Title	Ultimate Strength of T-Joint in Tubular Frame of Jack-Up Type Oil Rig (Report I) : Experimental Study of Ultimate Strength of Unstiffened and Stiffened T-Joints under Normal Load(Mechanics, Strength & Structure Design)
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Ultimate Strength of T-Joint in Tubular Frame of Jack-Up Type Oil Rig (Report I) †

− Experimental Study of Ultimate Strength of Unstiffened and Stiffened T-Joints under Normal Load −

Keiji NAKACHO*, Masakatsu MATSUISHI, Takaaki ISHIHAMA***, Noriyuki TABUSHI**** and Yukio UEDA*******

Abstract

A jack-up type oil rig consists of legs and a platform. The legs are tubular frame structures. The degree of redundancy of the legs is generally less than the degree of the platform. As the degrees of redundancy of the legs and the platform decrease, the reserved strength of the rig after the initial local failure (yielding, buckling) decreases. Therefore it is very important to know precisely the ultimate strength of the tubular joints of which failure may become the leading cause of overall failure of the legs.

An experimental investigation has been carried out in this study, into the local stiffness and strength of the T-joint of circular tubes under normal load. The following effects on the local stiffness and ultimate strength of the T-joint were studied, and the mechanisms of strengthening by the guide and the center rib were clarified.

(1) The thickness and the yield stress of the chord-wall
(2) The leg guide
(3) The center stiffening

KEY WORDS : (T-Joint) (Ultimate Strength) (Stiffness) (Normal Load) (Jack-Up Type Oil Rig) (Rib) (Guide)

1. Introduction

In general, offshore structures must be designed according to the rules set by the Classification Society. However, the rules and design guidelines for jack-up type oil rigs are not as well established as those for ships. Under these circumstances, it would be very helpful from the viewpoint of safety to evaluate the ultimate strength of a structure, which largely depends on the ultimate strength of the joints. In this series of studies, the authors perform both theoretical and empirical approaches in order to investigate the ultimate strength of the joints of a jack-up oil rig.

A jack-up oil rig consists of a platform and legs. The platform has quite a few built-in redundancies that are similar to those found in a ship. The legs, however, have far fewer built-in redundancies. So any damage of the legs may result in total collapse of the rig. Therefore, the legs are the most critical factor in any investigation into the ultimate strength of a rig.

In general, the legs of a jack-up type oil rig have a truss structure consisted of chords and braces which have tubular sections. The loads are transmitted through the joint connections (nodal points) of the members. It is therefore important to study intensively the local strength of these nodal points when evaluating the ultimate strength of the whole leg. With this in mind, the authors decided to investigate primarily the local strength of T-type joints. In this study, the experiments for several models were performed to evaluate the local stiffness and strength of T-type joints under normal load from the brace.

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2. Conventional Evaluation of Local Strength of Pipe Joints

2.1 Deformation and load transmission characteristics of jack-up type rig

When loads due to wind and wave are imposed on a jack-up type rig, the legs are horizontally deformed as shown in **Fig. 1**. This deformation is restricted by the sea floor, the engagement of the jacking unit and the rack, and the contact between the leg guide and the leg chord. Therefore, it is very important to clear the local strengths of these parts.

As shown in Fig. 1, the rib plate is placed inside of the chord in line with the rack plates outside. The rib plate and the leg guide are very important factors in the local strength of pipe joints. The authors had previously studied the local strengths of the rack plate and the rib plate [1], but little is known about the strength of joints in regard to the leg guide and the rib. When the leg guide is positioned at the same level and opposite side of the joint, a high contact pressure will occur between the leg guide and the leg chord due to the local high rigidity. Therefore, the authors investigate the local strength of a T-type pipe joint with a rib, which is supported by a leg guide.

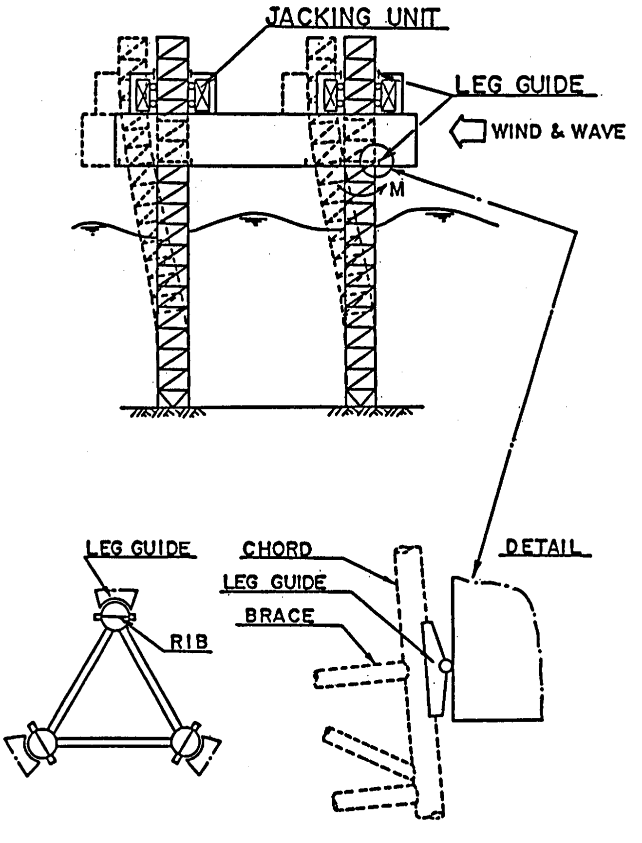


Fig. 1 Behavior of jack-up rig under load

2.2 Conventional method of assessing local strength of pipe joint

There have been a number of studies [2] done on the local strength of pipe joints, however, none of these studies have taken into account the effect of the leg guide and the rib plate. Therefore, no suitable method exists for assessing the local strength of pipe joints in jack-up type rigs. The Classification Society often recommends to use the API rule of punching shear stress [3].

This recommendation has primarily been applied to fixed-type offshore structures such as the jacket type, and is based on the assumption that the brace punches through the chord wall. The API rule stipulates that the working shear stress must not be larger than the allowable shear stress, which are calculated by the following formulas.

(1) Working shear stress

$$v_p = \tau \left(f_a \sin\theta / k_a + f_b / k_b \right) \qquad (1)$$

where

v_p : working shear stress

k_a, k_b : coefficients dependent on angle θ between chord and brace (When $\theta = 90^{\circ}$, $k_a = k_b = 1$)

τ, f_a, f_b : see **Fig. 2**

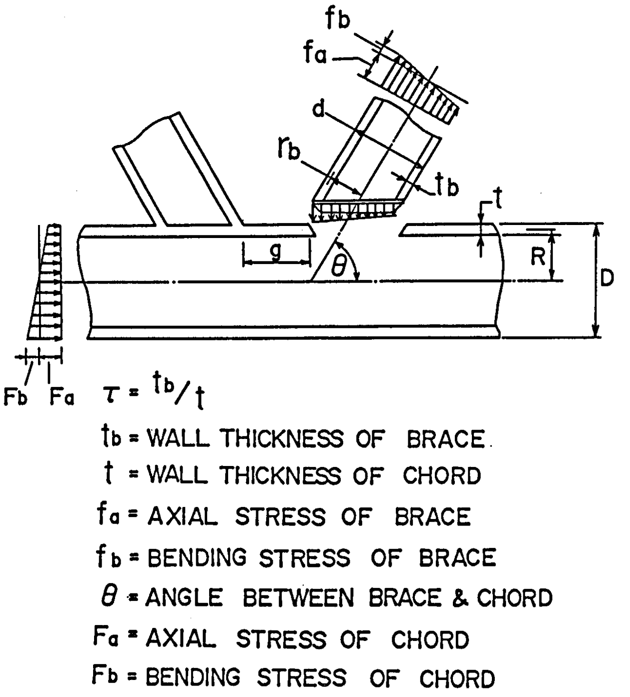


Fig. 2 Terminology and geometric parameters for tubular joint

(2) Allowable shear stress

$$V_p = Q_q\, Q_p\, Q_f\, \sigma_Y \Big/ \left(0.9\,\gamma^{0.7}\right) \qquad (2)$$

where

V_p : allowable shear stress

Q_q : coefficient dependent on joint shape and load condition

$Q_p = \cos\left((90^{\circ}) f_a \big/ (f_a + f_b)\right) + f_a \big/ (f_a + f_b)$

Q_f : coefficient dependent on axial stress acting to chord

$Q_f = 1.0 \quad \text{when} \quad A \leq 0.44$

$Q_f = 1.22 - 0.5\,A \quad \text{when} \quad A > 0.44$

$A = \left(|F_a| + |F_b|\right) \big/ \left(0.6\,\sigma_Y\right)$

F_a, F_b : see **Fig. 2**

σ_Y : yield stress of chord

$\gamma = R/t$

R : radius of chord

t : thickness of chord

3. Methods of Experiment

3.1 Experimental model

1/3-scale models were used in this study. The specifications for these models are given in **Table 1**.

Model-I has not a rib, and is loaded on a flat base. This model is used to obtain the base strength of the joint for comparison with the other models.

Model-II has not a rib like Model-I, but it is loaded on a leg guide. By comparing Model-II with Model-I, the effect of a leg guide on the strength of the joint could be easily cleared.

Model-III has a rib, and is loaded on a leg guide. The rib is welded inside of the chord at the angle of 60° to the axis of the brace (hereafter this rib will be called 60° rib). This model is the closest model to the actual joint and boundary condition. The result is compared with Model-II in order to examine the effect of a rib. In order to investigate the effect of chord–wall thickness on the ultimate strength of the joint, three models with different chord–wall thickness are prepared for Model-III.

Model IV also has a rib, and is loaded on a leg guide. But the angle of the rib is 90° to the axis of the brace (hereafter this rib will be called 90° rib). This model is compared with Model-III in order to examine the effect of the rib's angle.

3.2 Experimental procedure

The schematic of the setup of each model on the leg guide is shown in **Fig. 3**. The load on the top of the brace was gradually increased. The plastic deformation was produced initially at the largest stress, and developed widely. When the stiffness, which is the tangent of the load-displacement curve, remarkably reduces due to the plastic deformation, the load control was changed to the displacement control, measuring the corresponding load.

The load, displacements and strains were measured as follows.

(1) Load : The load was measured by means of the load meter of the testing machine and the load cell placed beneath the leg guide or on the model.

(2) Displacement : The displacements were measured by means of electric displacement transducers. The measured points were around the center section, and along the longitudinal lines of the top and bottom of the chord.

(3) Strain : The strains were measured by means of wire strain gauges. The strain gauges were attached on the inner and outer surfaces around the center section, along the longitudinal line of the top of the chord, around the connection between the brace and the chord, and on the center of the rib.

Particular attention was paid to the longitudinal and transverse balances of the normal load not to produce the moments for the center of the joint, referring the above measured results, on real time.

4. Results of Experiment and Consideration

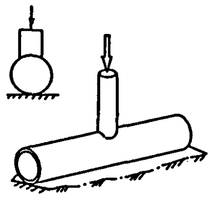
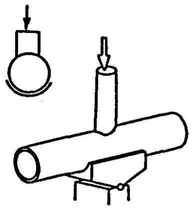
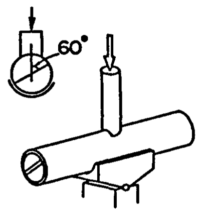
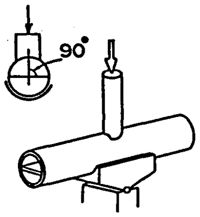
4.1 Initial Stiffness

The load-displacement curves obtained by the experiments are shown in **Fig. 4**. The displacement increases in proportion to the load in the early loading stage. The initial stiffnesses which are the tangents of the load-displacement curves, are grouped into two, in Fig. 4 (a). One is M-I, M-II, M-III, and the other is M-IV. The 90° rib strengthens the initial stiffness, while the leg guide and the 60° rib do not strengthen the stiffness. The reasons are as follows.

(1) There is a certain clearance between the chord and the guide except on the contact line. Until the chord contacts the guide widely, the guide does not restrict the deformation of the chord and does not affect the stiffness of the chord. The effect of the clearance will be discussed in the next report.

(2) The effectiveness of the rib depends on the magnitude of the deformation at the location where the rib is welded. When the chord has no rib inside, the change of the diameter of the chord by loading is largest in the direction of the axis of the brace (the diameter from 0° to 180°) and the direction perpendicular to the axis (the diameter from 90° to 270°). While it is very small near the diameter from 60° to 240°. The 90° rib is welded in the direction of the

Table 1 Particulars of models

		MODEL - I	MODEL - II	MODEL - III			MODEL - IV
				III - 1	III - 2	III - 3	
DIA OF CHORD (mm)		298.5	298.5	298.5			298.5
WALL THICKNESS OF CHORD (mm)		15.43	15.07	14.04	12.13	9.96	14.01
DIA OF BRACE (mm)		133.0	133.0	133.0			133.0
WALL THICKNESS OF BRACE (mm)		9.5	9.5	9.5			9.5
THICKNESS OF RIB (mm)		——	——	5.59	5.62	5.96	6.09
YOUNG'S MODULUS (Kgf/mm^2)		18,800.0	18,800.0	21,400	19,400	20,700	21,400.0
YIELD STRESS (Kgf/mm^2)		34.1	34.1	29.2	29.0	29.0	29.2
POISSON'S RATIO		0.31	0.31	0.29	0.30	0.29	0.29
SCHEMATIC VIEW							
ULTIMATE LOAD (tonf)	EXP.	73.7	93.5	81.0	62.7	41.2	80.2
	ANA	70.0	95.5	81.0	61.0	42.5	80.5

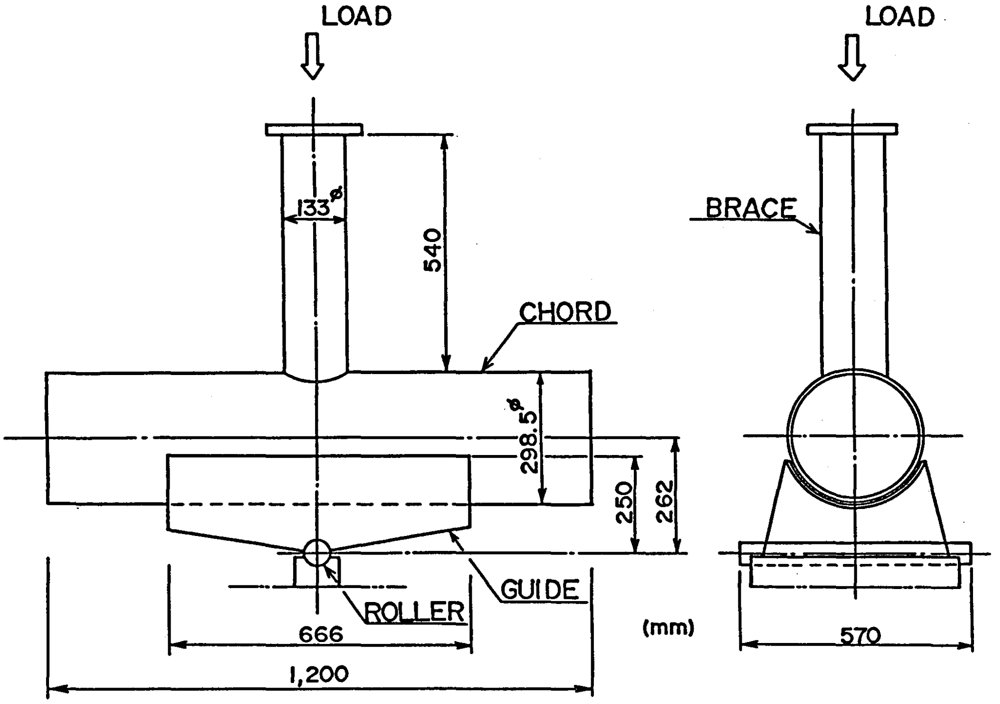
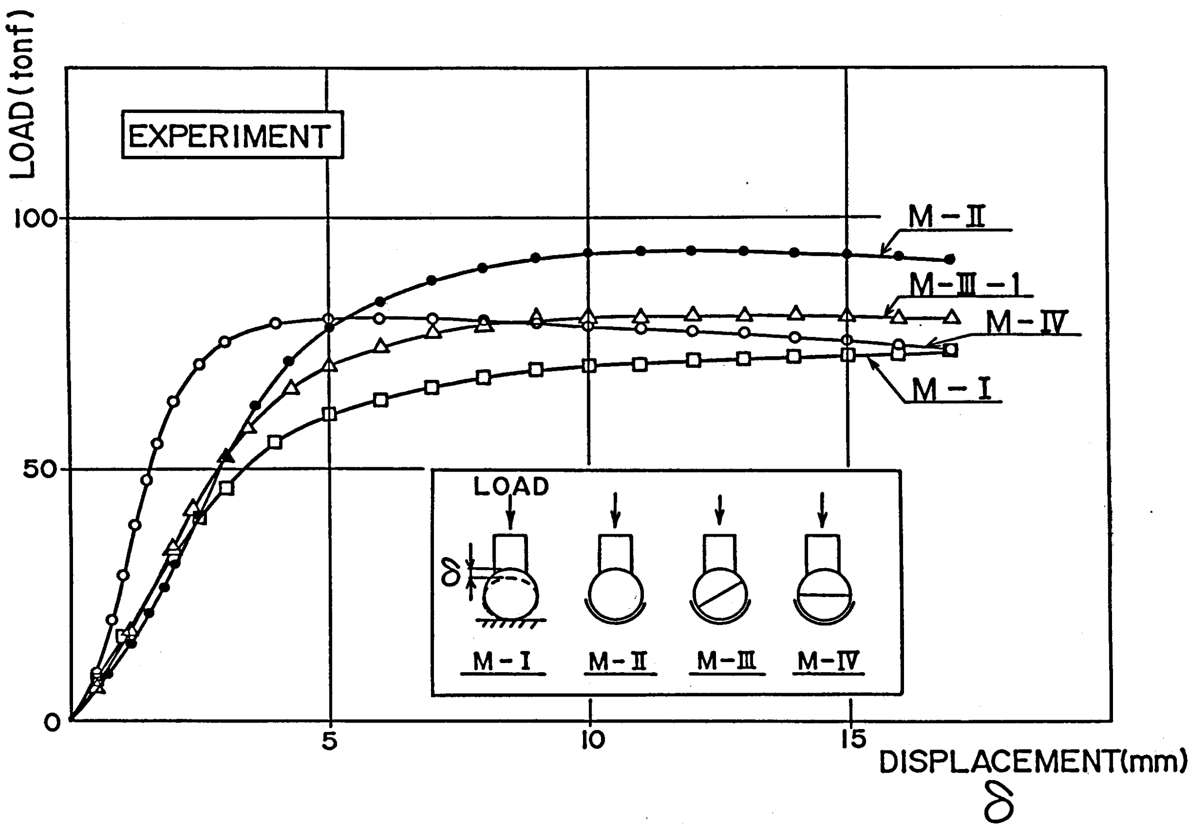
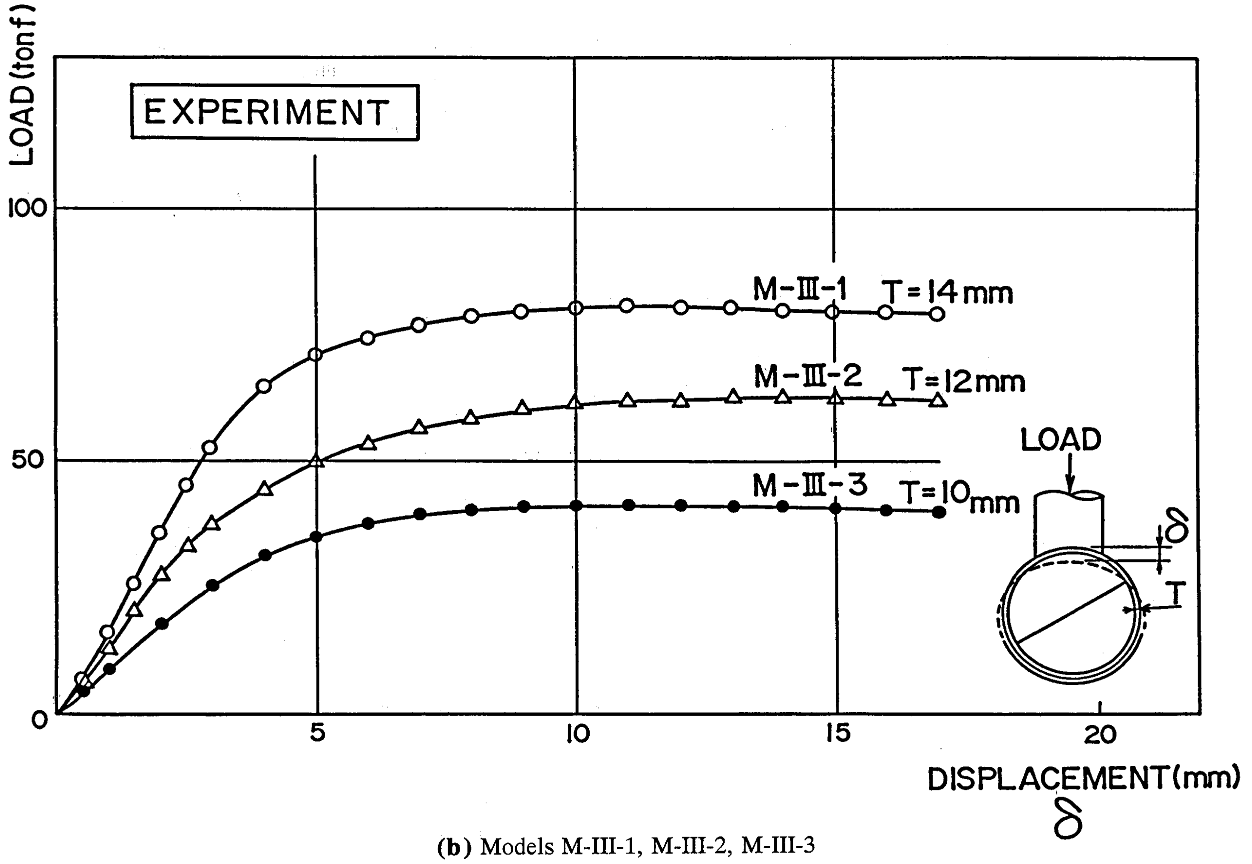


Fig. 3 Schematic of setup of model on leg guide



(a) Models M-I, M-II, M-III-1, M-IV



(b) Models M-III-1, M-III-2, M-III-3

Fig. 4 Measured load –displacement curves largest deformation, and is effective to restrict the deformation. The 60° rib is welded in the direction of the very small deformation, and is little effective.

From Fig. 4 (b), it is observed that the thickness of the chord-wall acts on the initial stiffness according to the second power of the thickness.

4.2 Ultimate strength

4.2.1 Effect of thickness of chord-wall

The ultimate strength of the normal unstiffened T-joint is expressed by the following experimental formula, which has no rib and is not put on the guide (both ends of chord are supported or fixed).

$$P_u = \sigma_Y T^2 f(d/D) \tag{3}$$

where

P_u : ultimate strength

σ_Y : yield stress

T : thickness of chord-wall

d : diameter of brace

D : diameter of chord

The ultimate strength expressed by Eq. (3) is proportional to the yield stress and the second power of the thickness of the chord-wall when the ratio d/D is the same. The Model-III-1, Model-III -2, and Model-III -3 have the same d/D ratio, so they have the same f(d/D). Their normalized ultimate strengths are shown in **Fig. 5**, which are divided by the yield stress and the second power of the chord thickness. The normalized ultimate strengths are almost the same. Accordingly, Eq. (3) may be applied to the T-joint with the 60° rib and on the leg guide, to estimate the effect of the thickness of the chord-wall.

4.2.2 Effects of leg guide and rib

The effects of the leg guide and the rib can be investigated by comparing the normalized ultimate strengths of Model-I, Model-II, Model-III and Model-IV, which are modified for the differences of the yield stress and the chord thickness. The yield stress and the chord thickness of each model are shown in Table 1. From the consideration in Sec. 4.2.1, the effects of the yield stress and the chord thickness may be taken out by dividing by the yield stress and the second power of the chord thickness. The normalized ultimate strengths of four Models are normalized again by the one of Model-I . The results are shown in **Fig. 6** (the analytical results in this figure will be described in the next report). From Fig. 6, it is observed that ;

(1) In the case of the unstiffened joints, the ultimate strength loaded on the leg guide is 30% higher than on the flat base (Model-I, Model-II).

(2) When the rib is incorporated, the ultimate strength on the guide is even 20% higher than without the rib, independent of the angle of the rib (Model-II, Model-III, Model-IV).

The reason why the ultimate strength increases is that the leg guide and the rib restrict the deformation of the chord. As the result, the chord locally deforms near the welding connection with the brace. The difference of the deformations is shown in **Fig. 7** (the analytical results in this figure will be described in the next report). The local deformation is harder to occur than the whole deformation, accordingly the ultimate strength increases. The 60° rib and the 90° rib have almost the same effect when the guide contacts the chord widely.

5. Conclusion

An experimental investigation was carried out in this study, into the local stiffness and strength of the T-joint of circular tubes under normal load. The main conclusions are as follows.

A. The local stiffness of the T-joint

(1) The effect of the thickness of the chord-wall

The thickness of the chord-wall affects the initial stiffness according to the second power.

(2) The effects of the leg guide and the center stiffening rib

Until the chord contacts the guide widely, the guide does not restrict the deformation of the chord and does not affect the stiffness of the chord. The effect of the clearance between the chord and the guide will be discussed in the next report.

The effectiveness of the rib depends on the magnitude of the deformation when the chord has no rib inside, at the location where the rib will be welded.

B. The local strength of the T-joint

(3) The effects of the thickness and the yield stress of the chord-wall

The thickness and the yield stress of the chord-wall have effects on for the ultimate strength of the joint according to the second power and the first power, respectively, similar to the normal unstiffened T-joint.

(4) The effects of the leg guide and the center stiffening rib

In the case of the unstiffened joints, the ultimate strength loaded on the leg guide is 30% higher than on the flat base. When the rib is incorporated, the ultimate strength on the guide is even 20% higher than without the rib. The 60° rib and the 90° rib have almost the same effect.

The reason why the ultimate strength increases is that the leg guide and the rib restrict the whole deformation of the chord. As the result, the chord locally deforms near the welding connection with the brace.

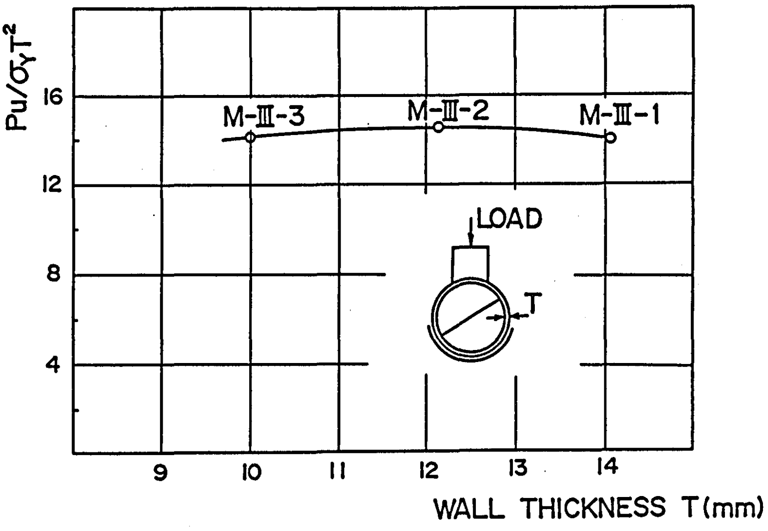


Fig. 5 Normalized ultimate strengths of models M-III-1, M-III-2, M-III-3

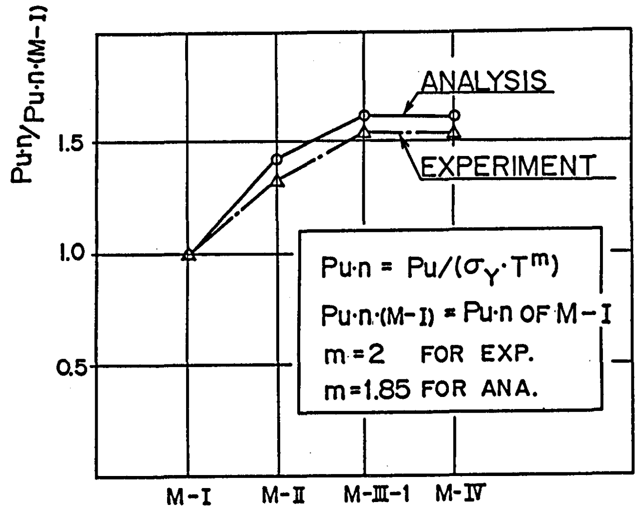
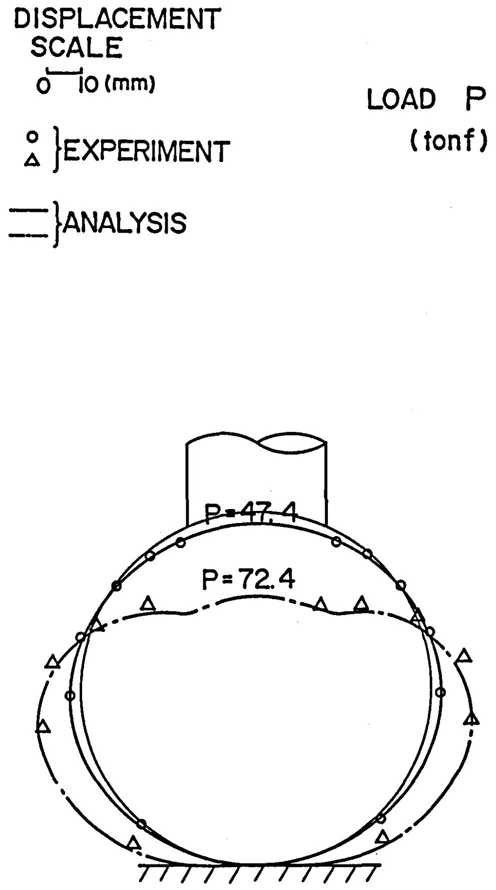
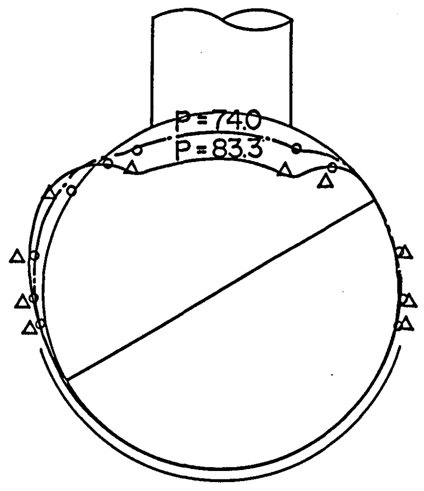


Fig. 6 Normalized ultimate strengths of models M-I, M-II, M-III-1, M-IV



(a) Model M-I



(b) Model M-III-1

Fig. 7 Deformations of center section of chord

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