내부 환보강 X형 및 T형 관이음부의 강도산정과 최적설계

Strength Prediction and Optimum Design of Internally Ring-Stiffened Tubular X- and T-Joints

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ABSTRACT

An effective reinforcement method for steel tubular joints having a large chord diameter is the use of internal ring stiffeners. This paper presents the results of a numerical study on the static strength of internally ring-stiffened tubular X- and T-joints subjected to brace axial compression loading. Nonlinear finite element analyses are used to compute the joint strength. The influence of geometrical parameters has been studied and the maximum reinforcement effect of a ring stiffener has been evaluated. A strength ratio is defined. by the ratio of ring-stiffened joint strength to unstiffened joint strength, and an equation for this strength ratio is derived by regression analysis. Design optimization for ring stiffener of tubular joints is carried out using metropolis genetic algorithm

Keywords: tubular joint, ring stiffener, finite element analysis, strength ratio, optimum design, metropolis genetic algorithm

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1. Introduction

Tubular members have been applied in a wide range of frame structures including offshore structures, bridges, buildings, amusement rides and numerous mechanical applications(Packer et al, 1997). In order to increase the load carrying capacity of tubular structures, critical tubular joints are often reinforced with various reinforcement systems. Among them, internal ring stiffeners have been used for steel tubular joints with a large diameter. The objective of this paper is to numerically assess the behavior of internally ring-stiffened tubular X- and T-joints and to establish a simple yet accurate static strength estimation procedure. And optimum design of ring stiffener is performed. Nonlinear finite element analysis is used to compute the static strength of ring-stiffened joints subjected to brace axial compressive loading. The influence of geometrical parameters of the joint and of the ring stiffener on joint static strength has been studied and the reinforcement effect of a single internal annular ring stiffener is thereby evaluated. A metropolis genetic algorithm (MGA) is applied for design optimization.

2. Numerical study

2.1. Scope of parametric study

The strength of an unstiffened joint can be represented in terms of various non-dimensional geometric parameters, such as β (= d/D), γ (= D/2T), and τ (= t/T) (Wardenier et al, 1991). Fig. 1 and Fig. 2 show tubular X- and T-joints stiffened by a centrally-located annular single internal ring stiffener. Two further non-dimensional parameters related to

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this ring stiffener can also be defined by (Cho et al, 2004; 2005):

$$\eta = h_r/D \tag{1}$$

$$\xi = t_r/T \tag{2}$$

where h_r is the width and t_r is the thickness of the ring stiffener, as shown in Figs. 1 and 2.

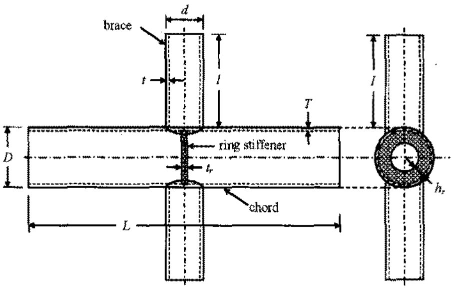

Fig. 1. Ring-stiffened tubular X-joint.

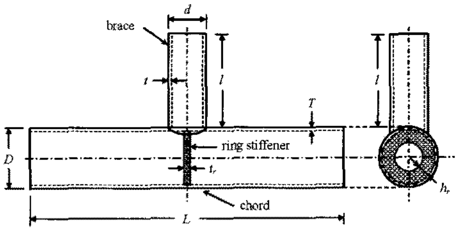

Fig. 2. Ring-stiffened tubular T-joint.

Table 1 summarizes the parametric study program for ring-stiffened tubular X- and T-joints undertaken herein. Joint dimensions of D = 800mm and L = 6400mm are used herein for all joints. The range of parameters in Table 1 is chosen based on common practice for offshore structures.

Table 1 Parametric study program for ring-stiffened tubular X- and T-joints

Parameter		Values
Joint	$\beta = d/D$	0.3, 0.5, 0.7, 1.0 (4 cases)
	$\gamma = D/2T$	12.5, 16.7, 20.0, 25.0 (4 cases)
	$\tau = t/T$	0.5*, 1.0 (2 cases)
Ring stiffener for X-joint	$\eta = h_r/D$	0.05, 0.075, 0.1, 0.125, 0.15, 0.2, 0.25, 0.3, 0.375 (9 cases)
	$\xi = t_r/T$	0.25, 0.375, 0.5, 0.625, 0.75, 1.0, 1.25, 1.5, 2.0 (9cases)
Ring stiffener for T-joint	$\eta = h_r/D$	0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35 (8 cases)
	$\xi = t_r/T$	0.25, 0.5, 0.75, 1.0, 1.5, 2.0 (6 cases)

* τ =0.5 is not considered in the case of β =1.0

2.2. Results of parametric FE analysis

The base joints with different geometric parameters, such as β, γ, and τ in Table 1, were analyzed for unstiffened X- and T-joints. The base joints consisted of 28 finite element models for X- and T-joints, each. In order to determine the ultimate strength of the tubular joints their load-displacement curves were examined. The finite element analysis program, ANSYS was used for numerical analysis of all tubular joints. Eight-noded shell elements with six degrees of freedom at each node were used in the FE models. Geometrical and material nonlinear finite element analyses were performed(Cho et al, 2004).

Numerical models for ring-stiffened X- and T-joints were assessed using various dimensions(Table 1) for the ring stiffener. The ultimate strengths of these ring-stiffened X- and T-joints were hence obtained by 3,630 FE analyses. In order to estimate the effect of the reinforcement on joint capacity, a strength ratio(S_R) was defined as

$$S_R = {}^{N_r}\!\big/_{N_{un}} \tag{3}$$

where N_r is the strength of a ring-stiffened joint and N_{un} is the strength of the corresponding unstiffened joint. Figs. 3 shows the example of variation of S_R with η for different ξ for X- and T-joints. As shown in Fig. 3, S_R increases as ξ and η become larger, but eventually reaching an upper limit. Maximum values of this strength ratio($S_{R,max}$) were calculated as 1.4 to 2.2 for X-joints, and 1.0 to 2.4 for T-joints, in the practical range of ring stiffener geometries. Variations of S_R with geometric parameters for all joints follow similar trends to Fig. 3.

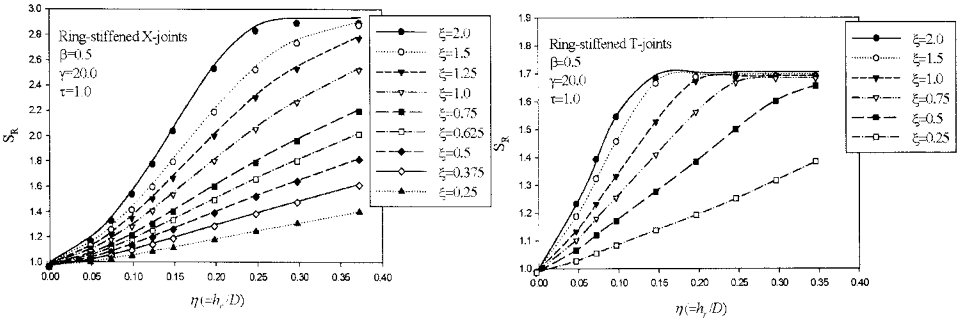

Fig. 3 Variation of strength ratio of ring-stiffened -joints (β=0.5, γ=20.0, τ=1.0).

2.3. Regression analysis for strength ratio

Regression analyses were then carried out using the results of these FE analyses and SPSS software, considering the practical range of ring stiffener variables given by eq.(4).

$$0.25 \le \xi \le 1.0,\quad 0.05 \le \eta \le 0.2 \tag{4}$$

The following nonlinear regression model was eventually proposed:

$$S_R = a_0 + a_1\xi + a_2\eta + a_3\xi\eta\gamma \tag{5}$$

where $a_i (i = 0,1,2,3)$ are regression coefficients which are presented in Tables 2(a) and 2(b). The predicted strength ratios using eq.(5) and the numerical data points are in good agreement.

Table 2(a) Coefficients for strength ratio equation $S_R = a_0 + a_1\xi + a_2\eta + a_3\xi\eta\gamma$ (case: τ=1.0)

Geometric conditions		Coefficients							
		X-joints				T-joints			
β	τ	a_0	a_1	a_2	a_3	a_0	a_1	a_2	a_3
0.3	1.0	0.967	0	0.590	0.224	0.972	-0.028	0.478	0.264
0.5	1.0	0.945	-0.010	0.661	0.177	1.017	-0.059	0.071	0.186
0.7	1.0	0.931	0.015	0.719	0.177	1.063	-0.095	-0.354	0.129
1.0	1.0	0.993	0.058	0.243	0.114				

Table 2(b) Coefficients for strength ratio equation $S_R = a_0 + a_1\xi + a_2\eta + a_3\xi\eta\gamma$ (case: τ=0.5)

Geometric conditions		Coefficients							
		X-joints				T-joints			
β	τ	a_0	a_1	a_2	a_3	a_0	a_1	a_2	a_3
0.3	0.5	0.977	0.001	0.595	0.222	0.967	0.009	0.670	0.237
0.5	0.5	0.954	-0.024	0.619	0.184	1.009	-0.024	0.226	0.166
0.7	0.5	0.940	0.001	0.671	0.180	1.059	-0.080	-0.289	0.121

3. Evaluation of ultimate strength estimation methods for ring-stiffened tubular X- and T-joints

3.1. Presented strength estimation equation for ring-stiffened tubular X- and T-joints

The predicted strength of a ring-stiffened joint ($N_{r,p}$) may be now considered as the product of the strength ratio (S_R) by eq.(5) and the strength of the unstiffened joint (N_{un}), as indicated by eq.(6):

$$N_{r,p} = S_R \times N_{un} \tag{6}$$

where $S_R = a_0 + a_1\xi + a_2\eta + a_3\xi\eta\gamma$, and $a_i(i = 0,1,2,3)$ are given in Table 2. The validity ranges of eq.(5) are $12.5 \le \gamma \le 25.0$, $0.05 \le \eta \le 0.2$ and $0.25 \le \xi \le 1.0$. In practice, the strength of the unstiffened joint (N_{un}) in eq.(6) would be computed by applicable design codes(e.g. API, 1993; IOS, 2001).

For use with the strength ratio in eq.(5), the equation coefficients in Table 2(a) were considered for simplification. It can be seen in Tables 2(a) and 2(b) that their coefficients are very similar, despite a difference in τ. To study the S_R coefficients the predicted strengths of ring-stiffened joints were separately calculated using the following three cases:

(1) Case 1: coefficients of S_R were used from Table 2(a) for τ = 1.0 and Table 2(b) for τ = 0.5.
(2) Case 2: coefficients of S_R were used from Table 2(a) only, for both τ = 1.0 and τ = 0.5.
(3) Case 3: coefficients of S_R were used from Table 2(b) only, for both τ = 1.0 and τ = 0.5.

The predicted strength and the numerical strength are in good agreement for all cases. Therefore, the coefficients for the strength ratio equation given by just Table 2(a) are henceforth suggested, for simplification of the strength equation.

3.2. Established strength estimation equation by Lee and Llewelyn-Parry (Lee et al, 2004; 2005)

Their model assumes that the stiffened joint strength can be considered as the sum of the strengths of the ring stiffener and the unstiffened joint, as given by eq.(7):

$$N_{r,p} = N_{stiff} + N_{un} \tag{7}$$

The validity ranges of eq.(7) are $10 \le \gamma \le 30$, $0.333 \le \beta \le 0.8$, and $0.4 \le \xi \le 0.8$, and N_{stiff} is the additional strength of the ring stiffener.

3.3. Comparison of available strength equations

The predicted ring-stiffened joint strengths, calculated using the strength equation presented herein, are next compared with those using Lee and Llewelyn-Parry's equation. The results of statistical analyses of the databases are summarized in Table 3. The method by the Authors is represented by eq.(6) and the method by Lee and Llewelyn-Parry is represented by eq.(7). The ring-stiffened joint strengths are the results of numerical analyses in Section 2.2.

As shown in Table 4 the statistical results for X-joints using the equation by the Authors, and that by Lee and Llewelyn-Parry, are very similar, but the result by the Authors' equation is slightly more accurate than Lee and Llewelyn-Parry in the case of β =0.3. In the case of β =1.0 for X-joints, the predicted strength could not be computed by Lee and Llewelyn-Parry because of their restrictive validity range. For T-joints, the ratios of predicted strength to numerical strength using the authors' equation gave a mean value of 1.0 and CoV ranging from 0.02 to 0.04. Analogous results by Lee and Llewelyn-Parry gave a mean of 1.05 to 1.10 with CoVs ranging from 0.03 to 0.09.

4. Optimum design of ring stiffener

As a numerical optimization algorithm, recently developed Metropolis genetic algorithm (MGA) is used(Ryu et al, 2006). In the algorithm, favorable features of Metropolis criterion of SA are incorporated in the reproduction operations of SGA. This way, MGA alleviates the disadvantages of finding imprecise solution in SGA and timeconsuming computation in SA. The objective function to be minimized is the volume of ring stiffener. The width(h_r) and thickness(t_r) of the ring stiffener are the design variables. And the design constraint are based on eqs.(4) and (5). Table 4 shows some of results of optimum design for ring-stiffened tubular X- joints using MGA. In this table, the optimum values are best results of 30 trials.

Table 3 Evaluation of strength estimation equations for ring-stiffened joints

β	Statistics	Predicted strength / Numerical strength			
		X-joints		T-joints	
		Presented	by Lee et al.	Presented	by Lee et al.
0.3	Mean	1.00	0.98	1.00	1.05
	Minimum	0.96	0.92	0.97	1.02
	Maximum	1.11	1.19	1.07	1.17
	CoV	0.01	0.02	0.02	0.03
	No. of data	288		160	
0.5	Mean	1.00	1.00	1.00	1.06
	Minimum	0.94	0.96	0.97	1.01
	Maximum	1.05	1.01	1.11	1.31
	CoV	0.02	0.01	0.02	0.04
	No. of data	288		160	
0.7	Mean	0.99	0.99	1.00	1.10
	Minimum	0.93	0.97	0.92	1.01
	Maximum	1.04	1.05	1.14	1.49
	CoV	0.02	0.01	0.04	0.09
	No. of data	288		160	
1.0	Mean	0.94	-		
	Minimum	0.90	-		
	Maximum	0.99	-		
	CoV	0.02	-		
	No. of data	144			

Table 4 Results of optimum design for ring-stiffened tubular X- joints using MGA(D=100cm)

β	γ	S_R	Objective values (cm^3)	h_r (cm)	t_r (cm)
0.3	12.5	1.1	2,704	10.08	1.04
		1.3	7,292	18.81	1.69
		1.5	13,511	19.73	3.02
		1.6	16,692	19.88	3.71
0.5	20.0	1.1	1,763	9.76	0.67
		1.3	3,808	19.71	0.82
		1.5	7,161	19.88	1.53
		1.7	10,513	20.00	2.23

5. Conclusion

A parametric numerical study has been performed on tubular X- and T-joints, stiffened internally by a single annular ring, and subjected to brace axial compression loading. Nonlinear finite element analysis was used to compute the ultimate strength of the stiffened joints, as well as the strength of their unstiffened counterpart joints. In this parametric study, it was found that an internal ring stiffener was efficient in improving the joint strength except for T-joints having the same brace and chord diameter.

A strength ratio (S_R) was defined as the ratio of ring-stiffened joint strength to unstiffened joint strength and the values for this ratio were determined. Maximum values of this strength ratio ($S_{R,max}$) were calculated as 1.4 to 2.2 for X-joints, and 1.0 to 2.4 for T-joints, in the practical range of ring stiffener geometries. A strength estimation equation for ring-stiffened joints under brace axial compression was then proposed as the product of this strength ratio and the strength of the corresponding unstiffened joint, where:

$S_R = a_0 + a_1\xi + a_2\eta + a_3\xi\eta\gamma$ and a_0, a_1, a_2, a_3 are given in Table 2(a).

The strength of unstiffened joints can be easily computed using applicable design codes or guides. The above calculation method is much simpler to use than the alternative approach and has been shown to be accurate. Finally optimum design for ring stiffener is carried out using metropolis genetic algorithm. This simple equation and approach may serve as a basis for future design recommendations for ring-stiffened tubular joints.

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