHERICAL NODES

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FABRICATION OF HOLLOW SPHERICAL NODES

3.1 Introduction

With the tubular members welded concentrically to the nodes, their center-lines are directed to the center of the sphere, whatever the angle of entry. The behaviours of such a joint is complex. First, such a joint exhibits plastic as well as elastic deformations under service loads. Secondly, the considerable number of members meeting at a joint generates rather complex tri-axial stresses in the spheres. Thirdly, the effects of the magnitude and distribution of the residual stresses, produced from subsequent fabrication operations such as flame cutting of plates, cold forming and welding, are too complex to evaluate by direct measurement. Fourthly, there are multiple ways in which the joint can fail. Hence, the theoretical determination of the spherical joint strength, even under static loading conditions, is most difficult.

As no rational procedure for selecting the plate thickness of such spheres was available, it was decided that the wall thickness (T) should be at least 5% of the outer diameter (D) of the sphere. The decision, although somewhat arbitrary, was influenced by published test results for connecting round members to round members using Hollow Structural Sections[6], as shown in Figures 3.1 and 3.2.

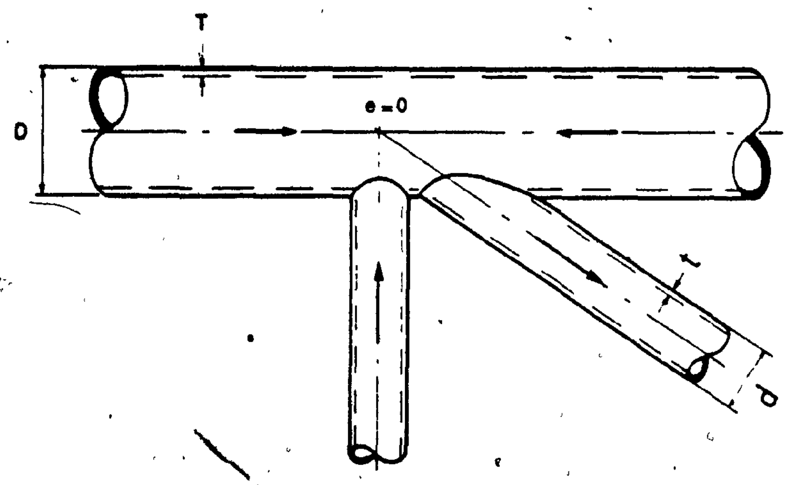


Figure 3.1 Round Web Members to Round Chord Members

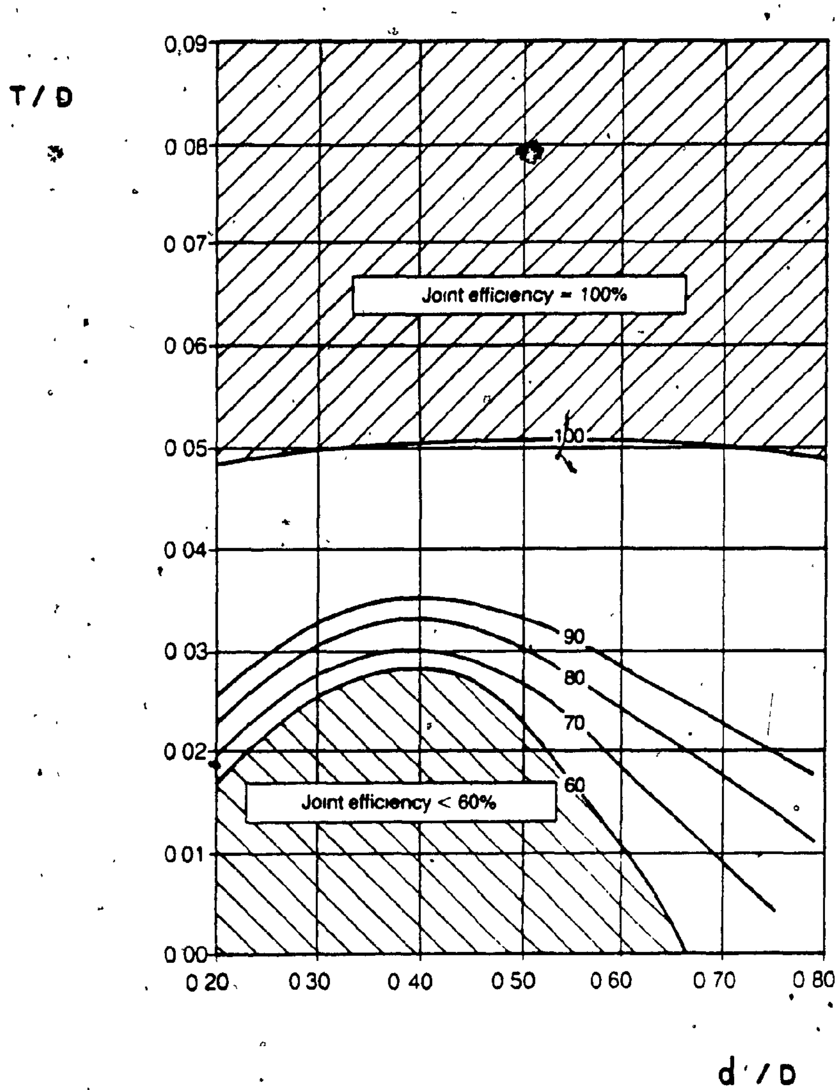


Figure 3.2 Joint Efficiency Values for Zero Eccentricity

Therefore, for a sphere having a diameter 12 in. O.D. (i.e. D = 12).

$$T = 0.05\ D$$
$$= 0.05 \times 12$$
$$= 0.60"$$

The other noteworthy observation from the results represented in the chart in Figure 3.2 is that for top and bottom grid chord members having 4 1/2" O.D. and 5 9/16" O.D. the values of d/D are given as:

For 4 1/2" O.D. HSS

$$\frac{d}{D} = \frac{4.5}{12} = 0.375$$

For 5 9/16" O.D. HSS

$$\frac{d}{D} = \frac{5.5625}{12} = 0.46$$

and for the plate thickness T = 0.50" the value of

$$\frac{T}{D} = \frac{0.50}{12} = 0.042$$

the joint efficiency would be 95%. This was considered contingent on the stress level in the tubular member.

To verify the adequacy of this arbitrary criterion for a sphere, axial load tests were performed on 1/2" and 5/8" nominal wall thickness sphere specimens and the results will be presented in Chapter 4.

3.2 Fabrication of Semispherical Shells

In the initial stage of the project, the use of cast steel hemispherical shells was pursued but none were available. It was then necessary to employ two hemispheres made from steel plates (blanks) and shaped by the spinning process. The blanks made from a 17" O.D. X 1/2" plate with a 15/16" diameter hole in the center of the plate, as shown in Figure 3.3, were all subjected to ultrasonic examination to detect any possible inclusions that would reduce the ductility in the through-thickness direction of the plate which could have resulted in local separation or lamellar tearing of the steel.

The spinning operation was carried out by rotating a blank on a rigid lathe fitted with a driving head-stock which was also utilized as a mandrel having the shape of the hemisphere, tail spindle and a roller forming tool. The blank was held in position by fixtures as it rotated and the material was formed by applying a steady pressure with the roller forming tool. The spinning started from the center of the blank, working towards the edge. Power spinning was employed for the 1/2" thick

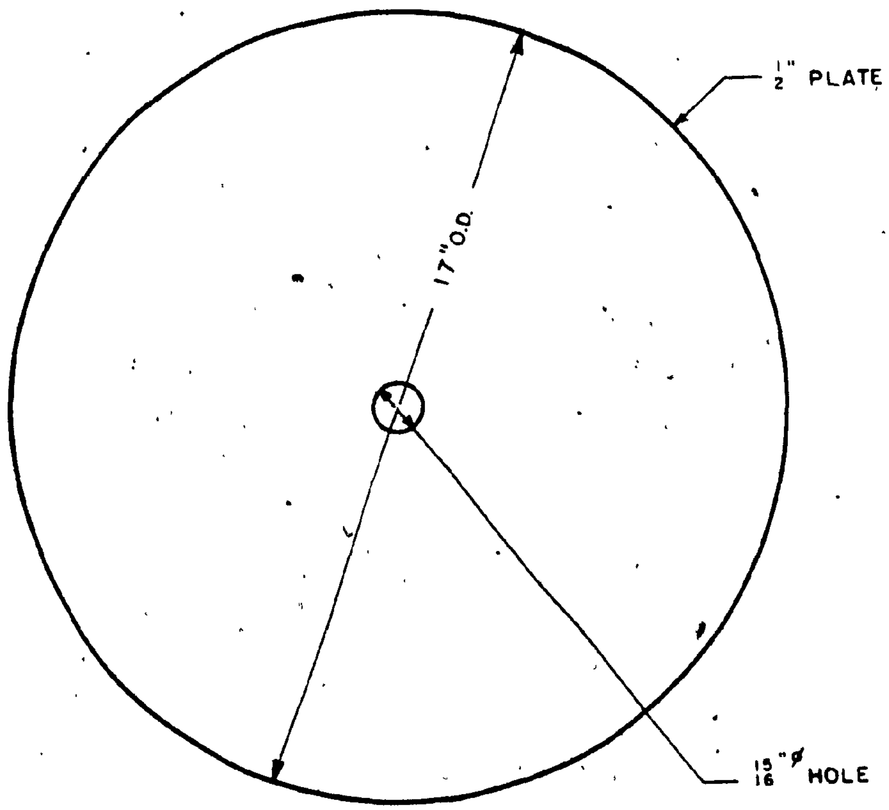


Figure 3.3 Blank for Forming Hemispheres

plate thus reducing the wall thickness of the metal at the edge of the hemisphere. This reduction in the thickness of the metal was acceptable based on the results obtained from the axial tests on the joint, provided the reduction in plate thickness did not exceed 1/8". The results in plate reduction for the 1/2" thick plate are represented in the graph of Figure 3.4.

The hemispheres were completed with a prepared 22°30" machined feather edge. They were trial assembled with a backing ring so as to ensure that a gap of 3/32" or less between the hemisphere I.D. and the backing ring be obtained, as shown in Figure 3.5 and as illustrated in Figure 3.6, and also to verify that the outside diameter tolerance of ± 1/16" was achieved.

3.3 Welding of Spherical Nodes

3.3.1 Welding process

Perhaps the most frequent criticism of welding is its cost. The cost of welding can be represented by:

$$C = \frac{L}{R} + X$$

Where C = cost of completed joint - \$/ft

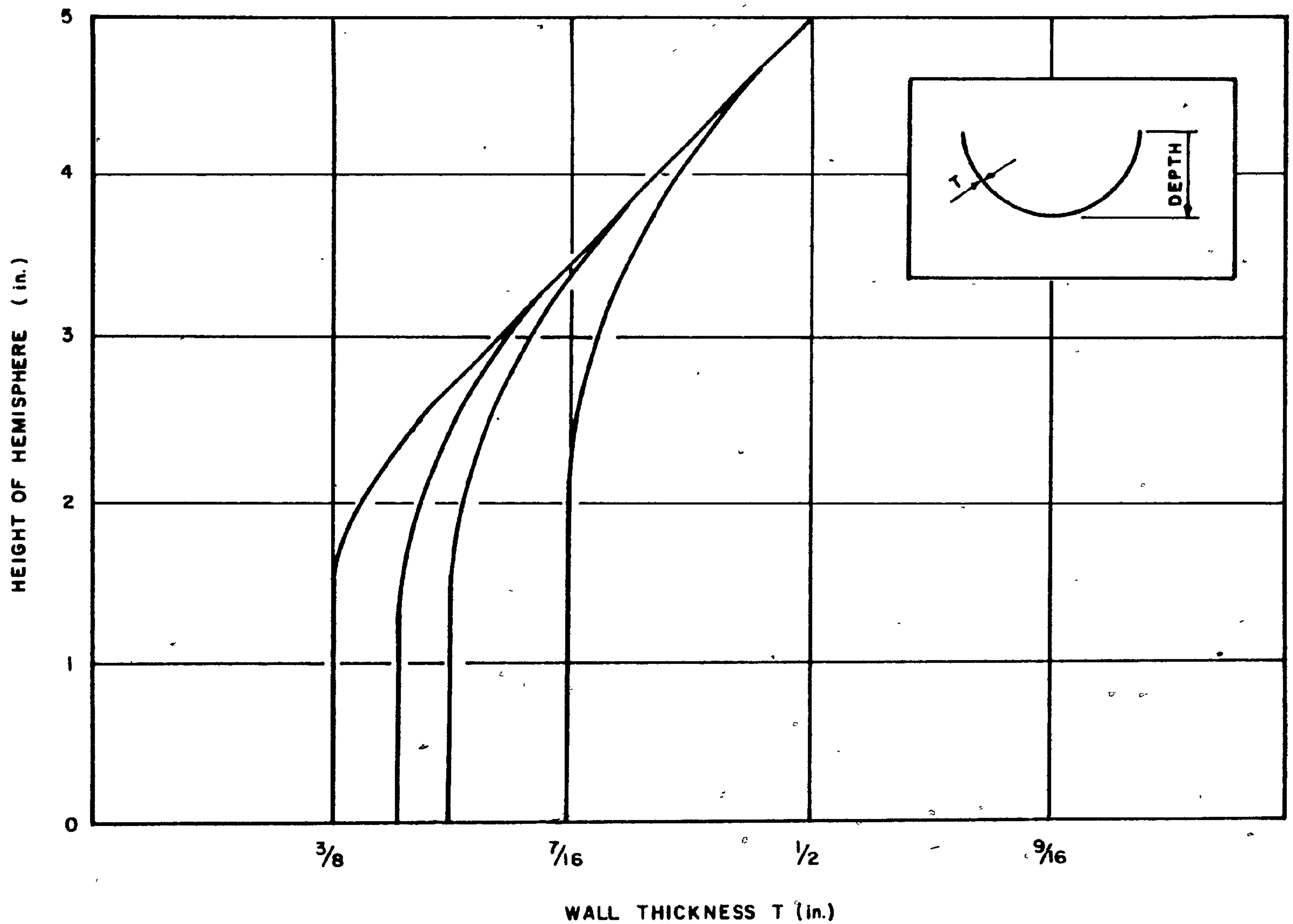


Figure 3.4 Relationship Between Wall Thickness and Height of Hemisphere

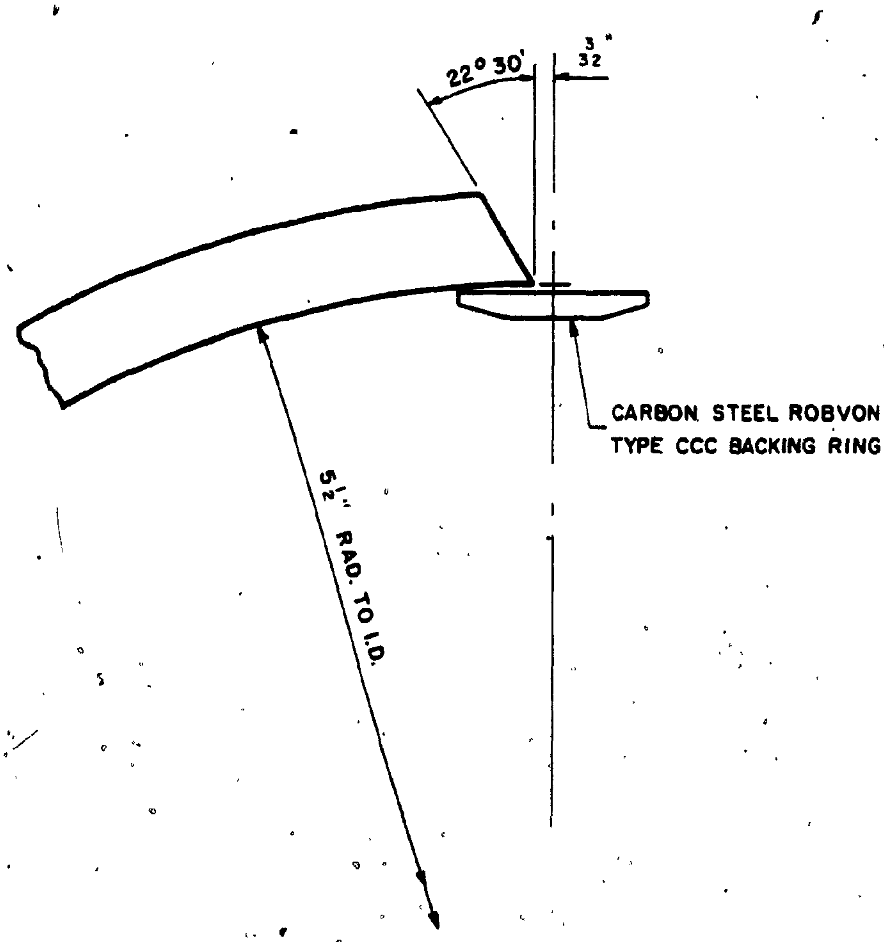


Figure 3.5 Prepared Edge Configuration of Hemisphere

Figure 3.6 Hemisphere with Backing Ring

L = cost of labor - $/ft

R = rate of joint completion - ft/hour

X = cost of consumable - $/ft.

and the rate of joint completion is a function of weld metal depositing rate, the volume of weld metal in the joint and the duty cycle of the welding process.

The depositing rate of the welding process is the rate at which metal can be deposited into the joint and excludes metal losses between the electrodes and the joint due to spatter.

Duty cycle is defined as the ratio of arcing time to paid time, or the percentage of time that a welder is actually welding, as distinct from cleaning and deslagging and adjusting equipment. There are a number of factors which can influence the duty cycle, but the single most significant factor is the degree of mechanization of the welding process. Hence, the welding process used for welding the spherical nodes were submerged arc and gas metal-arc welding as defined below:

The "submerged arc welding" process is essentially an automatic welding process in which the electrode is a bare wire fed from a coil to the point of welding by means of power driven rolls. Shielding is provided by feeding a granular fusible material, called flux, to the point of welding. The flux envelops the arc and the molten weld, protecting it from the atmosphere. In addition, part of this flux material is melted and converted into a slag which floats on top of the weld and gives further protection to the weld. This process is illustrated in Figures 3.7 and 3.8.

The "gas metal-arc welding" process is generally a semi-mechanized system, whereby the electrode consists of a coil of solid bare wire automatically fed through a hollow flexible cable to the gun and regulated in the joint. The wire is protected with an external gas shield. The process is semi-automatic when the gun is guided manually, as shown in Figure 3.9, and there is no slag to remove.

3.3.2 Splice Welding of Spheres

Prior to start of mass-production experimental weld tests were performed to determine the feasibility of fabricating steel spheres employing backing rings. The objective was to minimize welding costs and maximize production by fabricating a single repetitive spherical node.

The base material used for the test was four (4) pieces of HSS 12 3/4" O.D. X 11 3/4" I.D. X 1/2" wall thickness X 6" long, conforming to CSA G40.17 having a yield of 50 ksi. Each ends of the tubular section were prepared by machining a feather edge, as shown in Figure 3.10, to provide the weld joint configuration, as shown in Figure 3.11. The steel backing is a carbon steel Robvon type CCC backing rings supplied to fit a nominal round section of 12".

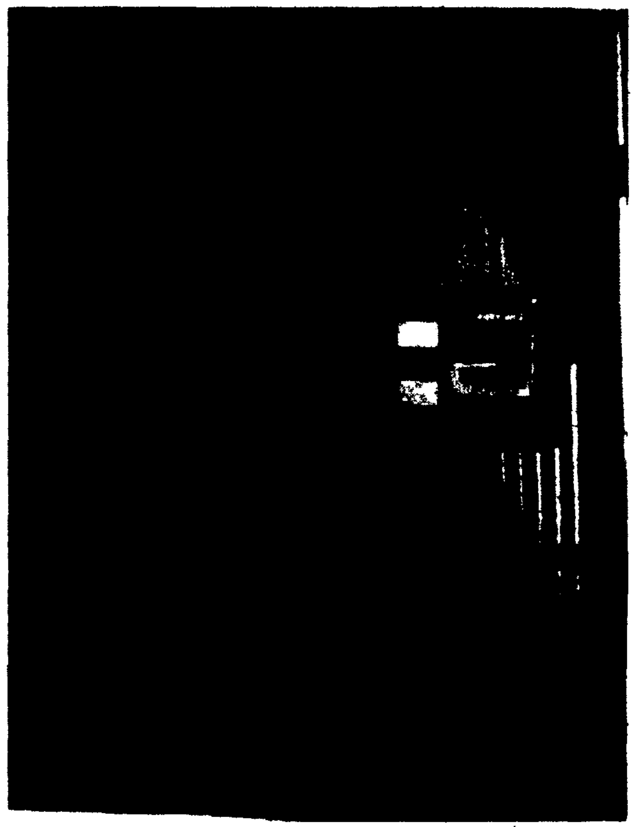


Figure 3.7 Submerged Arc Process for Welding of Spheres

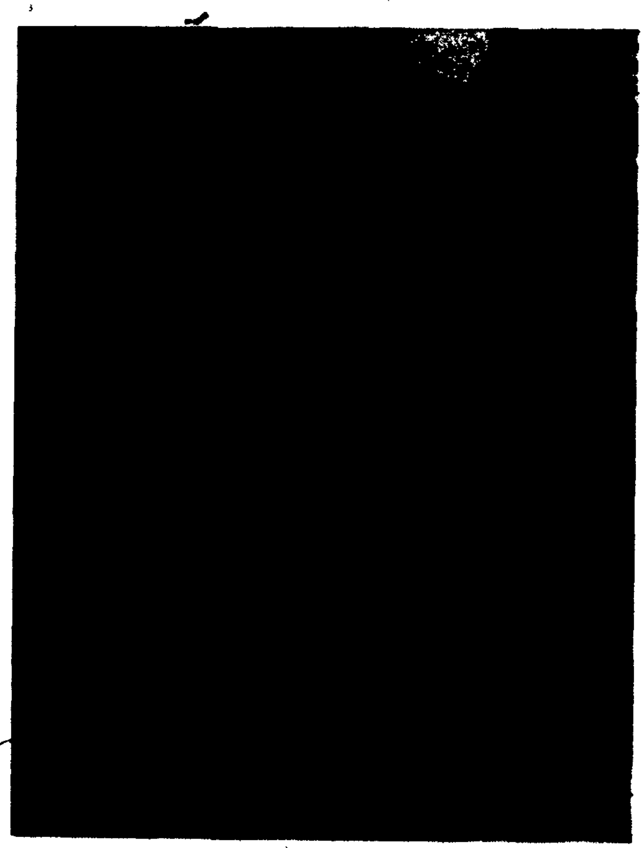


Figure 3.8 Close-Up View of Submerged Arc Welding Process

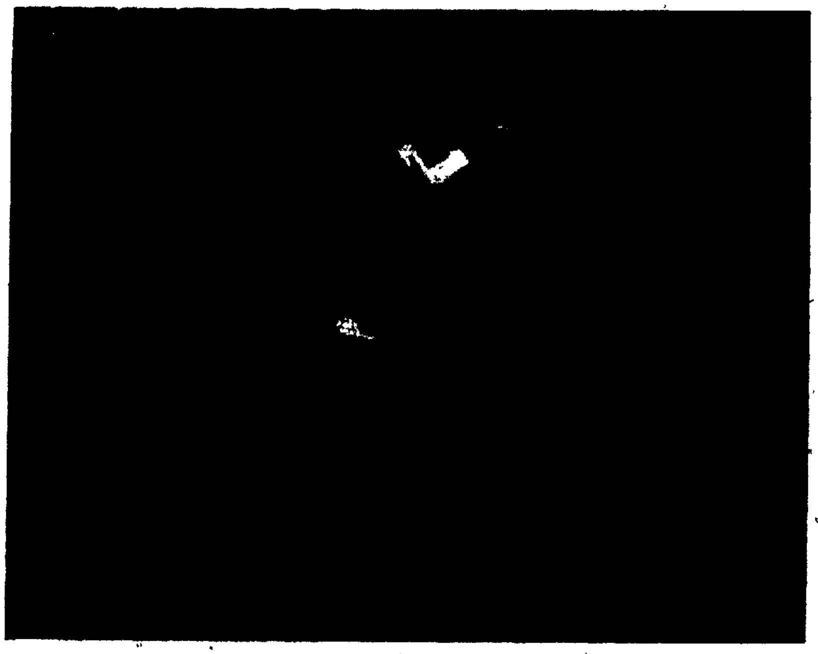


Figure 3.9 Gas Metal-Arc Welding Process

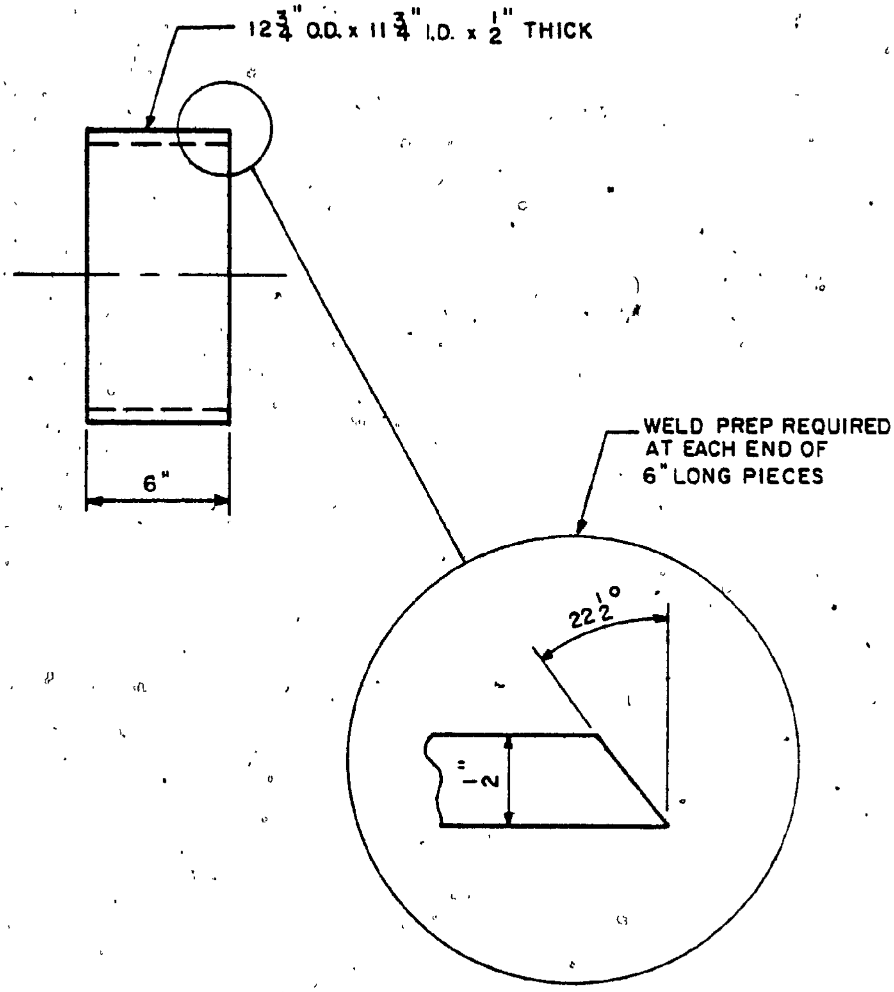


Figure 3.10 Preparation of Tubular Section for Weld Test

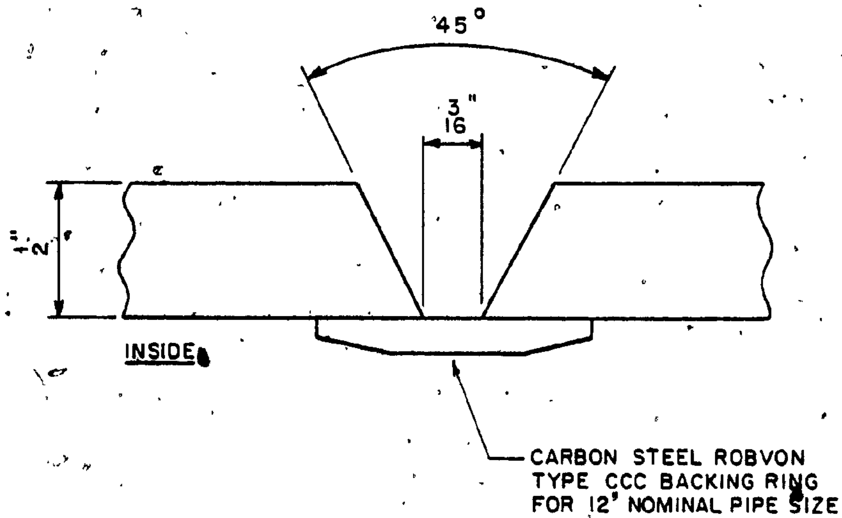


Figure 3.11 Joint Configuration for Weld Test

The splice welding was carried out by submerged arc welding process using the following welding equipment, consumables and current: -

A Lincoln SA 800 power source with a Linde UCC3 welding machine using a 3/32" diameter Lincoln L61/880 wire/flux combination conforming to CSA Standard W48.6 and DCSP current.

The welding time per tubular joint can be divided into three (3) categories which are as follows:

(a) Set-up time - i.e. fitting and cutting of backing ring to size, tack welding and set-up in positioner - 7 minutes.

(b) Three (3) passes were required to complete the weld. See Data Sheet D1, as shown in Table 3.1, for the welding sequence and parameters.

1st Pass -	welding time was	3 min. 40 sec.
2nd Pass -	welding time was	3 min. 15 sec.
3rd Pass -	welding time was	2 min. 58 sec.
Total Welding Time was		9 min. 53 sec.

(c). Miscellaneous time required e.g. cleaning rings and weld joint and removal of flux - 13 minutes.

Table 3.1 Welding Data Sheet for Weld Test

DS DONNÉES DE SOUDAGE / WELDING DATA

Procédé / Process	N° feuille de données / Data sheet no.	N° spécification de soudage / Welding spec'n no.
SUBMERGED ARC	D1	SS WS DMS PQR

Spec du métal de base / Material spec.: CSA-G40.17 Gr. 50

Position: 1G (flat)

Temp. de préchauffage / Preheat temp.: NIL

Temp. d'interpasse / Interpass temp.: NIL

Traitement de la racine / Root treatment: Robvon Type ccc Backing Ring

Métal d'apport - Filler metal

Nom commercial / Trade name: Lincoln L61 - EM12K

Flux

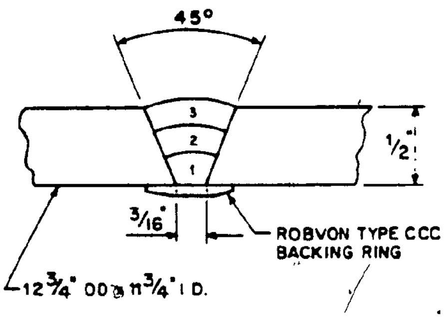
Nom commercial et taille des granules / Trade name and particle size: Lincoln 880-F62

Gaz - Gas

Gaz de protection / Shielding gas: À / AT PCH / CFH

Gaz de traînard / Trailing gas: À / AT PCH / CFH

Gaz de soutien / Backing gas: À / AT PCH / CFH



CROQUIS DU JOINT / JOINT GEOMETRY

T	Côté / Side	Couche / Layer	Passe / Pass	Amps ± 10%	Vitesse du fil R.P.M. / Wire feed speed I.P.M.	Volts ± 7%	Vitesse d'avancement P.P.M. / Travel speed I.P.M. ± 10%	Électrode Dia	Électrode Type	Électrode DTCP / ESO	Électrode Polarité / Polarity
½"	1	1	1	320	-	31	10.5	3/32"	L61	1-1½"	DCSP
		2	2	360	-	41	11.8	3/32"	L61	1-1½"	DCSP
		3	3	360	-	41	12.8	3/32"	L61	1-1½"	DCSP

Notes

Therefore, the total estimated time required to splice weld a tubular joint was 29 min. 53 sec.

Having found the joint configuration in the tests to be acceptable, the next step was to mass-produce the splice welding of spheres. For this operation, a jig was devised to hold and position the sphere weldment on a rotator, as shown in Figure 3.12 and as illustrated in Figure 3.13.

The only difference in the joint configuration with the spheres and that used in the tests is the gap between the backing ring and the feather edge of the weld joint preparation. A full size sketch, as shown in Figure 3.14, is made to illustrate the gap. Since the outside surface of the backing ring is flat, the gap due to the curvature of the sphere across the weld joint, was calculated to be 0.023".

Splice welding of spheres for the testing program, formed from 1/2" and 5/8" nominal thick plates were carried out by submerged arc welding process using the following welding equipment, consumables and current: -

A Lincoln SAN-600 power source in combination with a Lincoln Innershield NA-2 Automatic Welder was used for the weld test using a 0.045" diameter Lincoln L50/880 wire/flux combination conforming to CSA Standard W48.6 classification F72-EM 13K and DCRP current.

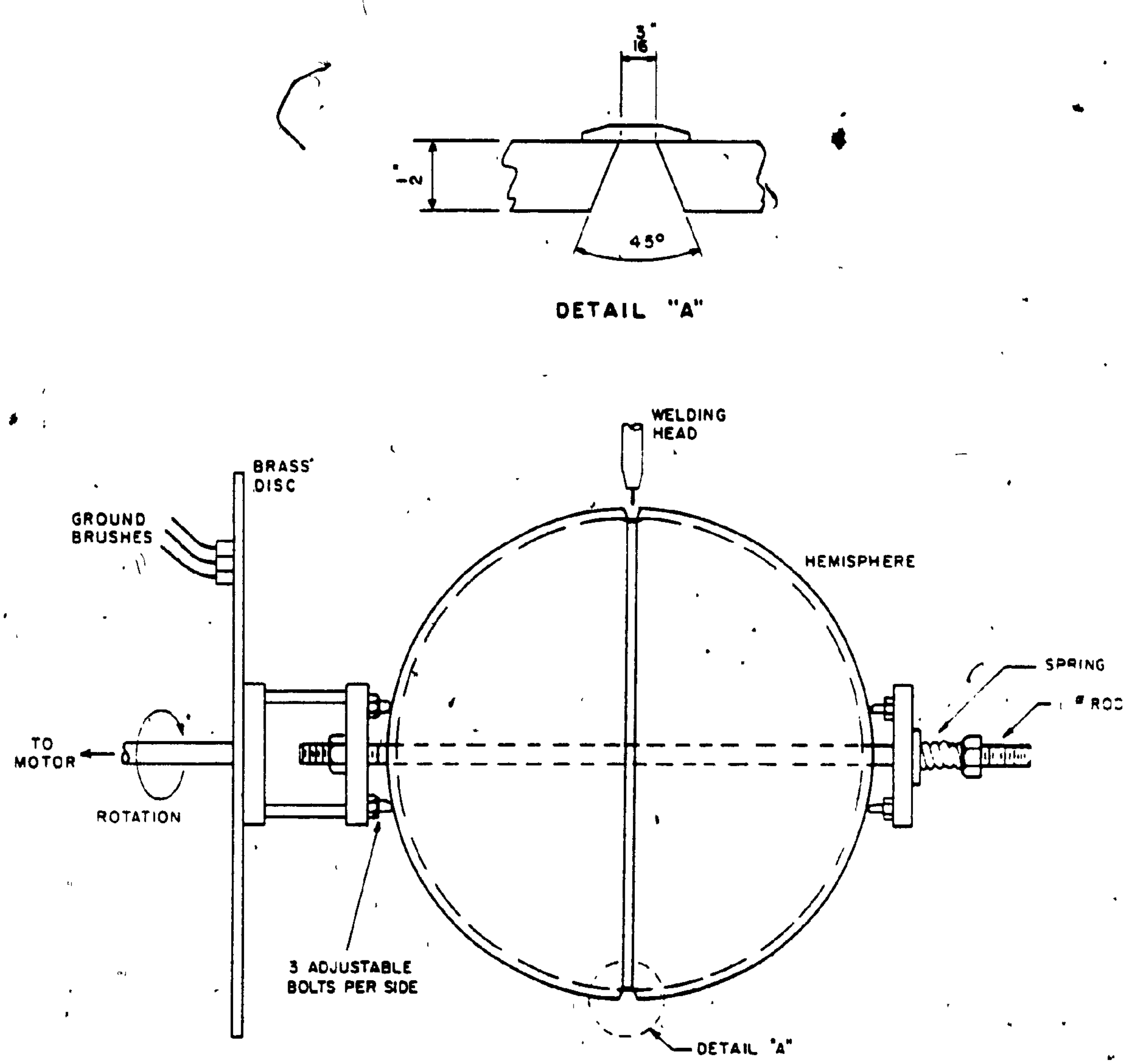


Figure 3.12 Detail Sketch of Jig and Sphere Assembly

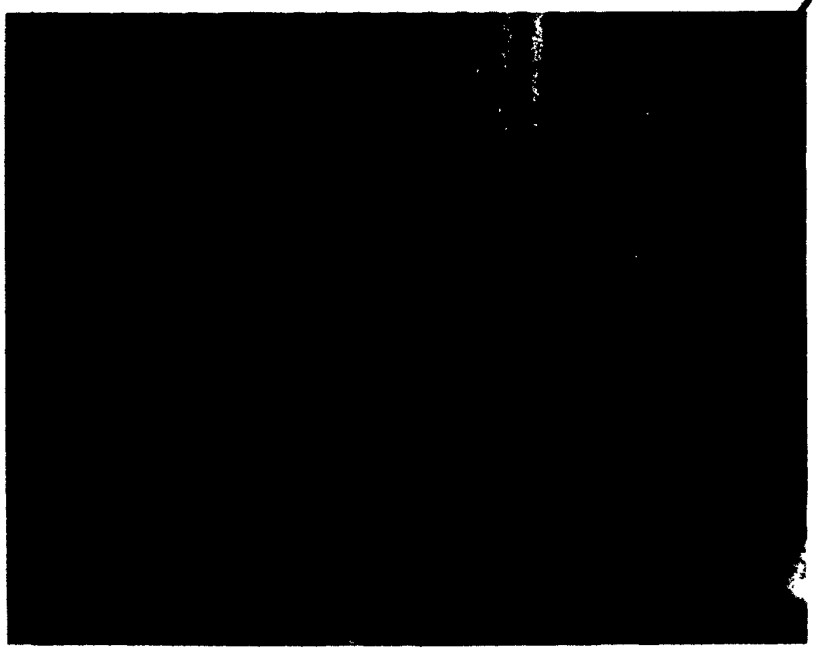


Figure 3.13 View of Jig and Sphere Assembly

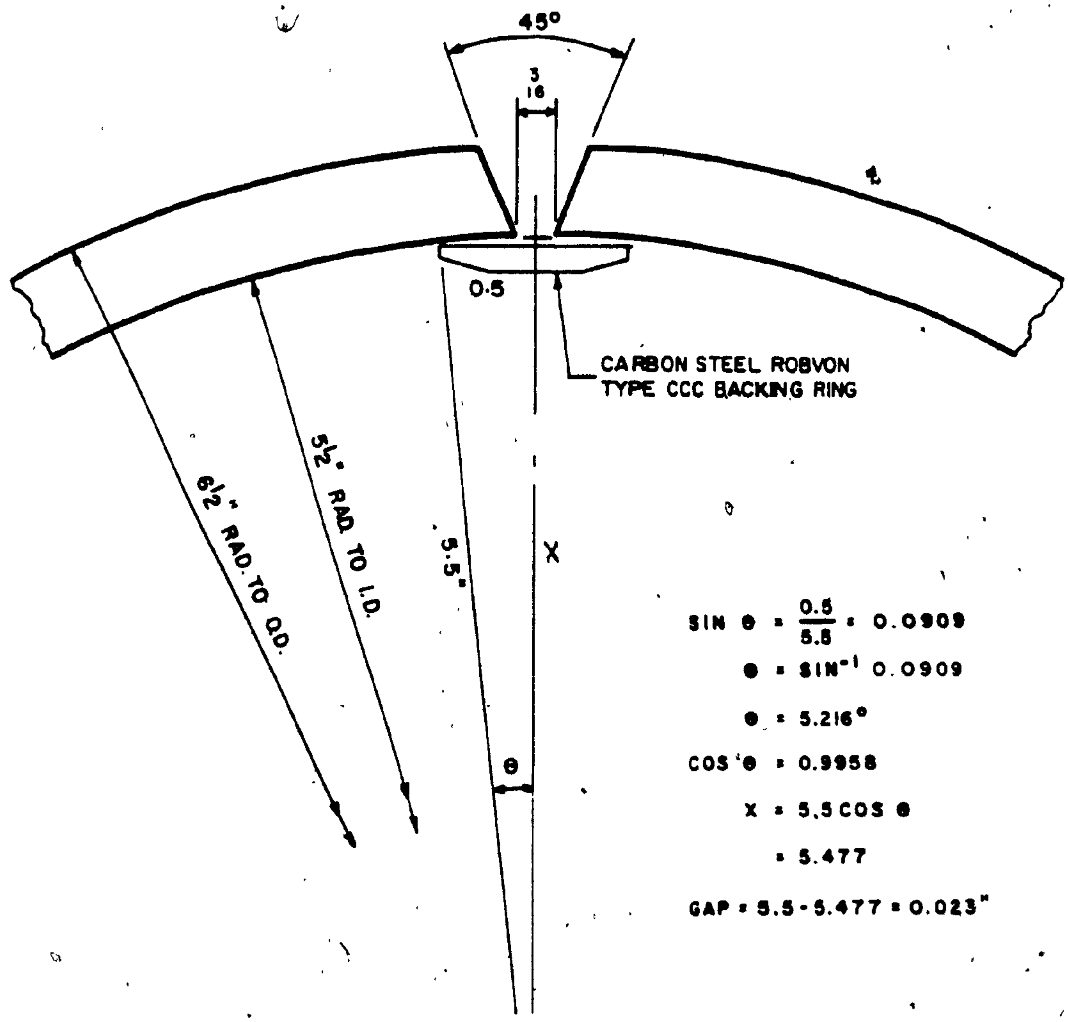


Figure 3.14 Weld Joint Configuration of Spherical Nodes

The time required to complete the splice welds for each sphere can be divided as follows:

A. Hemisphere #1 to #2 (5/8" nominal thick plate).

a) Set-up time - i.e. fitting of backing ring and mounting of sphere weldment in jig - 5 min.

Note: Backing ring was not tack welded in position, prior to welding of joint. Instead, each nub (see Figure 3.15) was broken off as it approached the welding head.

b) Nine (9) passes were required to complete the weld. See Data Sheet D2, as shown in Table 3.2, for the welding sequence and parameters.

1st Pass -	welding time was	3 min. 10 sec.
2nd Pass -	welding time was	3 min. 45 sec.
3rd Pass -	welding time was	3 min. 04 sec.
4th Pass -	welding time was	3 min. 02 sec.
5th Pass -	welding time was	3 min. 02 sec.
6th Pass -	welding time was	3 min. 02 sec.
7th Pass -	welding time was	3 min. 20 sec.
8th Pass -	welding time was	3 min. 20 sec.

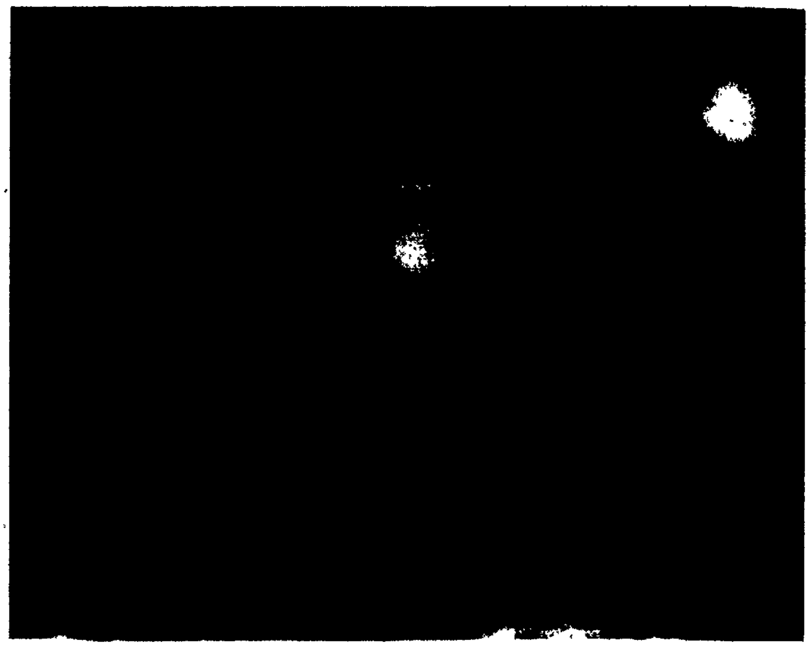


Figure 3.15 Close-Up View of Hemispehre with Backing Ring and Nubs

Table 3.2 Welding Data Sheet for Welding of Spheres

DS DONNÉES DE SOUDAGE / WELDING DATA

PROCÉDÉ / PROCESS	Nº FEUILLE DE DONNÉES / DATA SHEET NO.	Nº SPÉCIFICATION DE SOUDAGE / WELDING SPEC'N NO.
SUBMERGED ARC	D2	SS / WS / DMS / PQR

SPEC. DU MÉTAL DE BASE / MATERIAL SPEC.: CSA G40.12

POSITION: 1 G (flat)

TEMP. DE PRÉCHAUFFAGE / PREHEAT TEMP.: NIL

TEMP. D'INTERPASSE / INTERPASS TEMP.: NIL

TRAITEMENT DE LA RACINE / ROOT TREATMENT: Robyon Type ccc Backing Ring

MÉTAL D'APPORT-FILLER METAL

NOM COMMERCIAL / TRADE NAME: Lincoln L 50 - EM 13K

FLUX

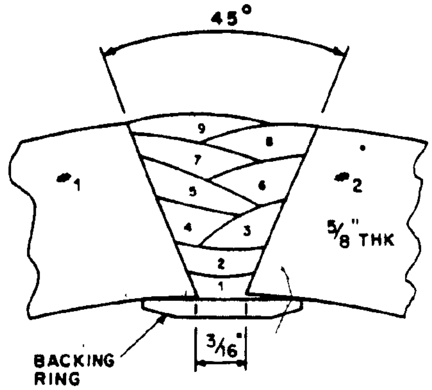
NOM COMMERCIAL ET TAILLE DES GRANULES / TRADE NAME AND PARTICLE SIZE: Lincoln 880-F72

GAZ-GAS

GAZ DE PROTECTION / SHIELDING GAS: À / AT PCH / CFH

GAZ DE TRAÎNARD / TRAILING GAS: À / AT PCH / CFH

GAZ DE SOUTIEN / BACKING GAS: À / AT PCH / CFH



CROQUIS DU JOINT / JOINT GEOMETRY

T	CÔTÉ SIDE	COUCHE LAYER	PASSE PASS	AMPS ± 10%	VITESSE DU FIL RRM / WIRE FEED SPEED IRM	VOLTS ± 7%	VITESSE D'AVANCEMENT P.P.M. / TRAVEL SPEED I.R.M. ± 10%	ÉLECTRODE DIA	ÉLECTRODE TYPE	ÉLECTRODE DTCP ESO	ÉLECTRODE POLARITÉ POLARITY
5/8"	1	1	1	170	-	32	11.3	.045"	L50	1-1½"	DCSP
		2	2	170	-	32	9.6	"	"	"	"
		3	3	170	-	32	11.9	"	"	"	"
		3	4	160	-	32	11.9	"	"	"	"
		4	5	160	-	32	11.9	"	"	"	"
		4	6	160	-	32	11.9	"	"	"	"
		5	7	170	-	32	10.8	"	"	"	"
		5	8	170	-	32	10.8	"	"	"	"
		6	9	170	-	32	12.0	"	"	"	"

NOTES

1) Robvon type ccc backing ring not tack welded in position.
2) Cleaning of flux required on first two passes only.

9th Pass -	welding time was	3 min. 00 sec.
Total Welding Time was		28 min. 45 sec.

c) Cleaning of flux - required only on first two passes.

1st Pass -	11 min. 30 sec.
2nd Pass -	4 min. 30 sec.
Total time to clean flux	16 min. 0 sec.

Therefore, the total time required required to splice weld hemisphere #1 to hemisphere #2 was 49 min. 45 sec.

B. Hemisphere #1 to #2 (1/2" nominal thick plate).

a) Set-up time - 5 min.

b) Seven (6) passes were required to complete the weld. See Data Sheet D3, as shown in Table 3.3, for welding sequence and parameters.

1st Pass -	welding time was	3 min. 30 sec.
2nd Pass -	welding time was	3 min. 40 sec.
3rd Pass -	welding time was	3 min. 40 sec.
4th Pass -	welding time was	3 min. 40 sec.
5th Pass -	welding time was	3 min. 40 sec.
6th Pass -	welding time was	3 min. 40 sec.
Total Welding Time was		21 min. 50 sec.

Table 3.3 Welding Data Sheet for Welding of Spheres

DS DONNÉES DE SOUDAGE / WELDING DATA

PROCÉDÉ / PROCESS: SUBMERGED ARC	Nº FEUILLE DE DONNÉES / DATA SHEET NO. D3	Nº SPÉCIFICATION DE SOUDAGE / WELDING SPECN. NO. SS WS DMS PQR

SPEC. DU MÉTAL DE BASE / MATERIAL SPEC.: CSA G40.12

POSITION: 1G (flat)

TEMP. DE PRÉCHAUFFAGE / PREHEAT TEMP.: Nil

TEMP. D'INTERPASSE / INTERPASS TEMP.: NIL

TRAITEMENT DE LA RACINE / ROOT TREATMENT: Robvon Type ccc Backing Ring

MÉTAL D'APPORT-FILLER METAL

NOM COMMERCIAL / TRADE NAME: Lincoln L50 - EM 13K

FLUX

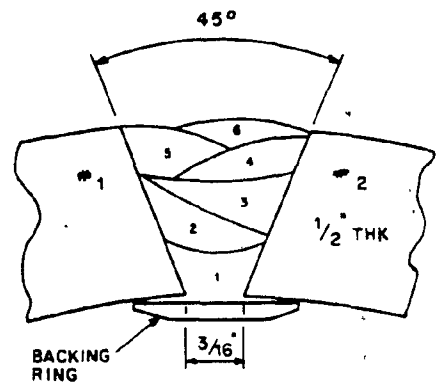
NOM COMMERCIAL ET TAILLE DES GRANULES / TRADE NAME AND PARTICLE SIZE: Lincoln 880 - F72

GAZ-GAS

GAZ DE PROTECTION / SHIELDING GAS: À / AT PCH / CFH

GAZ DE TRAINARD / TRAILING GAS: À / AT PCH / CFH

GAZ DE SOUTIEN / BACKING GAS: À / AT PCH / CFH



CROQUIS DU JOINT / JOINT GEOMETRY

T	CÔTÉ / SIDE	COUCHE / LAYER	PASSE / PASS	AMPS ± 10%	VITESSE DU FIL RRM / WIRE FEED SPEED IRM	VOLTS ± 7%	VITESSE D'AVANCEMENT PPM / TRAVEL SPEED IPM ± 10%	ÉLECTRODE DIA	ÉLECTRODE TYPE	ÉLECTRODE DTCP / ESO	ÉLECTRODE POLARITÉ / POLARITY
½"	1	1	1	160	-	32	10.0	.045"	L50	1-1½"	DCRP
		2	2	170	-	"	9.6	"	"	"	"
		2	3	"	-	"	"	"	"	"	"
		3	4	"	-	"	"	"	"	"	"
		3	5	"	-	"	"	"	"	"	"
		4	6	"	-	"	"	"	"	"	"

NOTES

1) Robvon type ccc backing ring not tack welded in position.

c) Cleaning of flux was only required on the 1st pass and was accomplished while welding the 2nd pass.

Therefore, the total time required to splice weld hemisphere #1 to hemisphere #2 was 26 min. 50 sec.

Where an excessive gap (3/32" or more) exists between the backing ring and the inside surfaces of the hemispheres, the first pass was made using the gas metal-arc welding process in accordance with Data Sheet D4, as shown in Table 3.4.

A complete welded joint of a sphere is shown in Figure 3.16.

3.4 Quality Control

In addition to the ultrasonic examination of the plates prior to the spinning process, before welding, all hemispheres were examined on the inside surfaces by using liquid penetrant. After welding, the weld and the adjacent material were also examined using liquid penetrant. No cracks were revealed in both cases.

3.5 Summary

One can observe from the test that the volume of weld metal deposited for the same joint configuration is 7% greater using 5/8" thick plate. However, the depositing rate with the same welding process is 85%

Table 3.4 Welding Data Sheet Using Gas Metal-Arc Process

DS DONNÉES DE SOUDAGE / WELDING DATA

PROCÉDÉ / PROCESS	Nº FEUILLE DE DONNÉES / DATA SHEET NO.	Nº SPÉCIFICATION DE SOUDAGE / WELDING SPEC'N NO.
GMAW ROOT PASS SAW FILL PASSES	D4	SS WS DMS PQR

SPEC. DU MÉTAL DE BASE / MATERIAL SPEC.: CSA G40.12

POSITION: 1G (flat)

TEMP. DE PRÉCHAUFFAGE / PREHEAT TEMP.: NIL

TEMP. D'INTERPASSE / INTERPASS TEMP.: NIL

TRAITEMENT DE LA RACINE / ROOT TREATMENT: Robvon Type ccc Backing Ring

METAL D'APPORT–FILLER METAL

NOM COMMERCIAL / TRADE NAME: GMAW E70S-3 (A675)
SAW Lincoln L50-EM 13K

FLUX

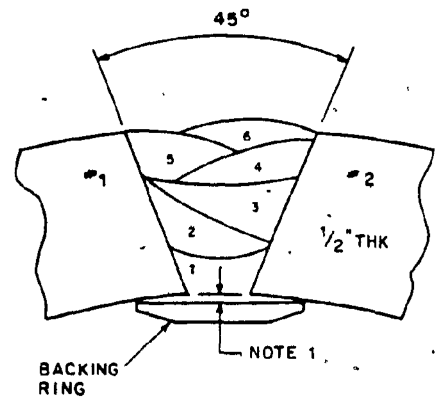
NOM COMMERCIAL ET TAILLE DES GRANULES / TRADE NAME AND PARTICLE SIZE: SAW Lincoln 880-F12

GAZ–GAS (for GMAW only)

GAZ DE PROTECTION / SHIELDING GAS: CO_2 À / AT 30-35 PCH / CFH

GAZ DE TRAINARD / TRAILING GAS: À / AT PCH / CFH

GAZ DE SOUTIEN / BACKING GAS: À / AT PCH / CFH



CROQUIS DU JOINT / JOINT GEOMETRY

T	CÔTÉ / SIDE	COUCHE / LAYER	PASSE / PASS	AMPS ± 10%	VITESSE DU FIL RPM / WIRE FEED SPEED IPM	VOLTS ± 7%	VITESSE D'AVANCEMENT PPM / TRAVEL SPEED IPM ± 10%	ÉLECTRODE DIA	ÉLECTRODE TYPE	ÉLECTRODE DTCP / ESO	ÉLECTRODE POLARITÉ / POLARITY
½"	1	1	1	160	-	25	Note 3	.045"	A675	1-1½"	DCRP
		2	2	170	-	32	9.5	"	L50	"	"
		3	3	"	-	"	"	"	"	"	"
		3	4	"	-	"	"	"	"	"	"
		4	5	"	-	"	"	"	"	"	"
		4	6	"	-	"	"	"	"	"	"

NOTES

1) Gap 3/32" or more.
2) Robvon carbon steel type ccc backing ring std. 12" size.
3) Clean backing ring and groove edges prior to welding.

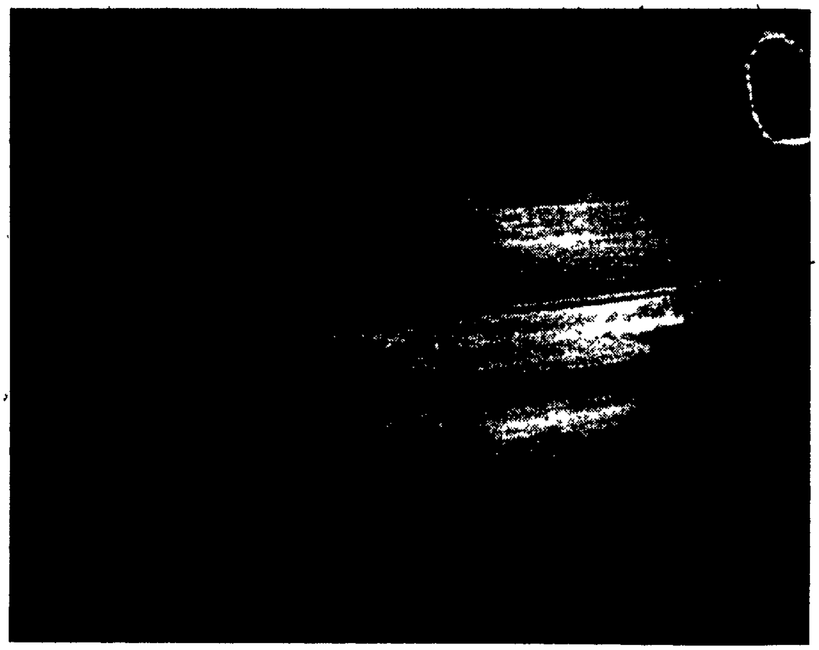


Figure 3.16 Complete Welded Joint of Sphere

greater for the 5/8" thick plate sphere. Thus, from the above, it can be seen that the depositing rate has a most significant impact on the cost of welding.

CHAPTER 4

EXPERIMENTAL PROGRAM

CHAPTER 4

EXPERIMENTAL PROGRAM

The details of tests and results are described in this chapter.

4.1 Test Specimens

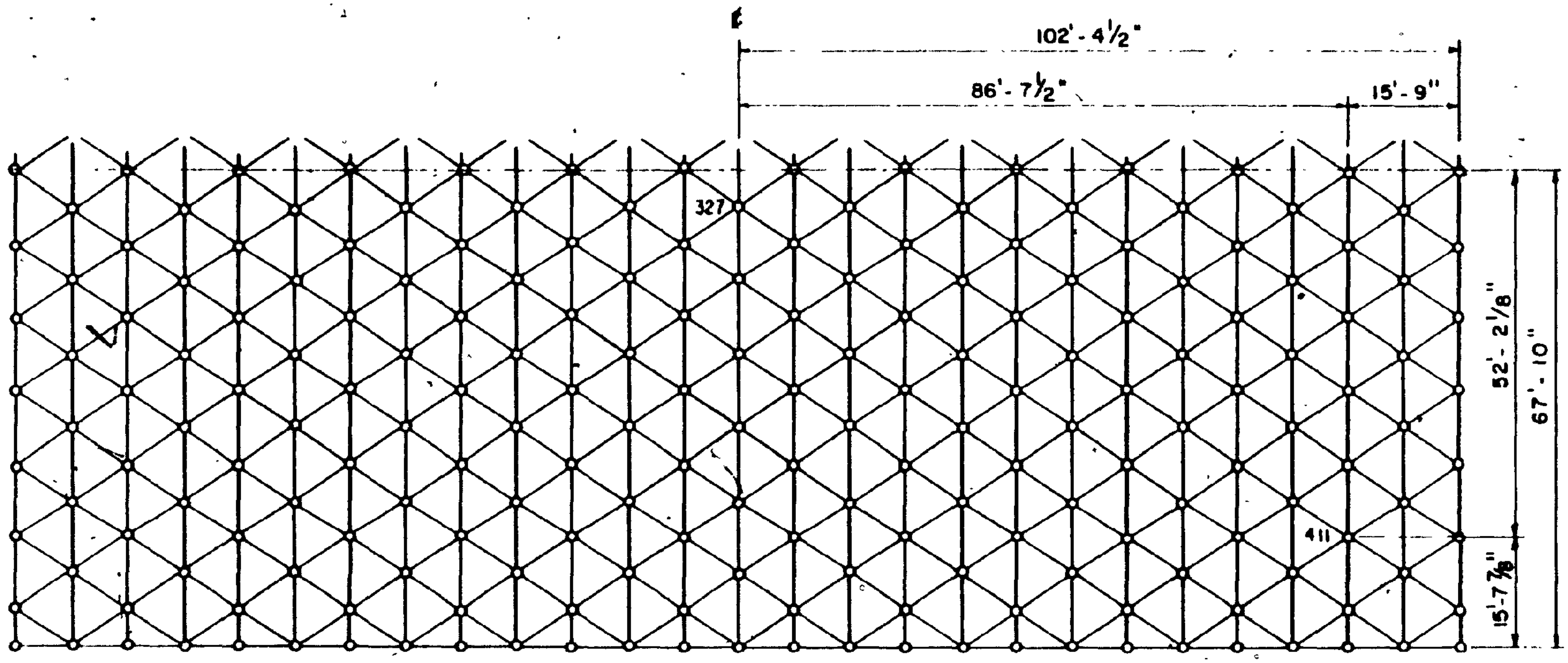
For simplicity the tests were limited to one plane representing two joints, in each grid layer of the structure, having the highest axial load combination that could occur in practice. The four representative joints located at the top and bottom chord are shown in Figures 4.1 and 4.2. The four diagonal members joining the double layer grid were omitted since the magnitude of the maximum load in a member was considered insignificant (i.e. 4.5% of the maximum load occurring at a joint in the horizontal plane).

The tests were carried out on a joint specimen for a series of loading cases representing the design maxima. These are the following: -

(1) the maximum compression loads in all the chord members;

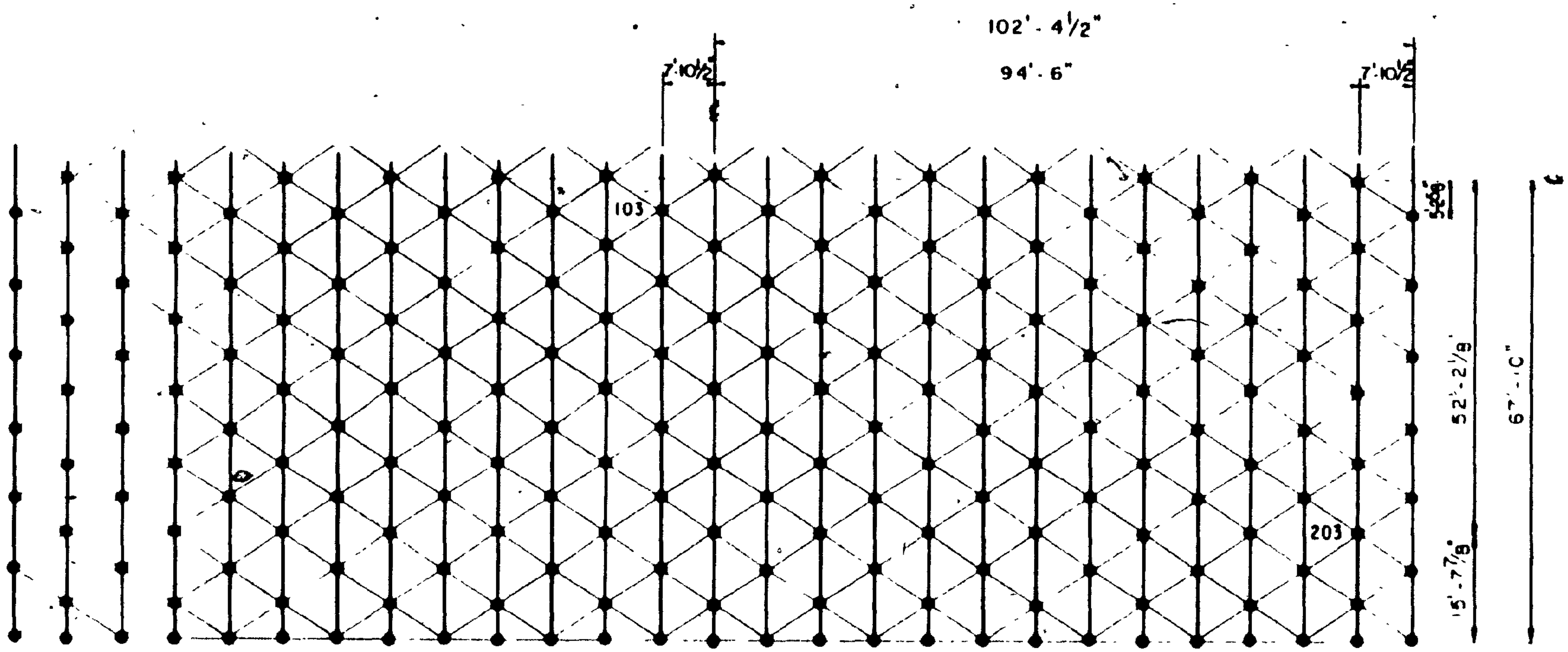
(2) the maximum tension loads in all the members;

(3) the maximum tension loads in four members and compression load in two members;



PLAN VIEW OF TOP CHORD MEMBERS.

Figure 4.1 Location Plan of Joints 327 and 411



PLAN VIEW OF BOTTOM CHORD MEMBERS

Figure 4.2 Location Plan of Joints 103 and 203

(4) the maximum compression loads in four members and tension loads in two members.

The joint specimens were two 12" diameter spherical nodes, each of different wall thickness being 1/2" and 5/8". Details and load cases of joint tested are indicated in Table 4.1.

The axial loads applied to the test specimens were achieved by welding six (6) HSS 4 1/2" O.D. X 0.3125" wall thickness conforming to CSA G40.16 having a yield strength of 50 ksi. Although the highest design compression load of 130 kips required a HSS 5 9/16" O.D. X 0.3750" wall thickness, it was decided to use the 4 1/2" HSS as this was the only size available at the time. The design for three of the joints being tested required the 4 1/2" HSS. Since the length of the HSS required for the tests were 6 1/2" long, the compression or tension capacity of the member would be identical. Thus -

$$
\begin{aligned}
P &= F_t A \\
&= 0.6\ F_y A \\
&= 0.6 \times 50 \times 4.11 \\
&= 123.3 \text{ kips} < 130 \text{ kips} \qquad \text{OK}
\end{aligned}
$$

Hence the 4 1/2" HSS were welded to the sphere specimen, at an angle of intersection of 60°, with a full strength weld.

TABLE 4.1 DETAILS AND LOAD COMIBNATION OF JOINT TESTED

Specimen	Joint	Location	Sphere Wall Thickness Nominal, in.	Max. Design Loads (Kips)		
				P1	P2	P3
1	327	Top Chord	0.625	- 48	-130	-48
2	103	Bott. Chord	0.625	43	130	43
3	203	Bott. Chord	0.625	80	10	-55
4	411	Top Chord	0.625	- 68	- 25	40
5	103	Bott. Chord	0.500	43	130	43
6	203	Bott. Chord	0.500	80	10	-55
7	411	Top Chord	0.500	- 68	- 25	40
8	327	Top Chord	0.500	- 48	-130	-48
9	-	-	0.500	150	0	0
10	-	-	0.500	220	0	0

Sign Convention: -

Indicate Tension
- Indicate Compression

4.2 Test Set-Up

The tests were carried out in the structural shop at Dominion Bridge-Sulzer Inc. in Lachine, Quebec. The test specimen was installed in a specially designed test frame, as shown in Figure 4.3, which was able to apply loads up to 234 kips (117 tons) in each member.

The loads are applied with three 150 ton capacity ENERPAC cylinder jacks. The jacks are double-acting, hollow plunger design that can accommodate a rod running through the cylinder. The jacks, when mounted on the frame can either push or pull on the members. The members directly opposite to the jacks are bolted to the frame. Figure 4.3 show the jacks mounted on the test frame for an axial compression load application. For a tension load application on the members, any one of the jacks can be mounted on the opposite side of the stub bracket.

The jacks are activated with an electric powered pump. Each pump is equipped with a four-way directional valve that allows finger tip control for powered advance and retraction of cylinders with holding in center position. The pump is equipped with hydraulic gauges which permit visual reading of the pressure generated by the pump and measures the input pressure in psi and external loads in tons. Each gauges are precisely calibrated and highly accurate - within ±2% of full scale. The calibration of the gauges were verified using a reference cell prior to the tests.

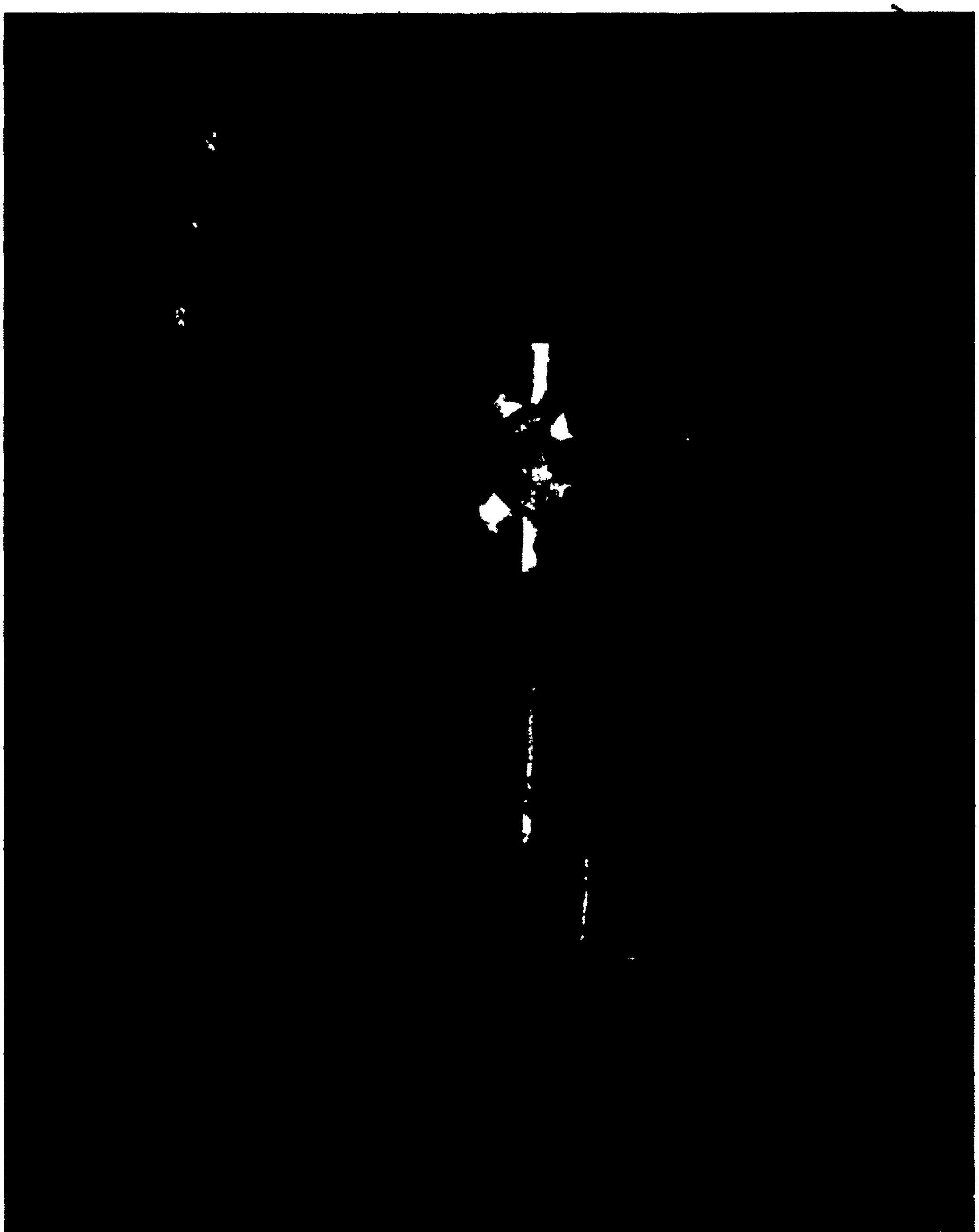


Figure 4.3 Frame for Testing of Joints

4.3 Testing Procedures

A typical specimen shown in the test frame is illustrated in Figure 4.3 and the test results are summarized in Table 4.2. Test results for all other joints are listed in Appendix A.

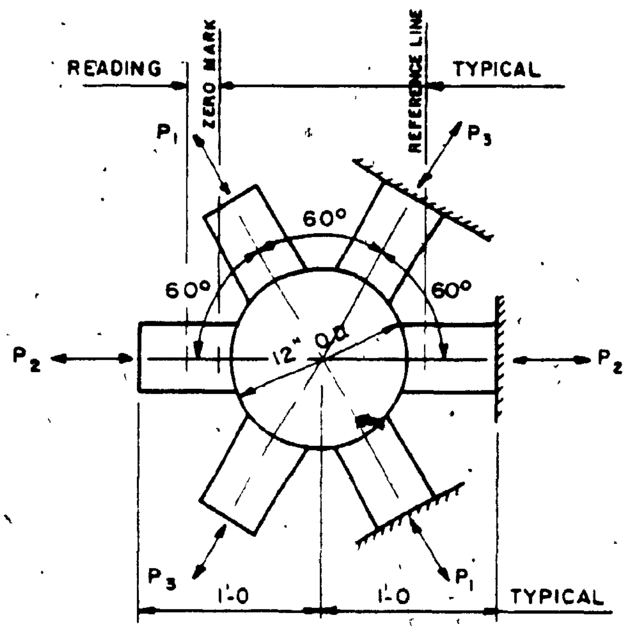
Before the start of each test, 25% of the service loads was applied in each member at the joint. This was to insure that all jacks and joint specimen were locked into position. The loads were then released to return to a zero load condition. Each tubular member welded to the specimen was center punch with a zero and a reference point location so as to measure any possible deformation of the joint during the testing operations.

The testing of each specimen was started by applying loads in increments of 20 to 30 kips alternately until 1.6 of the service load was reached and displacement readings were recorded at each step. At the end of each series of tests the jacks were activated again to a zero load condition and final readings were recorded for any deformation.

After completing the series of tests, a tensile test using the 1/2" thick wall sphere specimen and two tubes was performed as shown in Figure 4.4. One load of a 150 kips was applied then released to a zero load condition and final reading was recorded. The next load applied was equal to 1.7 the maximum tension load that could occur in

Table 4.2 Physical Test Results

SUBJECT	SPECIMEN Nº
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	1
	JOINT Nº 327 Top Chord



SIGN CONVENTION

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	-12	- 48	Nil	- 60	Nil	- 72	Nil	- 77	Nil	Nil
P_2	-32	-130	Nil	-163	Nil	-195	Nil	-208	3/32	Nil
P_3	-12	- 48	Nil	- 60	Nil	- 72	Nil	- 77	Nil	Nil

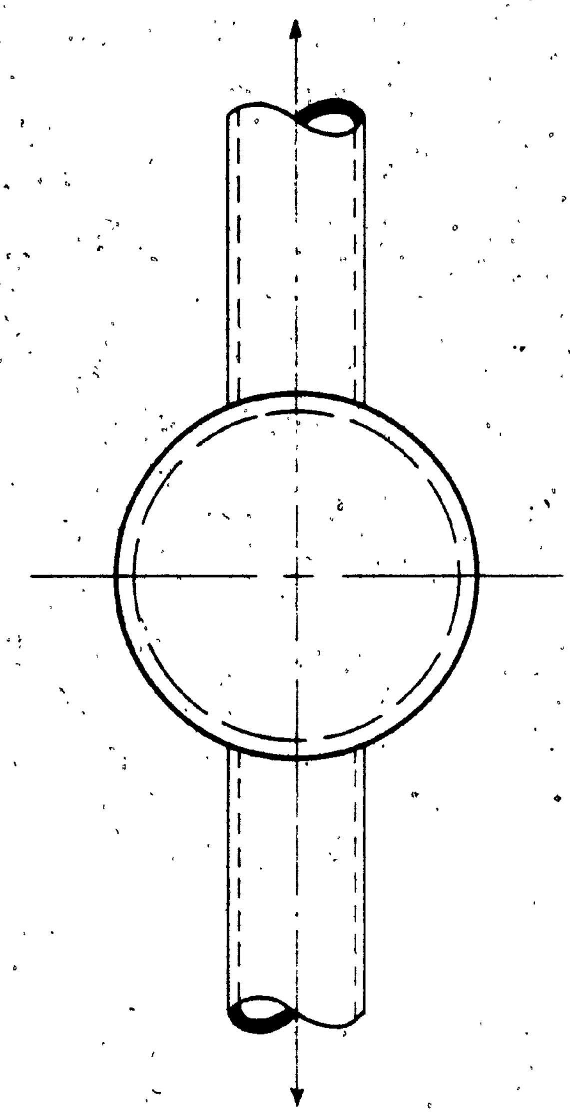


Figure 4.4 Tension Test on Sphere

the structure (i.e. 1.7 X 130 lets say 220 kips). The load was released to a zero load condition and final reading was recorded.

4.4 Summary of Test Results

The test results for each joint number on each specimen showed that no plastic deformation took place under the applied loads equal to 1.6 the service load. The 1/2" thick wall sphere specimen under the applied tensile load, with only two tubes, of 220 kips showed a 1/16" deformation. It is debatable whether the sphere or the tubular member was deformed since on the yield point for the two materials was surpassed under the applied load.

However, it was quite apparent from the result of the tests that the spherical joint had an adequate factor of safety for this project. The test could have been pursued employing thinner plate material but since this could present fabrication and/or distortion problems with the large amount of weld deposit the 1/2" nominal spherical node was considered acceptable.

CHAPTER 5

FABRICATION AND ERECTION

CHAPTER 5

FABRICATION AND ERECTION

5.1 Introduction

The existence of a concrete foundation wall, did not permit the use of conventional method of assembling a three-dimensional space frame; namely assembling on the ground and lifting the finished framework in its final position. The aim was then to fabricate subassemblies in the shop to make up box sections of a size that would be satisfactory for handling and shipping.

5.2 Fabrication

5.2.1 Trusses

Two types of Warren trusses were shop fabricated in sections making up one half-truss, as shown in Figure 5.1. Each section 67 ft. 10 in. long and 8 ft. deep consisted of fifteen (15) spherical nodal joints and twenty-eight (28) connecting tubular members.

The cambering of the truss was achieved by increasing and decreasing the lengths of the top and bottom chord numbers respectively and maintaining the original length of the diagonal members. The spheres were positioned accurately on a welding jig and the tubular members, cut

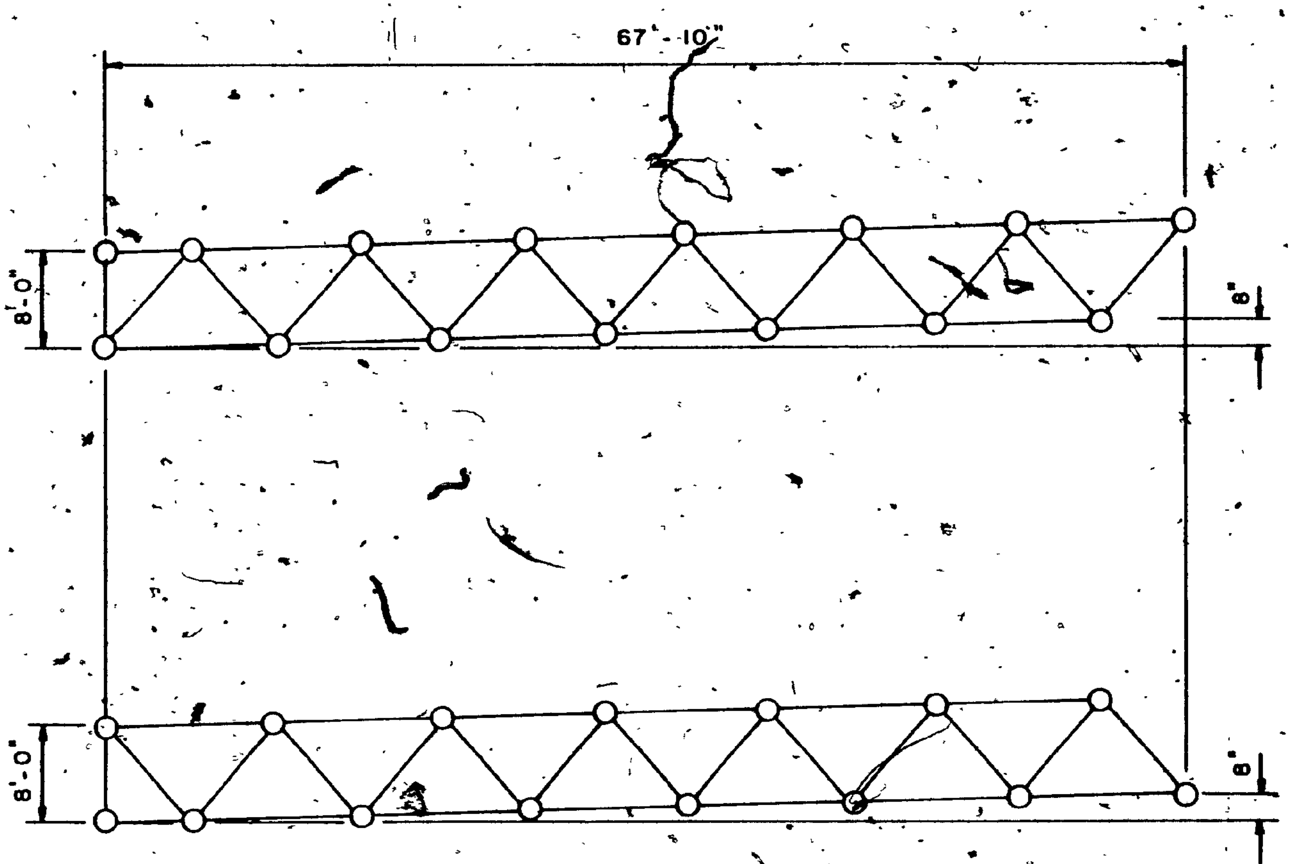


Figure 5.1 Warren Type Trusses

to the required length, were tack welded in place until a half-truss was formed. Final welding proceeded with the assembly position being changed to accommodate the welders.

5.2.2 Subassembly

The trusses were then assembled together to form a subassembly, shown in Figure 5.2. Each subassembly consisted of two half-trusses with forty one (41) members protruding from one truss ready to be field welded to an adjacent subassembly.

A total twenty six (26) subassemblies were fabricated each having an overall width of 15 ft. 9 in., a depth of 8 ft., a length of 67 ft. 9 in. and weighing between 12,400 lbs to 17,200 lbs.

5.2.3 Welding

The members were welded to the spheres by manual shielded arc welding process. A process using a coated electrode which is a mild steel rod, 14" or 18" long, coated with a flux which melts in the heat of the arc to provide a gaseous shield from the atmosphere. The coated electrode is gripped in an insulated holder which is manipulated or guided manually by the welding operator.

The weld was sized to suit the service load in each member. This was achieved by using either one of the following types of weld.

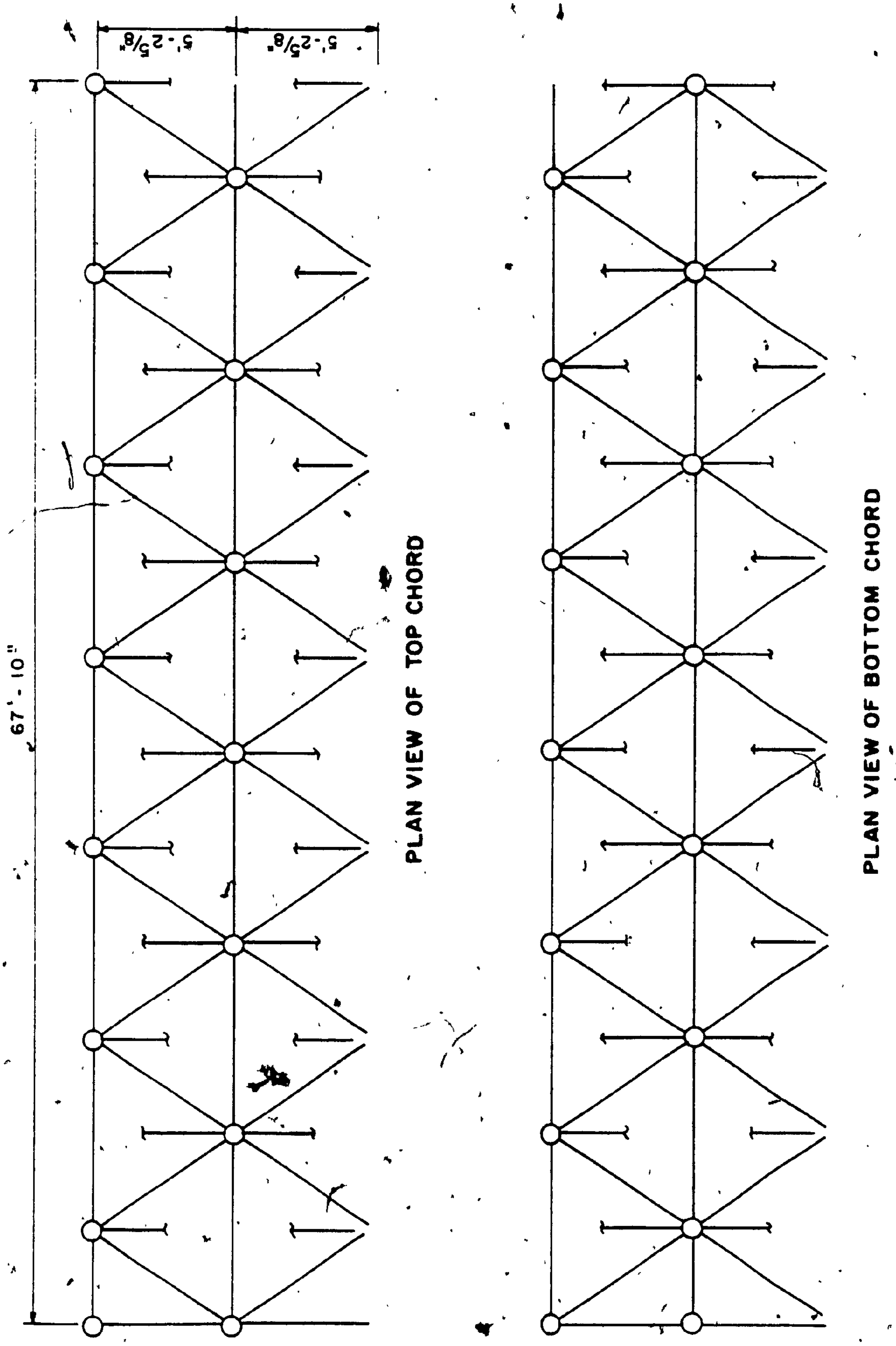


Figure 5.2 Subassembly

1. Fillet weld.

2. Partial penetration groove weld.

3. Complete penetration groove weld.

Only members requiring fillet weld sizes of 7/16" and over had to have the ends prepared for groove welds. Members requiring fillet weld size of 1/2" and under had the ends cut square. To ensure that the desired strength of the member would be achieved, each member was identified with a letter designation that referred to the type and quantity of weld required to develop the load in the member.

All welds were visually inspected and examined by magnetic particle method conforming to CSA-W59.

5.3 Erection

The subassemblies were trucked to the site, under provisions of a special road permit. Each of the subassemblies were hoisted to their relative location with temporary tubular scaffolds which were positioned at the one-third points in the short span direction, as shown in Figure 5.3. The scaffolds were equipped with screw jacks at the bottom of each scaffold leg to receive the camber shape and also to remove the dead load of the structure after completion of erection.

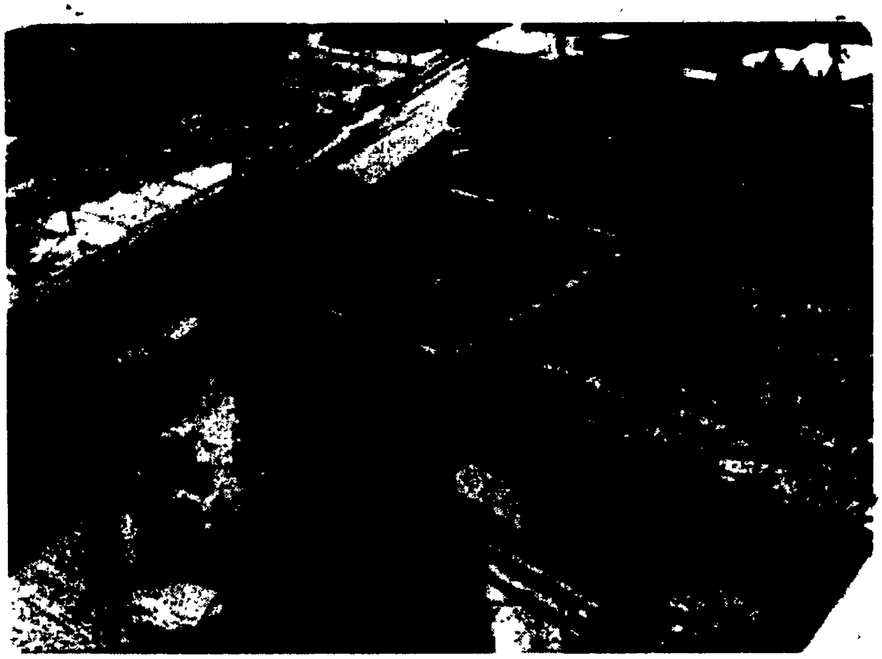


Figure 5.3 Partial Erection of Subassemblies Supported on Scaffolds

The subassemblies were joined to each other by welding the protruding members to their respective joints. This operation was repeated starting at the center of the building and working simultaneously towards the end walls. Upon completion of the space frame and nondestructive examination of the welds, the scaffolds were removed.

The scaffolds were released from under the roof structure by working on the screw jacks in the following carefully controlled manner.

Eight jack screws were worked on simultaneously by one man each - a total of eight men. One group of four men with a coordinator commenced at the north wall; the other group of four with a second coordinator started from the south wall. Therefore, with four lines of scaffolds legs, one man was working on each end of each line.

The four men of one group simultaneously unscrewed the jacks of the first leg in their respective lines by one quarter of one turn - no more. Then moving to the second jacks in their respective lines and simultaneously unscrewing them one quarter turn - no more. At the same time the other group were performing the same operations working from the other end of the lines. Both groups continued unscrewing the jacks one quarter turn until they met at the center, at which time all jacks had been unscrewed one quarter turn.

The whole process was repeated again commencing from the end walls by unscrewing the jacks one quarter increment until all jacks had zero load.

The scaffold towers nearest the end walls came free first so that when this occurred they would be unscrewed at least two full inches in order that they could be completely clear of the structure. The same applied to each tower in turn as it became free.

It was most important that this procedure be rigidly followed since if any one jack were to be unscrewed more than one quarter turn before moving to the next jack, serious damage could be caused to the roof tubes.

The deflection of the structure was then verified for final camber and lateral displacement after completion of removing scaffolds and found to be in accordance to the theoretical calculations.

CHAPTER 6

CONCLUSION

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This report provided an experimental method of determining the behavior of a hollow spherical joint applied with concentric axial loads. The worst critical load variation occurring in the space frame was considered.

The following conclusions can be drawn from the results of this investigation:

1. In all cases tested, the results of the tests proved that the choice of node configuration, diameter and plate thickness to be correct.

2. With the tensile test performed on the 1/2" thick hollow sphere employing two tubular sections, no excessive deformation was observed after the yield strength in both the tubes and the sphere had been surpassed.

The author realizes that the series of tests does not include all the members framing at a joint. Hence, further analytical and experimental work is deemed to be required on the subject of hollow spherical nodes with the objective of formulating design rules.

REFERENCES

REFERENCES

1. "A Design Guide: Long Span Steel Roof Structures", by the Committee of Structural Steel Producer & Committee of Plate Producers, American Iron & Steel Institute, 1000 16th Street Washington, D.C. 20036.

2. American Iron and Steel Institute, 1968. "Specification for the Design of Cold-Formed Steel Structural Members".

3. Canadian Institute of Steel Construction, 1976. "Handbook of Steel Construction". 6th Printing.

4. Canadian Standards Association, 1969. "Steel Structures for Building", Standard S16-1969.

5. Eberlein, Dr. - Ing. H., Lattice Space Structures a Comprehensive Survey", Acier-Stahl-Steel, 2/1975, pp. 50 - 66.

6. "Hollow Structural Sections - Design Manual for Connections", 2nd ed., Stelco Inc., 1981.

7. "Lattice Structures: State-of-the-Art Report", by the Task Committee on Lattice of Structures of the Committe on Special Structures of the Committee on Metals of the Structural Division, Journal of the Structural Division, ASCE, Vol. 102, No. ST11, Proc. Paper 12581, November 1976, pp. 2197 - 2230.

8. Makowski, Z.S., "Steel Space Structure", Michael Joseph Ltd., London, England, 1965.

9. Naslund, K.C., "Space Frame Structures", AISC Engineering Journal, October 1964, Volume 1, No. 4, pp. 126 - 130.

10 Rapp, R.E., "Space Structures in Steel, Architectural Record, November 1961.

11. "Space Structures" a study of methods and developments in three-dimensional construction resulting from the International Conference on Space Structures, University of Surrey, September 1966, edited by R.M. Davies, Blackwell Scientific Publications, Oxford and Edinburgh.

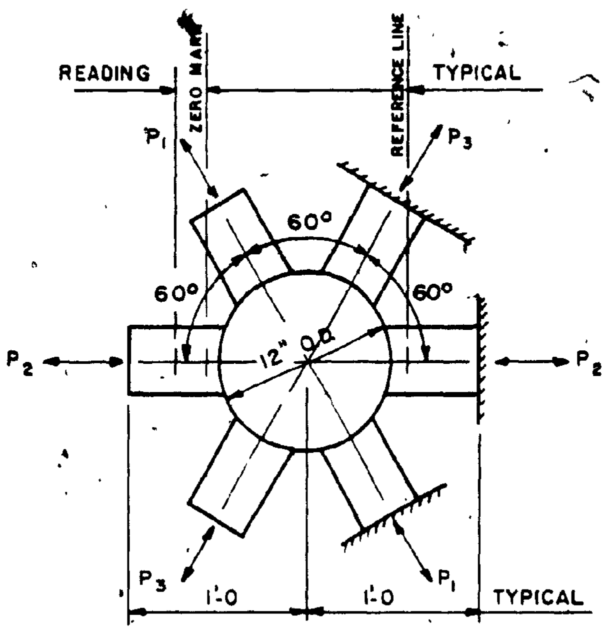
12. Wachsmann, K., "The Turning Point of Building" Reinhold Publishing Corporation, New York, N.Y., 1961.

APPENDIX A

SUPPLEMENTAL RESULTS

Table A.1 Physical Test Results

SUBJECT	SPECIMEN Nº 2
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	JOINT Nº 103 Bottom Chord



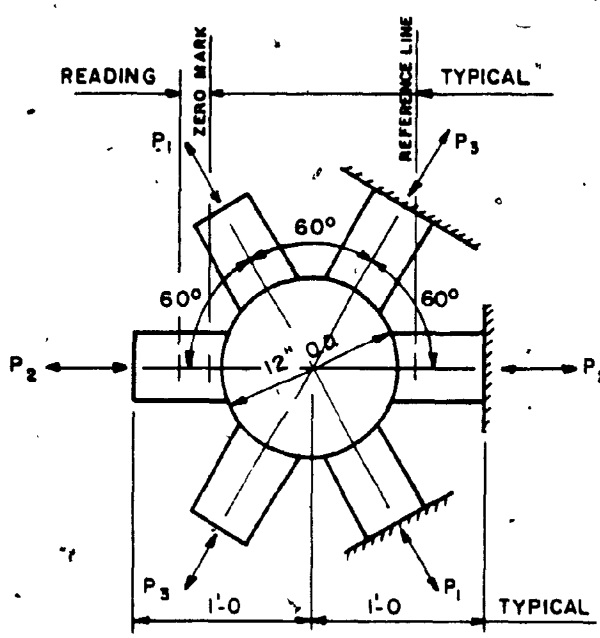
SIGN CONVENTION:

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	11	43	Nil	54	Nil	65	1/32	69	1/32	Nil
P_2	32	130	1/64	163	1/32	195	1/32	208	1/32	Nil
P_3	11	43	Nil	54	Nil	65	1/32	69	1/32	Nil

Table A.2 Physical Test Results

SUBJECT	SPECIMEN Nº
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	3
	JOINT Nº 203 Bottom Chord



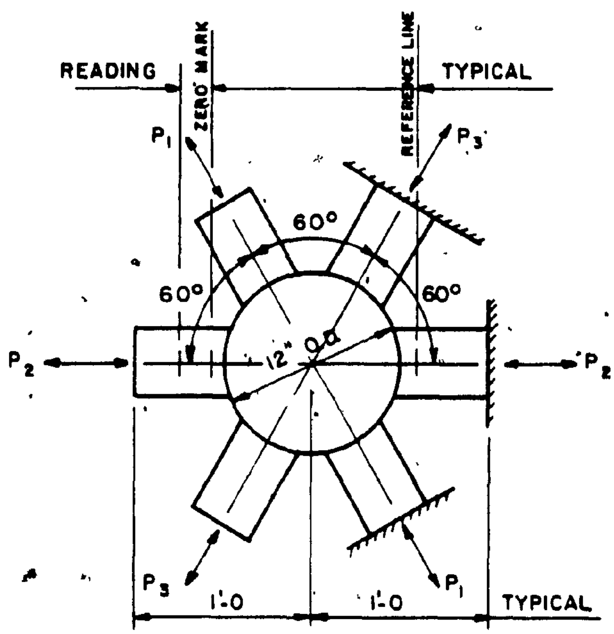
SIGN CONVENTION:

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	20	80	1/64	100	1/64	120	1/32	128	1/32	Nil
P_2	3	10	Nil	13	Nil	15	Nil	16	Nil	Nil
P_3	-14	-55	Nil	-69	Nil	-83	Nil	-88	Nil	Nil

Table A.3 Physical Test Results

SUBJECT	SPECIMEN N°
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	4
	JOINT N° 4/1 Top Chord



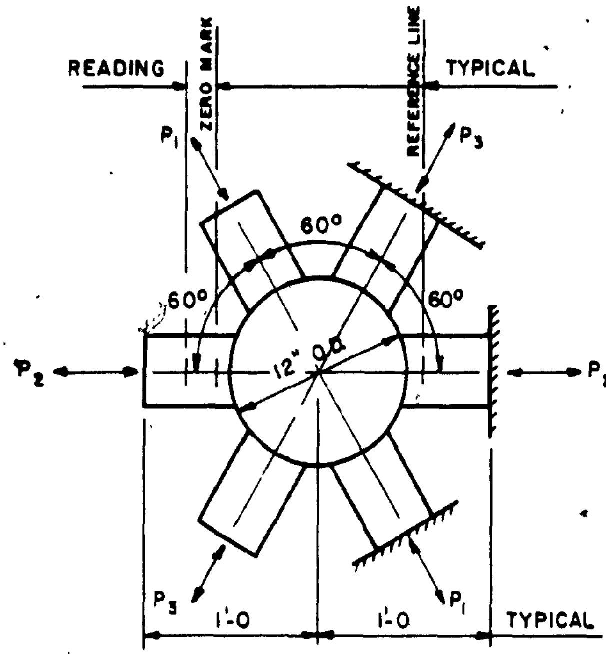
SIGN CONVENTION:

\+ INDICATE TENSION
\- INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	-17	-68	Nil	-85	Nil	-102	Nil	-109	Nil	Nil
P_2	- 6	-25	Nil	-31	Nil	- 38	Nil	- 40	Nil	Nil
P_3	10	40	Nil	50	Nil	60	1/32	64	1/32	Nil

Table A.4 Physical Test Results

SUBJECT	SPECIMEN N° 5
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	JOINT N° 103 Bottom Chord



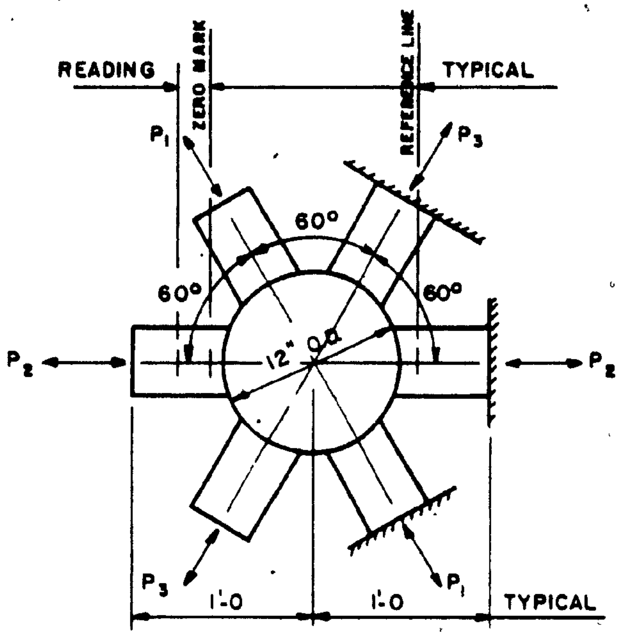
SIGN CONVENTION:

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	11	43	Nil	54	Nil	65	Nil	69	Nil	Nil
P_2	32	130	1/64	163	1/16	195	3/32	208	3/32	Nil
P_3	11	43	Nil	54	Nil	65	Nil	69	Nil	Nil

Table A.5 Physical Test Results

SUBJECT	SPECIMEN Nº
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	6
	JOINT Nº 203 Bottom Chord



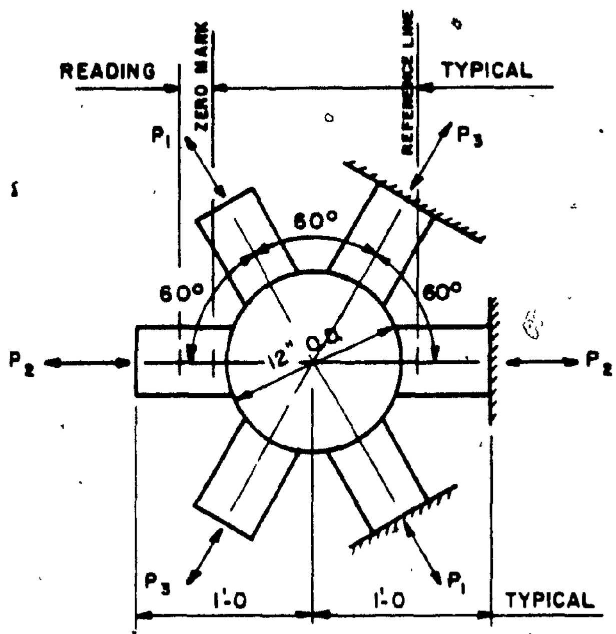
SIGN CONVENTION :

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	20	80	Nil	100	1/32	120	1/32	128	1/32	Nil
P_2	3	10	Nil	13	Nil	15	Nil	16	Nil	Nil
P_3	-14	-55	Nil	-69	Nil	-83	Nil	-88	Nil	Nil

Table A.6 Physical Test Results

SUBJECT	SPECIMEN Nº
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	7
	JOINT Nº 411 Top Chord



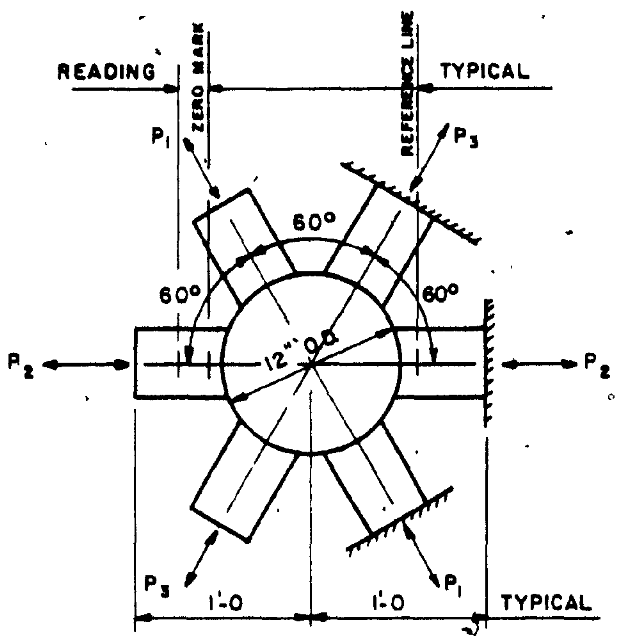
SIGN CONVENTION:

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	-17	-68	Nil	-85	Nil	-102	Nil	-109	Nil	Nil
P_2	- 6	-25	Nil	-31	Nil	- 38	Nil	- 40	Nil	Nil
P'_3	10	40	Nil	50	1/32	60	1/16	64	1/16	Nil

Table A.7 Physical Test Results

SUBJECT	SPECIMEN N° 8
C.E.G.E.P. du Vieux Montréal Space Frame of Gymnasium Roof	JOINT N° 327 Top Chord



SIGN CONVENTION:

+ INDICATE TENSION
− INDICATE COMPRESSION

AXIAL LOAD KIPS	P/4	P	READING IN INCHES	1.25P	READING IN INCHES	1.5P	READING IN INCHES	1.6P	READING IN INCHES	FINAL READING AT ZERO LOAD
P_1	-12	- 48	Nil	- 60	Nil	- 72	1/64	- 77	1/32	Nil
P_2	-32	-130	1/64	-163	3/64	-195	1/16	-208	7/64	Nil
P_3	-12	- 48	Nil	- 60	Nil	- 72	1/64	- 77	1/32	Nil