Steel and Composite Structures, Vol. 3, No. 5 (2003) 321-331 321
DOI: http://dx.doi.org/10.12989/scs.2003.3.5.321

Comparative behaviour of stiffened and unstiffened welded tubular joints of offshore platforms

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(Received April 7, 2003, Accepted August 4, 2003)

Abstract. The paper presents the results of an experimental investigation conducted on welded tubular joints, that are employed in offshore platforms, to study the behaviour and strength of these joints under axial brace compression loading. The geometrical configuration of the joints tested were T and Y. The nominal diameter of the chord and brace members of the joint were 324 and 219 mm respectively. The chord thickness was 12 mm and the brace 8 mm. The tested joints are approximately quarter size when compared to the largest joints in the platforms built in a shallow water depth of 80 m in the Bombay High field. Some of the joints were actually fabricated by a leading offshore agency which firm is directly involved in the fabrication of prototype structures. Strength of the internally ring-stiffened joints was found to be almost twice that of the unstiffened joints of the same configuration and dimensions. Bending of the chord as a whole was observed to be the predominant mode of deformation of the internally ring-stiffened joints in contrast to ovaling and punching shear of the unstiffened joints. It was observed in this investigation that unstiffened joint was stiffer in ovaling mode than in bending and that midspan deflection of unstiffened joint was insignificant when compared to that of the internally ring stiffened joint. The measured midspan deflection of the unstiffened joint in this investigation and its relation with the applied axial load compares very well with that predicted for the brace axial displacement by energy method published in the literature. A comparison of the measured deflection and ovaling of the unstiffened joint was made with that published by the author elsewhere in which numerical prediction of both quantities have been made using ANSYS software package. The agreement was found to be quite good.

Key words: offshore platforms; tubular joints; internally ring-stiffened; unstiffened; testing; behaviour; strength.

1. Introduction

Offshore platforms serve as artificial bases, supporting drilling and production facilities above the elevation of waves. The most popular structure for shallow water depth of up to 200 m is the jacket platform (Thandavamoorthy 2002). Cylindrical steel tubular sections, because of their merit over other structural shapes, are used quite commonly in the construction of jacket structures (Chen and Han 1985). In the past four decades, thousands of large tubular structures have been built for offshore oil drilling and production. At present there are more than 7000 offshore platforms worldwide (Digre *et al*. 1994). In the tubular frame, the intersection between the brace and the chord (main leg) is welded and

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forms tubular joints. A joint without reinforcement of any sort is called an unstiffened joint while that with reinforcement is termed as stiffened joint.

The joints must be properly dimensioned during the design stage so that they perform satisfactorily in service and achieve a reasonable balance between economy and risk of failure. The basic design requirements of joints are that they must possess adequate static strength and satisfy fatigue endurance requirements (UEG 1985a). If the capacity of a joint is found to be inadequate during the design stage, it can be enhanced by introducing stiffeners to the inside of the chord as this is an efficient method to reduce stress concentration, increase load carrying capacity and fatigue life of joint (Bozhen 1990), decrease the bending stress in tube walls and avoid attraction of additional wave forces. These types of joints are called internally ring-stiffened joints.

Internally ring-stiffened tubular joints are used widely in the construction of fixed steel platforms (Wimpey 1991) and it is estimated that there are at least two thousand ring-stiffened joints in North Sea structures (Tahan *et al*. 1992). Sawada *et al*. (1979) have carried out static and fatigue tests on T joints stiffened by an internal ring consisting of four pieces built by butt welding. Under axial brace loading cracks appeared in the butt welds of the ring and hence it was difficult to quantify the effect of the crack on the ultimate load. In view of this difficulty, usage of single piece rings has been advocated. However, with a single stiffener at centre of the chord member, deformation of the chord wall still persisted and ovalization of the tubular member itself occurred because the bending action of the chord wall serves to extend the area over which the stiffening is effective. One ring stiffener is effective over an axial distance along the chord of approximately one-half times the square root of the product of the chord wall thickness and the chord radius (Graff 1981). Therefore stiffening of the chord with three internal rings, one at the centre and the remaining two at the brace faces, is found to be the most effective way of strengthening of tubular joint (Shiyekar *et al.* 1983).

Extensive studies have been carried out on unstiffened tubular joints, as a result of which the behaviour under various types of loading has been well understood and methods of assessing the capacity have also been very well developed and in this process a database has been created (UEG 1985a, 1985b, 1985c, Lalani *et al*. 1986). But little effort has been made to study in detail the behaviour and capacity of internally ring-stiffened tubular joints. However, limited experimental and numerical studies to the extent of the estimation of stress concentration factors for internally ring-stiffened joints have been carried out (Shiyekar and Kalani 1983, Shiyekar *et al*. 1983, Ramachandra Murthy *et al*. 1991, Nwosu *et al*. 1995). In these studies a small load below the elastic limit was applied on the joint to determine the stress distribution around weldment. This load was insufficient to disclose the exact behaviour of the internally ring-stiffened joints. Moreover in these studies the treatment given to internally ring-stiffened joints was mainly based on the behaviour of the unstiffened joints. Data on the behaviour of internally ring-stiffened joints up to ultimate load are scarce. Therefore, there is a need to have basic understanding of the complete behaviour of the internally ring-stiffened joints. The comparative behaviour and strength between both category of joints has seldom been investigated. The advantage of the joints stiffened internally with rings in enhancing the capacity has not been brought out clearly in terms of specific quantity. Therefore experimental programme was planned to conduct monotonic tests on both unstiffened and internally ring-stiffened joints of the same size and dimensions to bring out in clear terms the difference in their behaviour and strength (Thandavamoorthy 1998).

The paper presents in detail the experimental investigations carried out on tubular joints both unstiffened and stiffened internally with three annular rings. Results of the static tests on unstiffened T joints and internally ring-stiffened T and Y joints under axial brace compression loadings are presented. Comparison of the behaviour of the internally ring-stiffened joints under axial brace compression loadings has been made with that of the unstiffened joints of the same dimensions and configurations under identical loadings. Experimental results were compared with the published theoretical ones and the correlation was found to be good.

2. Experimental programme

The geometrical configuration and nominal dimensions of the unstiffened joint is shown in Fig. 1 and that of the internally ring-stiffened T joint in Fig. 2 and Y joint in Fig. 3. In the internally ring-stiffened joint, three annular rings, each 12 mm thick and 75 mm wide, have been welded to the inside of the chord member at the intersection of the brace. While one of the rings has been welded at the centre of the brace, each of the other two, at either face of the brace as shown in Figs. 2 and 3. The dimensions of both categories of tubular joints are given in Table 1. The ends of the chord and brace members were sealed by 32 mm thick flange plates to facilitate mounting of the specimen in the test set-up.

While the diameters of the chord and the brace, given in Table 1, are measured values, the thicknesses are nominal ones, since it was not possible to measure the thicknesses. In all, two unstiffened joints of T configuration and two internally ring-stiffened tubular joints, one T and one Y, were tested. The material qualities of both chord and brace members of one of both stiffened and unstiffened joints were in conformity with the API5L GB (API, 1993) grade steel with the yield strength of 240 MPa and an ultimate tensile strength of 415 MPa. The remaining two joints, one in each category, belonged to the material quality specified in IS:226 (1975).

With the dimensions that have been chosen for the tubular joints, these correspond to a large number of the joints in the platforms of the Bombay High field. This field with 148 fixed platforms (Kekre 1994) is the biggest Indian oil and gas fields in the Arabian Sea. Compared with the largest joints in

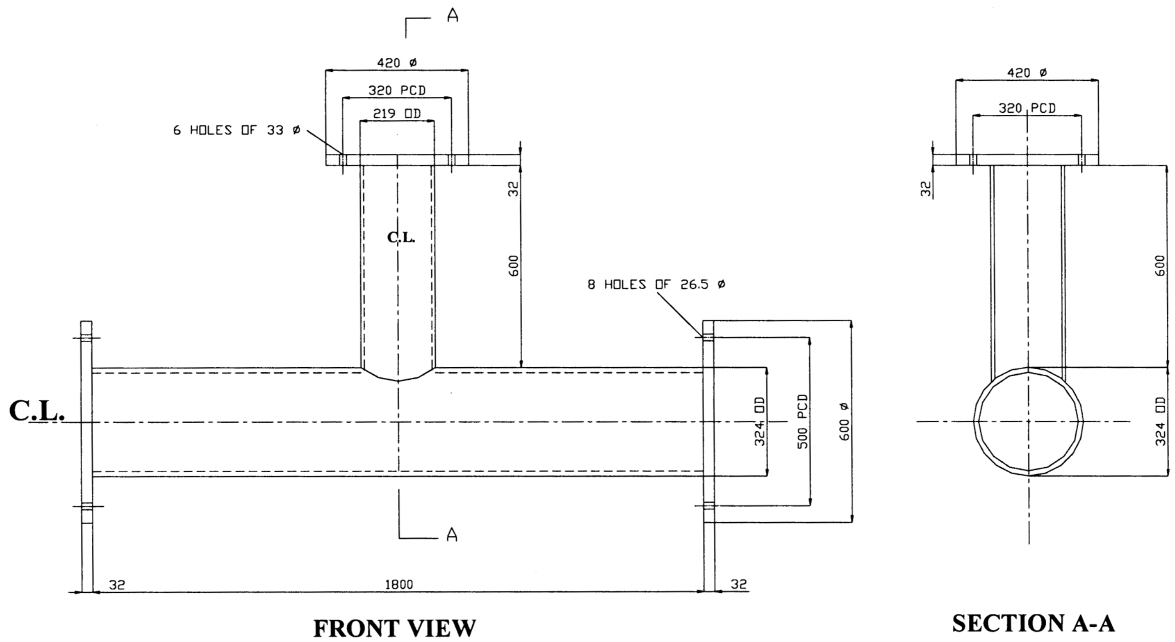


Fig. 1 Typical dimensions of unstiffened T joint

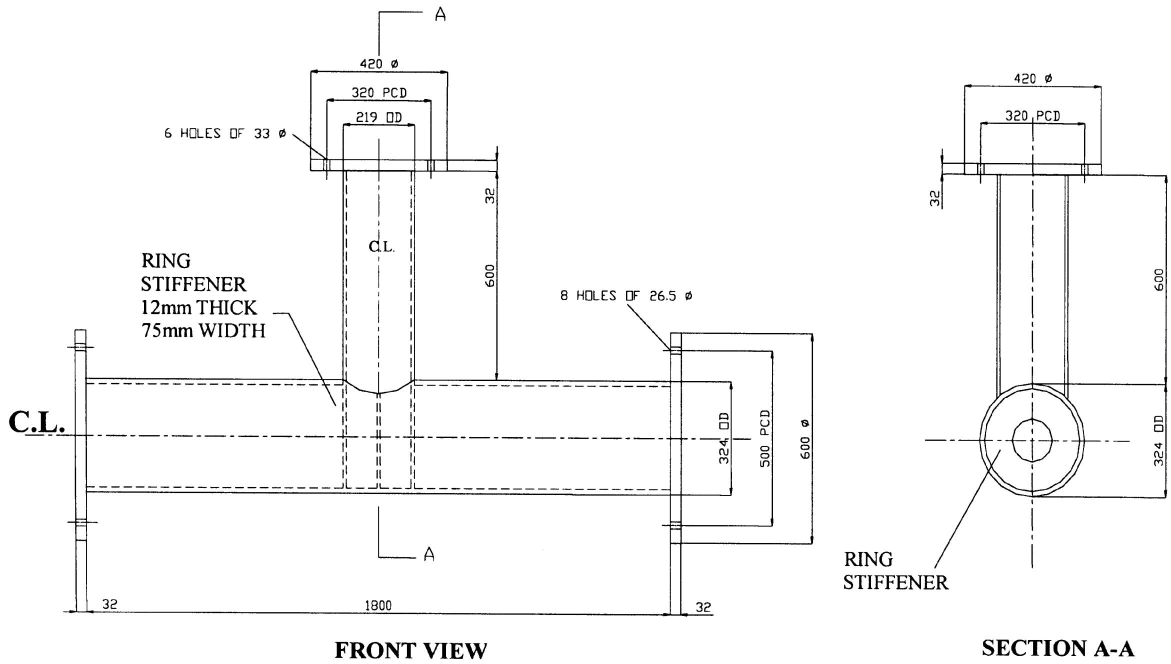


Fig. 2 Dimensions of typical internally ring-stiffened T-joint

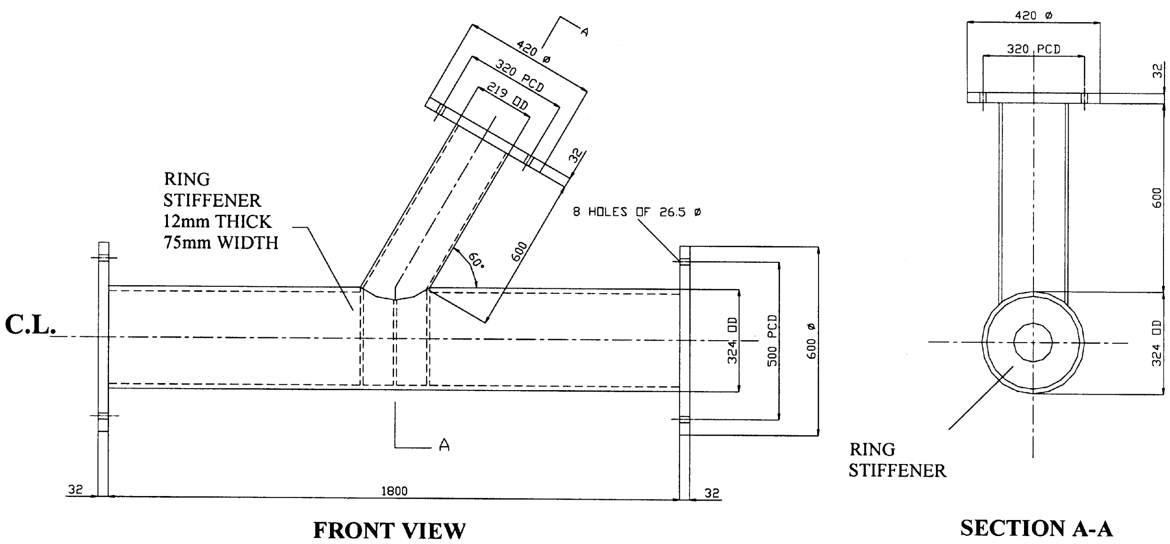


Fig. 3 Dimensions of typical internally ring-stiffened Y-joint

these platforms, the actual test joints are approximately quarter size.

In the fabrication of the tubular joint test specimens, it has been emphasized that fabrication procedures, dimensions, materials, welding, quality control, etc., correspond as precisely as to actual offshore structures. Some of the tested joints were, in fact, fabricated with the same grade of steel used for offshore structures by M/s Mazagoan Dock Ltd., Bombay, which firm is directly involved in the fabrication of

Table 1 Dimensions of tubular joints

S. No.	Specimen No.	Dimensions of joints (mm)				Remarks
		Chord		Brace		
		Diameter[a]	Thickness[b]	Diameter[a]	Thickness[b]	
1	UDT1[d]	323.08	12	221.54	8	Stiffened
2	UDY1[c]	327.22	12	221.23	8	Stiffened
3	UDTU1[c]	324.80	12	219.80	8	Unstiffened
4	UDTU2[d]	326.0	12	221.00	8	Unstiffened

Note: a.-Measured values
b.-Nominal Values
c.-API5L GB steel (1993)
d.-IS: 226 steel (1975)

the prototype structures. This means that the tubular joints tested can be considered to be representative for a large number of platforms built in the Bombay High in shallow water depths of up to 80 m and also similar other environments elsewhere in the world.

The joints were fixed to the steel pedestals by bolting. The base of the pedestals were, in turn, fixed to the strong concrete floor by means of 60 mm size mild steel bolts. The entire assembly was placed under a reaction frame (Fig. 4). On the flange of the brace member, a built-up steel joists assembly and two numbers of 2000 kN Enerpack hydraulic jacks were placed as shown in Fig. 4. They were arranged

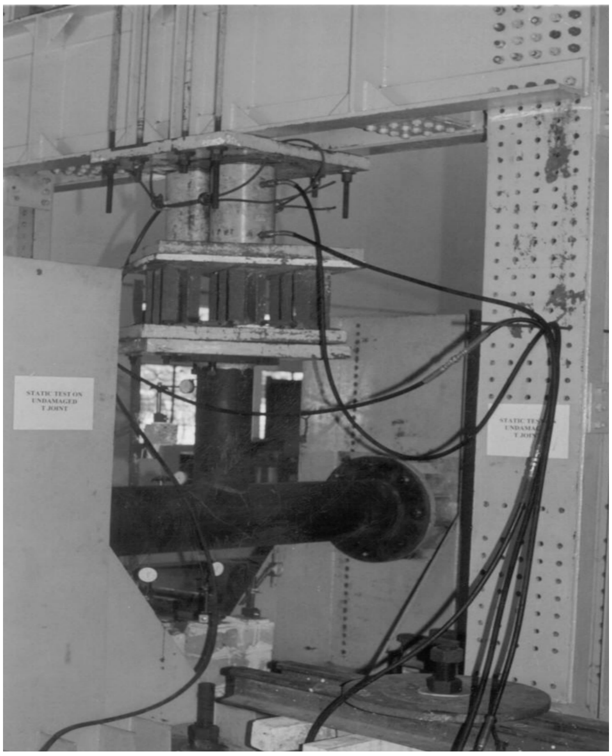
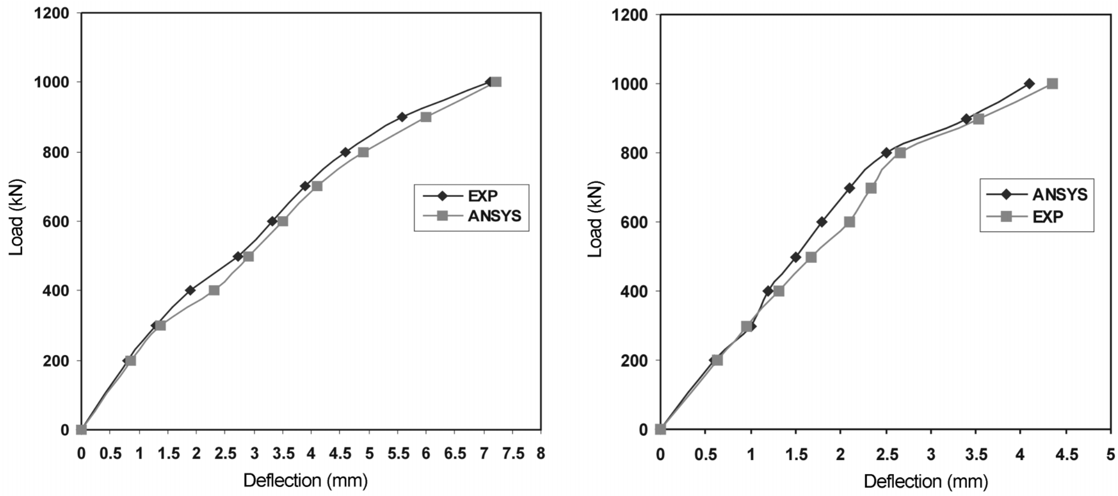


Fig. 4 Test set up

Table 2 Measured and predicted loads

S. No.	Specimen No.	Ultimate load (kN)	
		Experimental	Theoretical
1	UDT1	1887.60	1985.21
2	UDY1	1834.00	1834.05
3	UDTU1	985.60	610.69
4	UDTU2	996.20	611.86

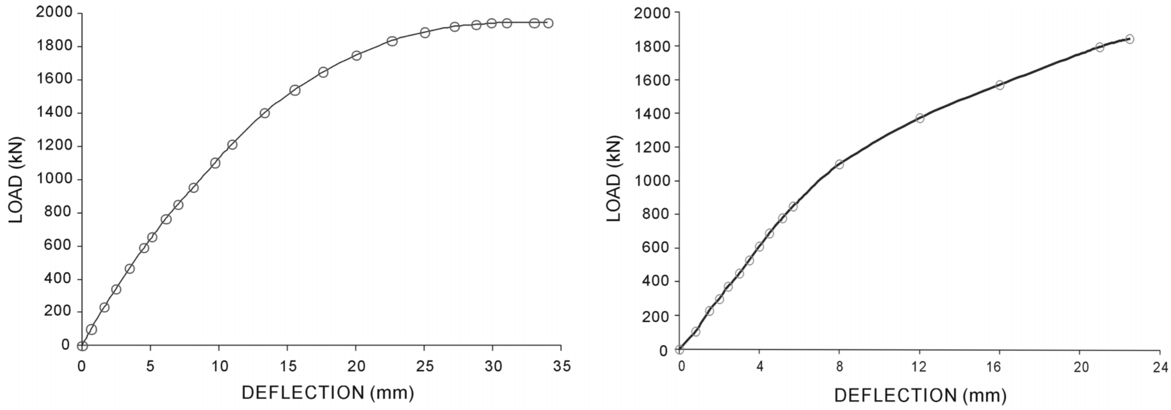


(a) Typical load-Midspan deflection curve (b) Load vs Ovalation Deformation, Typical

Fig. 5 Behaviour of unstiffened joint

below the cross beam of the reaction frame. Another 1000 kN hydraulic jack and a 1000 kN Proceq load cell were placed in a self-straining frame that was kept by the side of the reaction frame on the test floor. All the three hydraulic jacks were connected through distributors to the electrical pumping unit by means of high pressure rubber hoses. Axial brace compression loading was applied on the joints by means of the hydraulic jacks mounted on the brace. Load was applied on the specimen in equal increments.

Three dial gauges were mounted beneath the joint (Fig. 4), one directly at mid-span under the load point and others approximately at third points, to facilitate measurement of the deflection under load. In the case of Y joint dial gauges were fixed perpendicular to the chord member. In the case of unstiffened joint, a dial gauge was placed horizontally (Fig. 4) at the centre of the chord member at the intersection to measure its ovaling deformation. A dial gauge was placed laterally at the brace end to see whether there was any out-of-plane displacement of the brace as a whole. For each load increment, deflection readings of all the gauges were recorded. Load was monotonically increased till the joint reached its ultimate strength. The ultimate loads sustained by both category of joints are given in Table 2. Typical load-midspan deflection curve of unstiffened joint is shown in Fig. 5(a). The ovaling deformation vs. load for the unstiffened joint is shown in Fig. 5(b). Typical load vs. mid-span deflection curve for the T joint UDT1 is depicted in Fig. 6(a). In the case of Y joints, the component of the deflection along the direction of loading was resolved from the measured values. Corresponding load-deflection curve for the mid-span for Y joint UDY1 is illustrated in Fig. 6(b). A comparison of the deflections at mid-span of the both unstiffened and stiffened T joints is shown in Fig. 7.



(a) Load-deflection curve of T-joint (b) Load-deflection curve of Y-joint

Fig. 6 Behaviour of internally ring-stiffened joint

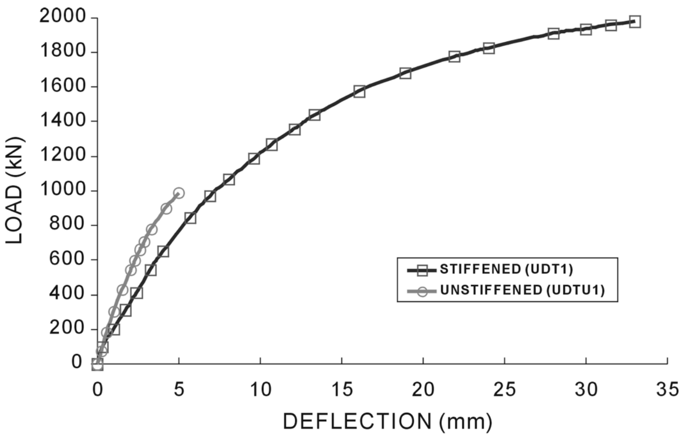


Fig. 7 Comparison of midspan deflections of unstiffened and stiffened joints

3. Results and discussion

The ultimate load resisted by the two unstiffened joints UDTU1 and UDTU2 were 985.6 kN and 996.2 kN, respectively. Using the closed form solution suggested by Yamasaki *et al.* (1979) for the evaluation of ultimate strength of tubular joints, the loads sustained by the two unstiffened joints UDTU1 and UDTU2 were determined and the values are summarized in Table 2. The closed form solution is able to predict only about 60 per cent of the experimental values. The internally ring stiffened T joint sustained an ultimate load of 1887.60 kN and Y joint 1834.00 kN. The ultimate strength of the stiffened joints were determined theoretically based on a methodology developed by the author and published elsewhere (Thandavamoorthy 1998). The theoretical values are given in Table 2. The agreement between the experimental and theoretical values is found to be good. A comparison of the ultimate strength of the internally ring-stiffened with that of unstiffened joints (Table 2), has disclosed that the ultimate strength of ring-stiffened joints is almost twice that of the unstiffened joints of the same configuration and dimensions and tested under identical loading and with the same boundary conditions.

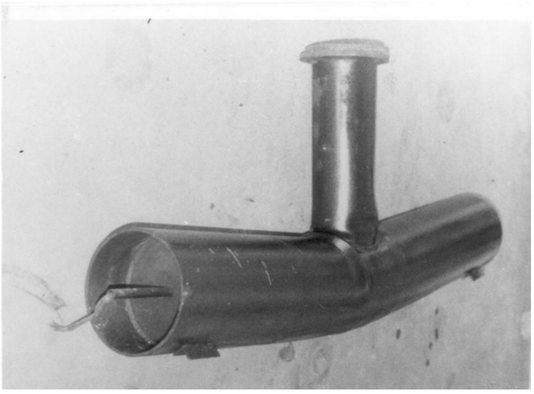


Fig. 8 Bending of the stiffened joint

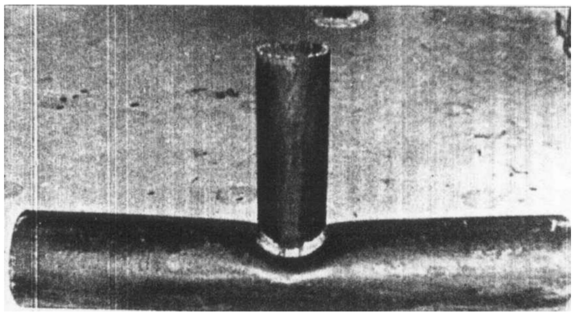


Fig. 9 Punching shear failure of unstiffened joint

In the case of internally ring-stiffened joints, the shape of the load-deflection curve (Fig. 6) is similar to that of a prismatic beam subjected to flexural loading. At ultimate load, in both cases of T and Y joints, large deflections at mid-span were noticed during testing. The maximum midspan deflection registered by the T joint was 32 mm and Y joint 24 mm at ultimate load. Due to the inducement of an axial force in the chord member of the Y joint, the joint became stiffer and hence the maximum deflection was reduced when compared to that of the T joint.

The stiffened joint has exhibited a strain hardening characteristics. This has imparted enormous ductility to the joint. The chord member as a whole was bent like a prismatic member (Fig. 8). Absolutely no deformation of the chord wall and consequent ovaling in the vicinity of the welded intersection of the internally ring-stiffened joints were observed in this experimental investigation. Right from the inception of the loading till failure, bending was observed to be the predominant mode of deformation under axial brace compression loading. This predominant flexural behaviour of the ring-stiffened joints, quite different from that of the unstiffened joints, truly represents the realistic global behaviour of the structure, as the prototype structure also behaves in much the same way. This is quite evident from the global responses obtained from the collapse tests conducted by Bolt *et al*. (1994) on large scale tubular frames representative of offshore jacket structures.

In contrast to this, in the case of the unstiffened joint, it was observed that the chord wall in the vicinity of the welded intersection deformed continuously under loading till a large deformation occurred at ultimate load resulting in punching of the brace into the chord. This phenomenon resulted in the ovaling of the chord member in the vicinity of the welded intersection (Fig. 9). It has been reported by Hauch and Bai (2000) that a pipe subjected to increasing pure bending will fail as a result of increased ovalization of the cross section. Up to a certain level of ovalization, the decrease in moment of inertia will be counter-balanced by increased pipe wall stresses due to strain hardening. When the loss of moment of inertia can no longer be compensated for by strain hardening, the moment capacity has been reached and catastrophic cross-sectional collapse will occur if additional bending is applied. The ovaling of the chord member has the cascading effect of drastically reducing the load carrying capacity of the joint.

Thandavamoorthy and Senthil Anand (2002) have carried out numerical investigation using ANSYS software package to determine the ultimate strength and study the behaviour of unstiffened joint. In this investigation, the ovaling and punching shear failure of the joint, as observed in the experiment, has

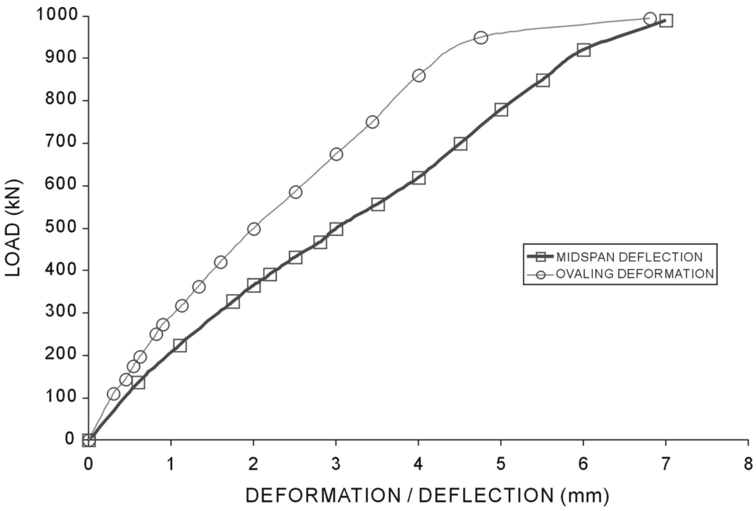


Fig. 10 Superposition of midspan deflection and ovaling deformation

been simulated numerically. The numerically predicted midspan deflection is shown in Fig. 5(a) and the ovaling deformation in Fig. 5(b). Fig. 5 clearly indicates a close agreement between the midspan deflection and ovaling deformation of the unstiffened joint predicted numerically and that observed in the experiment.

In the context of the development of energy based method for the prediction of elastic plastic force displacement and/or moment rotation responses of tubular joints, Leen and Hyde (2000) have reported that the brace axial displacement at failure of joints ranged from about 3 mm to 8 mm. The variation of the brace axial displacement with force was also presented. The trend predicted by Leen and Hyde (2000) exactly matches with the variation obtained by the author in this experimental investigation. Also, numerical values of displacement are found to be in good agreement with that measured by the author.

From a comparison of the mid-span deflections of both unstiffened and stiffened joints (Fig. 7), it is observed that the mid-span deflection of the unstiffened joints is not at all significant when compared to that of the stiffened joints. Also, within the range of midspan deflection undergone by the unstiffened joint, the behaviour of unstiffened joint is stiffer than the internally ring-stiffened joint. This is because of the reason that due to ovaling of the chord member, it was rendered stiffer than the chord member of the stiffened joint resulting in the reduction in the midspan deflection values. The mid-span deflection and ovaling deformation of a typical tested unstiffened joint are superimposed in Fig. 10. Ovaling and bending of the unstiffened joint occurred simultaneously under loading right from its inception. At the initial stages of loading, the ovaling deformation is almost equal in magnitude to the mid-span deflection. Afterwards, the mid-span deflection is higher indicating that the joint is more flexible bending-wise than ovaling. At the failure load, the ovaling deformation and the mid-span deflections are almost equal. This means the ovaling and bending stiffnesses of the joint are equal both at the initial and ultimate loads. These particular aspects of the response of the unstiffened joint as well as the bending of the stiffened joint have not been reported earlier.

4. Conclusions

Experimental results obtained from the testing of both unstiffened and internally ring-stiffened tubular joints under axial brace compression loading and a comparison of results clearly show the difference in behaviour between both categories of joints. In the case of stiffened joint, bending was observed to be the predominant mode of deformation. This is similar to that of a prismatic member subjected to flexural loading. This is in contrast to the primary mode of failure of ovaling and punching of the chord member of the unstiffened joints. However, this drastic change in behaviour of the internally ring-stiffened tubular joints has not been reported earlier.

It has been observed from the experimental investigation that welding of three annular ring stiffeners to the inside of the chord member has resulted in completely eliminating the local bending and ovaling of the chord wall in the vicinity of the welded intersection. This arrangement has also imparted enormous bending stiffness to the chord as a whole with the result the behaviour of the internally ring-stiffened joints has drastically changed from the punching shear to bending deflection. The predominant bending behaviour of the chord member truly represented the realistic global behaviour of the structure as the prototype structure behaves in much the same way.

A comparison of the mid-span deflections of unstiffened and stiffened joints showed that the mid-span deflection of the unstiffened joints was insignificant when compared to that of the stiffened joints. Little attempt has been made earlier to compare the behaviours of both categories of joints. It was observed in this investigation that the unstiffened joint was stiffer in ovaling mode than in bending deflection. The numerical value of the midspan deflection of the unstiffened joint and its variation with the load compares very well with that predicted for the brace axial displacement by the energy method published in the literature. The experimental and published numerical results, using ANSYS software, of the midspan deflection and ovaling of the unstiffened joint compare very well.

Strength of the internally ring-stiffened joint was observed to be almost twice that of the unstiffened joint of the same dimensions under identical loading type. The experimentally measured strength of the stiffened joint is in close agreement with that predicted theoretically earlier by the author. The closed form solution available in the literature for the determination of the ultimate strength of the unstiffened joint is able to predict only upto 60 per cent of the experimental value.

Acknowledgments

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