Pakistan Journal of Applied Sciences 1 (1): 33-38, 2001

Deformation of Circular and Elliptical T-Tubular Joint Chords Under Different Loading Modes

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Abstract: T-tubular joints of elliptical and circular cross-sections tubes for the main tube (chord) welded to circular cross-section tubes for the branches (braces) have been tested experimentally. Three cases, of joint connections, namely Case 1, Case 2 and Case 3 were selected. For Case 1, the brace is perpendicular to the circular chord outer diameter, while in Case 2, the brace was perpendicular to elliptical chord minor diameter and for Case 3 the brace was perpendicular to the elliptical chord major diameter. The chord was held as fixed-fixed condition for all cases. The material used for all tubes was mild steel. Four basic loading modes of tension, compression, in-plane bending and out of plane bending, were implemented. Load-displacement and moment-angle relations were obtained from each case and under each loading mode.
For axial tension and compression loading modes, Case 3 shows an 17.0 and 12.2% improvement respectively in the ultimate load when compared to Case 1 while 24.0 and 27.3% increase in the ultimate moment were found for in-plane and out-of-plane bending load modes respectively. On the other hand a reduction of 21.1, 27.7, 17.1 and 7.5% in the ultimate load and moment for tension, compression, in-plane bending and out-of-plane bending loading modes respectively was found when Case 2 compared to Case 1. Comparison of circular chord tubular joints test results and their empirical equations shows a good agreement. In general Case 3 shows a significant improvement in the static strength for all loading modes when compared to Case 1, while a great benefit was observed for the in-plane bending loading mode.

Key words: Tubular joints, Elliptical chords, T-joints, Axial loading, Bending, Deformation.

Introduction

Tubular joints are widely used as the main part for the construction of offshore structures. Tubes of different cross-sections have been used, while the circular type is the most common. Chords of square hollow cross-sections have been used by Ono et al (1994), or rectangular hollow cross-sections which were used by Kim et al (1994), are very general. The circular cross-section tubes are preferable than other types of sections and used extensively in offshore structure because their drag characteristics minimize wave forces on the structure, and their closed cross-section provides for buoyancy needed during installation in the ocean environment. The circular tubes are also more convenient to use, for joints than other tube shapes because of their availability in different sizes. These structures are usually under static and dynamic loading. The basic loading modes are axial tension or compression, bending and torsion or any combination of these modes. Experimental tests are generally the way to find the strength of any tubular joints. Experimental and empirical equations were developed for most types of circular joints while still there is a gap for other shapes or cross sections. Department of Energy (U. K.) report, (1990), has collected most of the experimental test results besides existing empirical equations. Steel is the basic material for these tubular joints. Different types of steels were used by Sparrow et al (1987), while mild steel is more common. Other types of materials such as; lead-tin alloy was also used by Fessler et al (1996). In this investigation one shape of steel T-joint models was tested experimentally. Many experimental tests were also carried out by Kanatani et al (1986), with different loading modes, but this was limited for circular tubular joints. Few experimental tests were carried out by Khalid et al (1998), on one shape of elliptical chords T-tubular joints and compared to the circular chords tubular joints. The chord tube was either circular or an elliptical cross-section shape while the brace was of circular cross-section tube. Four basic loading modes of tension, compression, in-plane bending and out of plane bending loads were applied. The main objective of this project is to study the effect of elliptical chords on the static strength of T-tubular joints compared with circular chord tubes under different loading modes.

Materials And Methods

Throughout this work three cases, namely Case 1, 2 and 3 of T-joints have been used. The geometry and the dimensions of the models tested are shown in Figure 1. In Case 1, the brace is perpendicular to the circular chord outer diameter, in Case 2 the brace is perpendicular to the elliptical chord minor diameter. While for Case 3, the brace is perpendicular to the elliptical chord major diameter. The chord tube for Case 1 was of circular shape with diameter D =76.2 mm. The elliptical chord tubes for the Case 2 and 3 were formed from circular tubes similar to those used for case one. The deformed tubes would have a minor diameter of D = 60 mm and a major diameter of D = 90 mm. All chord tubes have the same wall thickness of T = 2.00 mm, and chord length of L = 440 mm. All the braces were of circular cross-sections of diameter d = 42.5 mm, the wall thickness t = 2.00 mm and the brace length l =200 mm. Braces ends were milled carefully to suit the chord circular and elliptical surfaces and welded vertically at the middle of each chord. Four loading modes of tension, compression, in-plane bending and out of plane bending loading were applied separately. All the tubes for chords and braces were of the same material, mild steel. Three tensile specimens were taken from the chord tubes for each of the three cases at different positions and tested for their yield and ultimate tensile strength. The average values of the yield strength was found to be σ_y = 315 N/mm² and the ultimate strength was σ_u = 362 N/mm², while the modulus of elasticity was E = 200 GN/m².

In order to create the loading modes needed on the brace while the chord was kept under fixed-fixed end conditions, a rig has been designed and fabricated as shown in Figure 2. The set-up was arranged in such a way that the rig would be fixed to the instron machine. The chord ends will be fixed to the rig then the load will be applied vertically for all cases under different loading modes. For tension loading, flange and bar were welded to the free end of the brace to make gripping easier. For compression, in-plane bending and out of plane bending loading ball joint was used to create a point load then create the moment needed. The experimental rig was designed carefully to stand all the expected loads and moments with a factor of safety of 2.0 as a base. The rig was fixed to a computer-controlled servohydraulic instron universal-testing machine. The load is applied using the instron actuator. The value of the load applied and the displacement was captured and stored by the computer. Load-displacement relations were recorded for each test carried out. For bending load these records were transferred to moment angle relations. The brace angle was calculated using the displacement moved by the brace free end with respect to its original position. The load of interest is the maximum ultimate load, which the joint could stand. After reaching that load the test would be stopped.

Results and Discussion

A total of 36 experimental tests have been carried out. For every test done, the load-displacement curve was drawn. Three models for each loading mode of each case were tested. Tension loading results for all cases are shown in Figure 3 while Figure 4 shows the compression loading results for all cases. In addition, the in plane bending loading test results for all cases are shown in Figures 5. Furthermore, the out of plane bending moment test results for all cases are shown in Figure 6. It could be noticed from the experimental results shown in Figures (3 to 6) that, in the early stage of loading there is a linear relationship in elasticity and the increment of deformation increases gradually up to the yielding point. Afterwards a non-linear relationship in plasticity up to the maximum load or strength would occur. After the maximum strength is reached, the load drops and failure occurs.

The test results show that for tension loading case failure occurs at the chord position near the weld region where yielding of the chord appears to happen around the brace and a distortion of the chord from the area around the brace has been observed. As the load increases a crack at the hot spot (toe) which eventually leads to gross separation of the brace from the chord. While for compression loading case failure is associated with buckling and plastic deformation of the chord wall at the brace chord intersection. On the other hand for in-plane bending loading case, failure occurs due to fracture through the chord wall on the tension side of the brace and plastic bending and buckling of the chord on the compression side. For out-of-plane bending case, local buckling of the chord wall in the vicinity of the brace saddle on the compression side occurs. This is associated with fracture on the tension side of the brace after excessive plastic deformations.

The experimental results drawn from this study, for the ultimate loads and moments, were tabulated and presented for all cases in Table 1.

Moreover, the average values of the three experiments for each case and loading mode were compared to each other and presented in terms of percentages. These average values, appear in Table 1, shows that under tension loading the ultimate load for Case 3 is 17.0% higher than Case 1 while Case 2 is 21.1% lower than Case 1. Under compression loading the ultimate load for Case 3 is 12.2% higher than Case 1 while Case 2 is 27.7% lower than Case 1. On the other hand, for in-plane bending loading the ultimate bending moment for Case 3 is 24.0% higher than Case 1 while Case 2 is 17.1% lower than Case 1. Under out-of-plane bending loading the ultimate bending moment for Case 3 is 27.3% higher than Case 1 while Case 2 is 7.5% lower than Case 1.

For circular chord tubular joints results, non-dimensional static strength values used by Department of Energy (U.K.) report, (1990), were used for comparison. The non-dimensional values are calculated only for Case 1 while no equations are available for the other two cases. The non-dimensional ultimate strength can be calculated for tension and compression loading as:

$$+A^* = +A/(\sigma_y T^2) \quad \text{.............(1)}$$

and

$$-A^* = -A/(\sigma_y T^2) \quad \text{.............(2)}$$

While for in-plane and out-of-plane bending

$$B_I^* = B_I/(\sigma_y T^2 d) \quad \text{.............(3)}$$

and

$$B_O^* = B_O/(\sigma_y T^2 d) \quad \text{.............(4)}$$

On the other hand, the empirical equations used for the comparison are:

For tension loading:

$$A^* = (11.70 + 32.26\beta) \quad \text{.............(5)}$$

For compression loading:

$$-A^* = (1.61 + 24.89\beta)Q_B^{0.5} \quad \text{.............(6)}$$

For in-plane bending loading:

$$B_I^* = (6.20 - 0.27)\gamma^{0.5} \quad \text{.............(7)}$$

For out of plane bending loading:

Table 1: Experimental Results for Ultimate Loads and Moments for all Cases

Case	Loading Mode	Values of Load (kN) and Momentt (Kn. M)			Average
		Test 1	Test2	Test3	
	+A (kN)	55.61	53.55	52.38	53.85
Case 1	-A (kN)	25.35	25.20	25.00	25.18
	IPB (kN.m)	0.77	0.74	0.77	0.76
	OPB (kN.m)	0.38	0.40	0.42	0.40
	+A (kN)	42.67	44.30	40.46	42.48
Case 2	-A (kN)	17.81	18.41	18.94	18.39
	IPB (kN.m)	0.60	0.67	0.63	0.63
	OPB (kN.m)	0.36	0.39	0.35	0.37
	+A (kN)	66.37	62.80	65.40	64.86
Case 3	-A (kN)	28.31	29.55	29.00	28.95
	IPB (kN.m)	1.02	0.98	0.99	1.00
	OPB (kN.m)	0.51	0.55	0.59	0.55

Table 2: Non-dimensional strength for circular chord joints (Case 1)

Loading Mode	Values of A^* and B^*			Average Values	Empirical Equations	Difference %
	Test 1	Test 2	Test 3			
+A (A^*)	48.90	47.09	46.06	47.35	31.06	34.40
-A (A^*)	22.29	22.81	21.99	22.36	16.54	26.03
IPB (B^*)	15.93	15.31	15.93	15.72	15.58	0.89
OPB (B^*)	7.86	8.28	8.69	8.28	7.06	14.73

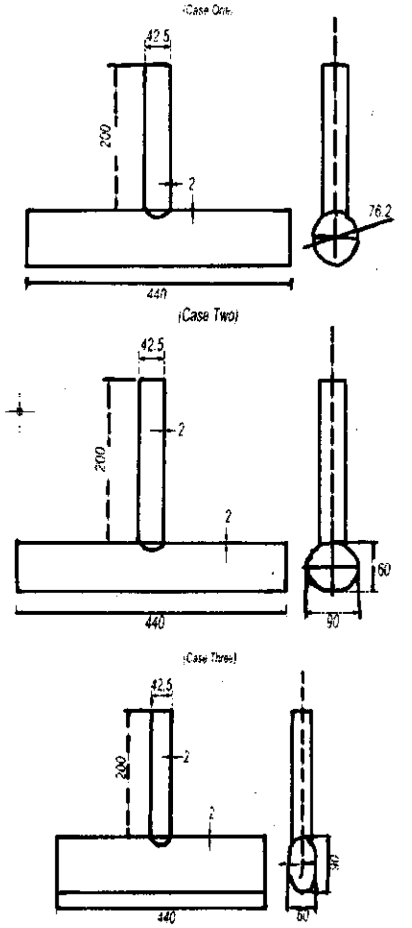

Fig. 1: Geometry of the Models tested (all dimensions in mm)

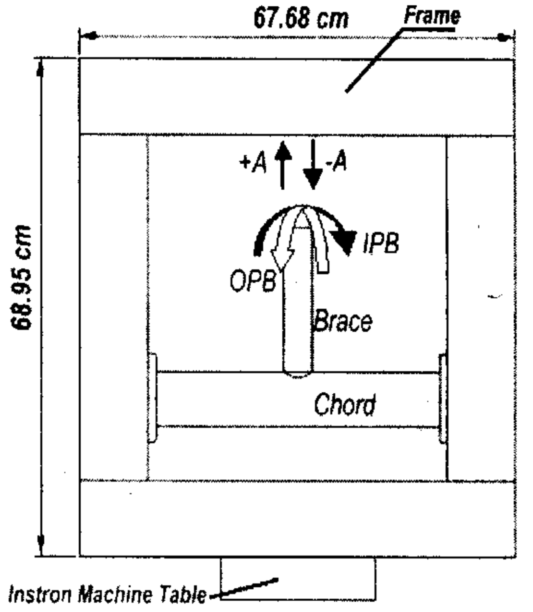

Fig. 2: The experimental Rig

$$B_O^* = (1.88 + 8.64\beta)Q_\beta^{0.5} \quad \text{.....(8)}$$

Using the equations 5 to 8 for Case 1, circular chord tubes the non-dimensional strength for all the loading modes were calculated and tabulated in Table 2. Also shown in Table 2 are beside the experimental results.

From Table 2 it could be noticed that the percentage difference varies between 0.89 to 34.40%. This may attribute to the size effect problem, which says that the strength of large diameter tubular joints is lower than that

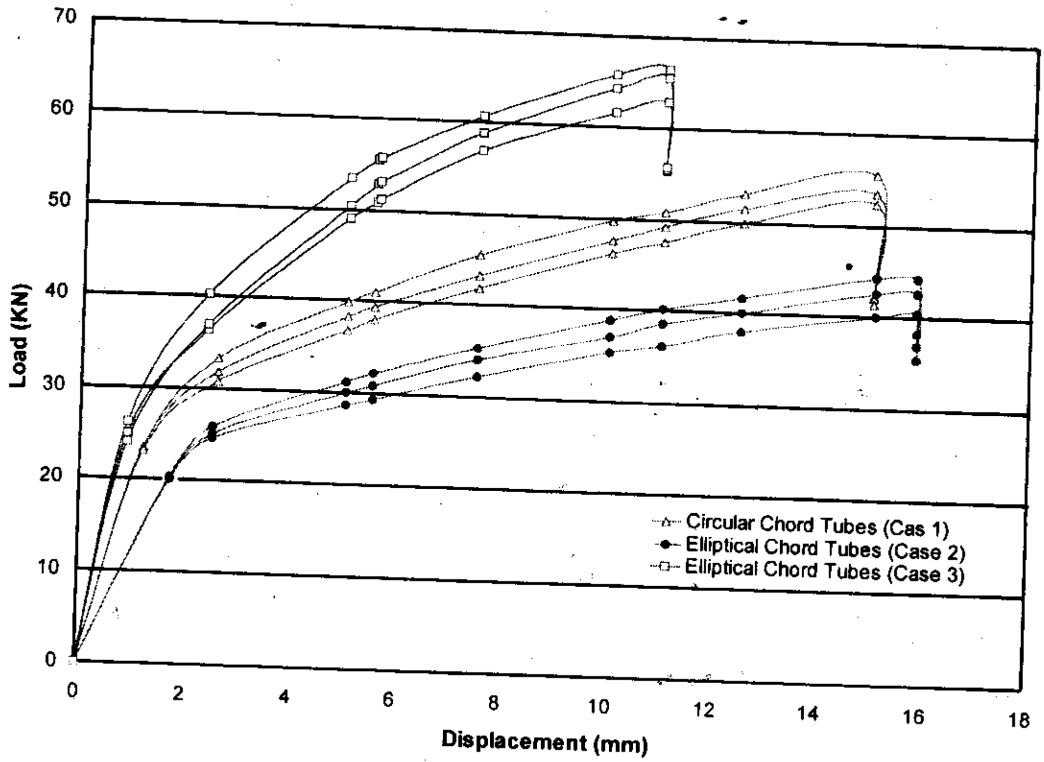

Fig. 3: Experimental Results of Axial Tensio Loading

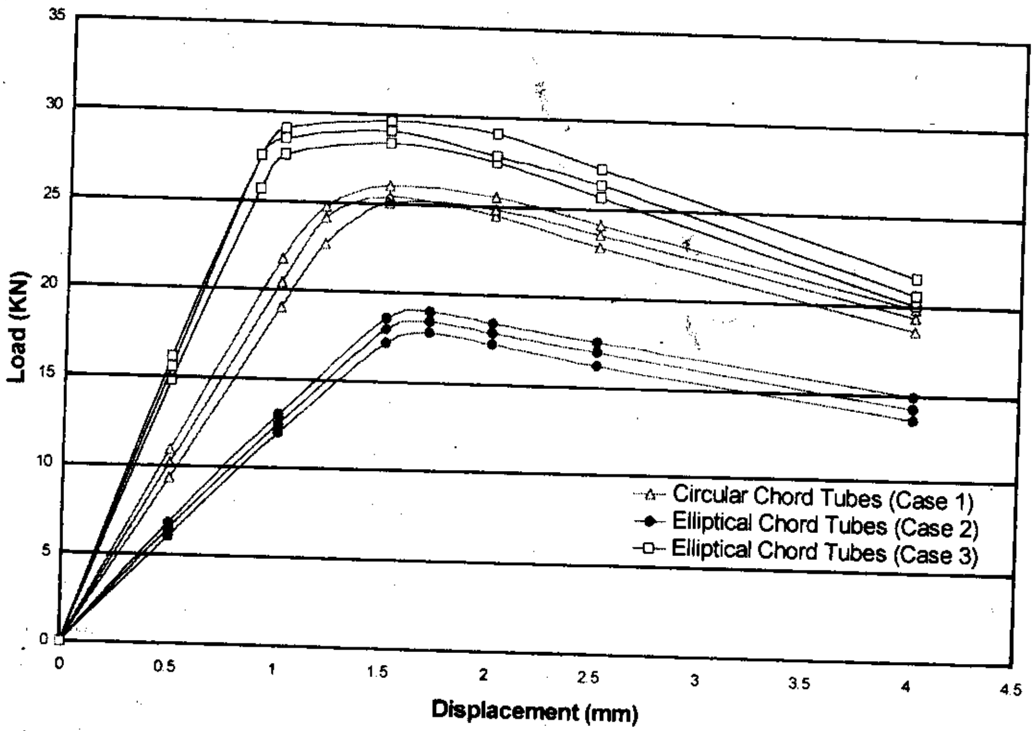

Fig. 4: Experimental Results for Axial Compression Loading

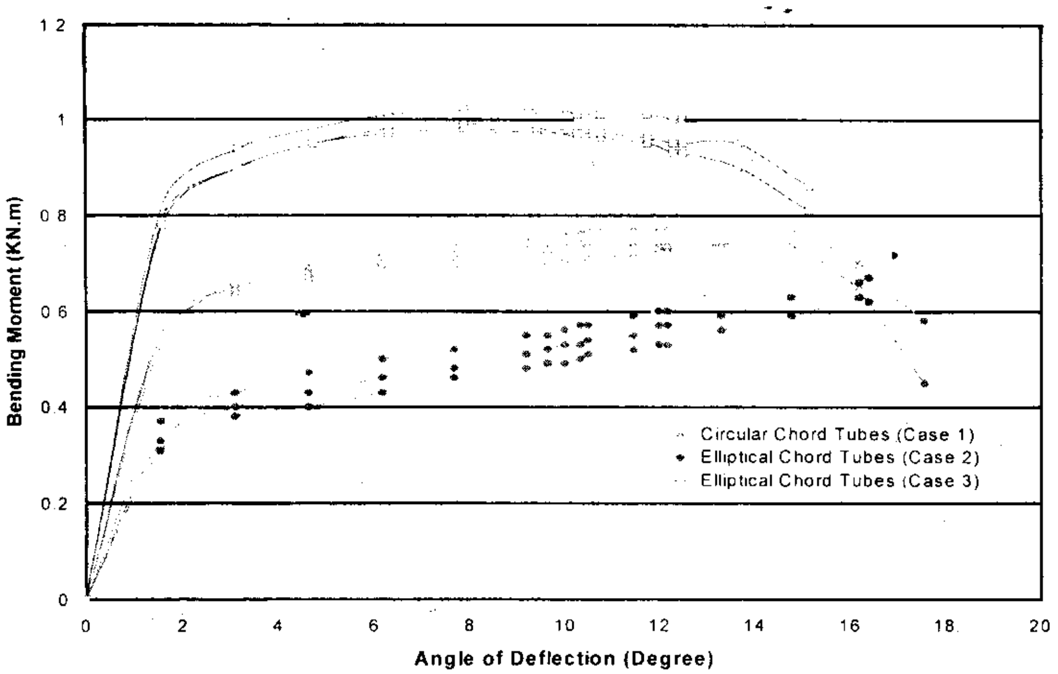

Fig. 5: Experimental results for In=Plane Bending Loading

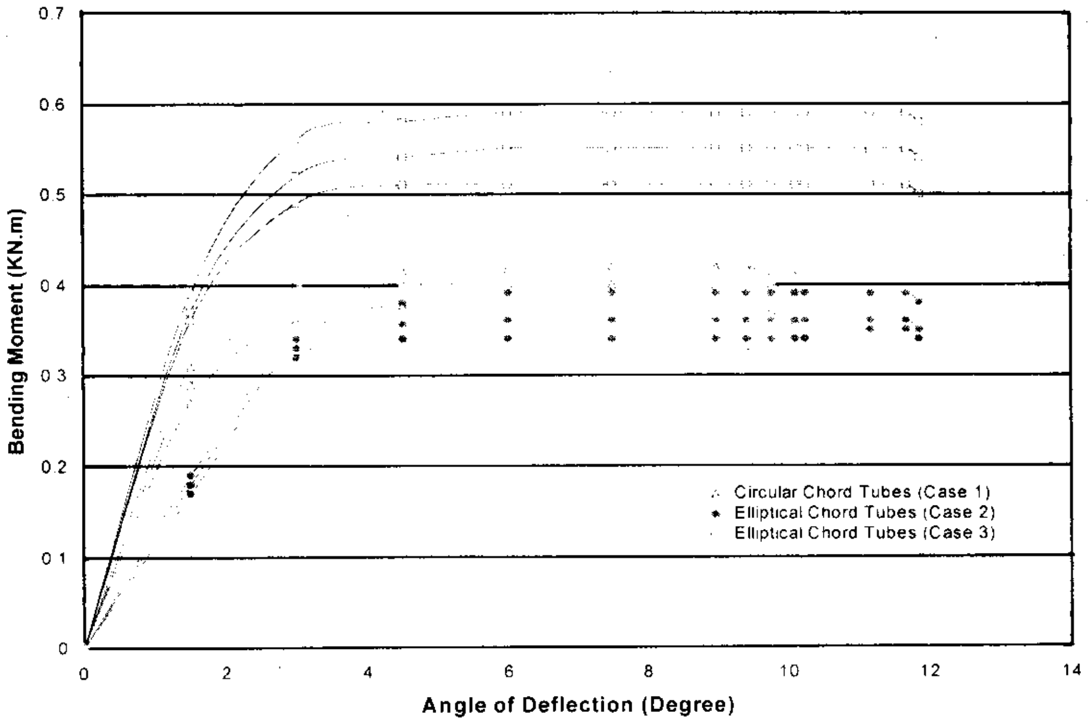

Fig. 6: Experimental results for Out of Plane Bending Loading

of an averaged sized tubular joints even if the geometrical parameters remain the same. It is inferred that this is due to the relative volume of the welds. A smaller diameter tube has a relatively large weld size than tubes of larger diameter (Makino et al, 1986).

The experimental tests were conducted carefully under the same conditions. This is achieved by fixing the rig to the Instron machine once while the specimens are interchangeable for each loading mode. Also the testing speed was kept constant at 2.5 mm/min actuator movements to achieve similar strain rate. This procedure is followed for all the cases under different loading modes. It is clear from the experimental results that the ultimate loads for tension is highest followed by compression, in-plane bending and then out-of-plane bending loading for all cases. It has also been observed that the elliptical chords tubular joints of braces perpendicular to the major diameter (Case 3) are significantly stronger when compared to both elliptical chords tubular joints of braces perpendicular to minor diameter (Case 2) and circular chords tubular joints (Case 1). On the other hand elliptical chords tubular joints of braces perpendicular to the minor diameter (Case 2) are weaker when compared to the circular chords tubular joints. The main conclusions, which could be drawn from this investigation, are summarised as follow:

1 The ultimate load for tension is double that for compression for all cases.
2 The ultimate moment for IPB is double that for OPB for all cases.
3 The ultimate load for models of circular braces connected to the elliptical chords major diameter (Case 3) shows a significant improvement when compared to models of circular braces connected to circular chords (Case 1) for all loading modes.
4 The non-dimensional forms for the different loading modes were found to be very useful tool for comparison and load prediction.
5. For each Case the experimental results show good agreement with each other for each loading mode (percentage difference is between 1.4 to 3.6%).
6. The percentage difference between the experimental test results and empirical equation results for Case 1 under different loading modes varied between 0.89 to 34.40%.
7. Failure for all the cases starts away from the weld joint and it happens on the chord. No weld failure occurs.

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