23rd Australasian Conference on the Mechanics of Structures and Materials

2014

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Publication details

Lu, C, Ma, X & Mills, JE 2014, 'Modelling and parametric analysis of bolted connections on retrofitted transmission tower leg members', in ST Smith (ed.), *23rd Australasian Conference on the Mechanics of Structures and Materials (ACMSM23)*, vol. I, Byron Bay, NSW, 9-12 December, Southern Cross University, Lismore, NSW, pp. 571-576. ISBN: 9780994152008.

MODELLING AND PARAMETRIC ANALYSIS OF BOLTED CONNECTIONS ON RETROFITTED TRANSMISSION TOWER LEG MEMBERS

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ABSTRACT

This paper examines the load-displacement behaviour of cruciform connections and splice joints on reinforced steel transmission tower legs. The load-displacement behaviour was studied by experimental tests and the results were compared with 3D nonlinear finite element models developed using ABAQUS. The detailed 3D models simulated the bolted connections by using brick elements and considering the clearance in connections. A subsequent parametric analysis showed that friction coefficients, torque values and bolt numbers play an important role in these connections and that adding extra bolts was the most effective approach to improve the load-displacement behaviour of these bolted connections.

KEYWORDS

Steel angle, transmission tower, retrofitting, splice, connector, bolt-slip.

INTRODUCTION

The practical retrofitting method of attaching parallel reinforcing components on critical legs (Figure 1.a) has been widely applied on lattice transmission tower structures in Australia and elsewhere. In this method, critical legs and parallel reinforcing components are connected through cruciform bolted connections (Figure 1.b). The cruciform connections transfer external loads from the critical legs to the reinforcing components, so that lower loads are carried in critical legs and the overall load carrying capacity is increased. In addition, splice joints (Figure 1.c) are also used in lattice transmission tower structures for connecting lengths of critical leg members. Hence, cruciform and splice connections are important factors in the structural behaviour of retrofitted transmission tower legs.

Experimental research on butt-splice connections introduced the 'slip resistance' concept, based on a series of influencing factors such as bolt arrangements, material surface properties, material strength and bolt torque values (Kulak et al. 1987). Based on this research, Ungkurapinan et al. (2003) conducted an experimental study on the load-displacement behaviour of bolted connections constructed with steel equal angles. A theoretical and experimental load-displacement expression was developed in this research. This load-displacement behaviour of bolted connections was then applied in failure analysis of lattice transmission towers (Jiang et al. 2010; Jiang et al. 2011).

(a) Retrofitting method (b) Cruciform connection (c) Splice joint

Figure 1. Retrofitting connection and transmission tower connection

Studies on cruciform connections have also been undertaken. An experimental study indicated that the load-transferring behaviour of cruciform connections relies on bolt arrangements (Denton et al. 2005; Tongkasame 2008). Zhuge et al. (2012) expanded these research finding by numerical analysis. Mills et al. (2012) further proposed a retrofitted transmission tower test and concluded that the cruciform connection has an adequate load-transferring capability in a tower system.

However, the influencing parameters and failure modes on the combination of cruciform and splice connections have not been researched. In addition, the current Australian standard - 'Design of steel lattice towers and masts' (Standards Association of Australia 1994) does not include relevant design guidelines for tower leg elements retrofitted by these two types of bolted connections. Hence the current authors have studied the load-displacement behaviour of cruciform connections and splice joints by experimental tests and then the results were compared with numerical models developed in ABAQUS. Subsequently, a parametric study considering friction coefficients, bolt numbers, torque values was undertaken using the verified numerical models.

EXPERIMENTS AND NON-LINEAR FINITE ELEMENT MODEL DEVELOPMENT

Test Specimens

Six tests in total were conducted using identical splice/cruciform specimens designated as Spl-A to Spl-C and Cru-A to Cru-C. The properties of test specimens are summarized in Table 1.

In the splice specimens, the upper and bottom main members were connected to form one continuous element through the middle twelve-bolt splice joint (Figure 2.a). In the twelve-bolt cruciform connections, a main member was connected to a reinforcing member through side cleat elements (Figure 2.b). For each of the connections, a torque value of 150 N.m was applied on the bolts. For the splice specimens, all members were constructed using 65 mm × 65 mm × 5 mm equal steel angle with grade 300 (i.e. nominal yield strength of 300 MPa). For the twelve-bolt cruciform connections, the main members were constructed using 65 mm × 65 mm × 5 mm equal steel angle with grade 300, while in order to avoid premature failure of the reinforcing member, it was constructed using 125 mm × 125 mm × 12 mm equal steel angle with grade 300 (Figure 2.b). The bolts used for all test specimens were Grade 8.8 M16 high strength bolts (i.e. 16 mm diameter, 800 MPa nominal yield strength).

Table 1. Summary of test specimen properties

Test specimen	Test specimen	Steel yield strength (MPa)	Bolt grade	Torque (N.m)
Twelve-bolt splice joints	Spl - A, B, C	300	8.8 M16	150
Twelve-bolt cruciform joints	Cru - A, B, C	300	8.8 M16	150

(a) Twelve-bolt splice joint (b) Twelve-bolt cruciform connection

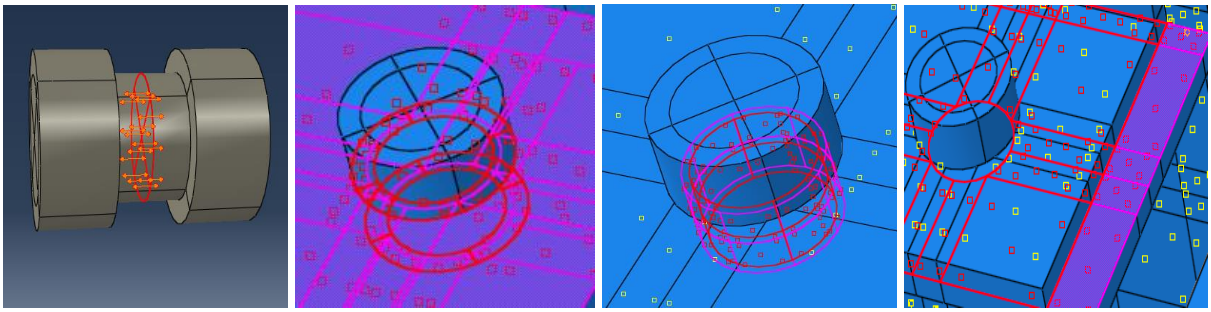
Figure 2. Joint and connection arrangement

Test Set-up and Procedures

All test specimens were connected to the base plate with eight bolts (Figure 2.a). A loading rate of 1 kN/sec was steadily applied onto specimens. Meanwhile, the displacement of the plate and the loading force was recorded every second. Testing was stopped when visible buckling occurred in members.

Nonlinear Finite Element Model Development

Following the experimental tests, 3D finite element models of splice and cruciform connections were developed using ABAQUS. Numerical specimens were modelled in 3D deformable brick elements. In order to develop a clamping mechanism in the models, a bolt-pretension force was applied to the inside plane (Figure 3.a) of the bolts (ABAQUS 2010). Its value was calculated to be 46.875 kN based on the equation of T=0.2FD, where the 'F' is the proposed pretension force, 'T' is the applied torque value in the experimental tests and 'D' is the bolt diameter. The normal and tangential interaction property (ABAQUS 2010) was applied on contact surfaces (Figure 3.b-3.d) to simulate compression, face shear and the bolt slip phenomenon between steel plates and bolts. In the tangential interaction module, a modified friction coefficient (Fc) of 0.17/0.19 was adopted in the models. Due to the relatively low loading rate, the loading acceleration was ignored and the general-static solver was chosen for calculations.



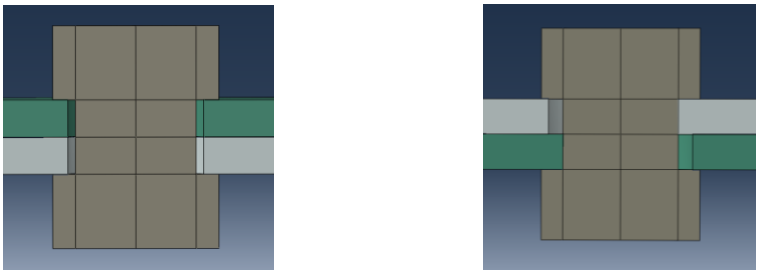
(a) Bolt pretension plan (b) Bolt cap to plate (c) Bolt to hole (d) Plate to plate

Figure 3. Bolt pretension plane and contact surfaces

The bottom base was fixed in all translation and rotation directions to simulate the experimental conditions. The top loading plate was simplified as a rigid shell element and only vertical movement was allowed during the loading process. In addition, within the loading step, two specific amplitude curves were introduced into the bolt-pretension and vertical displacement to improve the convergence behavior.

In order to accurately simulate the experimental load-displacement curve and provide a verified numerical model for the later parametric study, the ABAQUS models were developed using two possible assembly configurations in the experimental specimens, namely:

1) Centre to centre (CTC) type: the centre of the bolt shank and bolt holes are coincident to simulate a full bolt slip phenomenon (Figure 4.a)
2) Edge to edge (ETE) type: the bolt shanks` surfaces touch the bolt holes` surfaces to simulate a full shearing phenomenon (Figure 4.b)



(a) CTC configuration (b) ETE configuration

Figure 4. Bolts and holes configuration

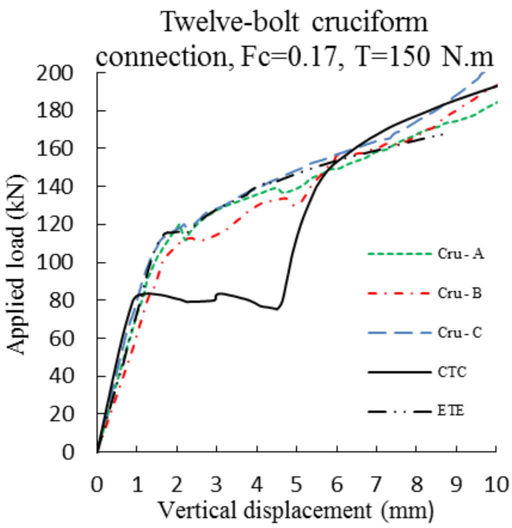
RESULTS AND DISCUSSION

Experimental and numerical results of Spl-A to Spl-C specimens and Cru-A to Cru-C specimen with two types of assembly configuration are graphically summarized in Figure 5.a and Figure 5.b. The displacement of both twelve-bolt splice and cruciform specimens increased with the applied load. Compared with the twelve-bolt splice joint, the load-displacement curve of the twelve-bolt cruciform connections showed a slightly gentler initial stiffness, lower turning points and a slightly lower ultimate load-carrying capacity.

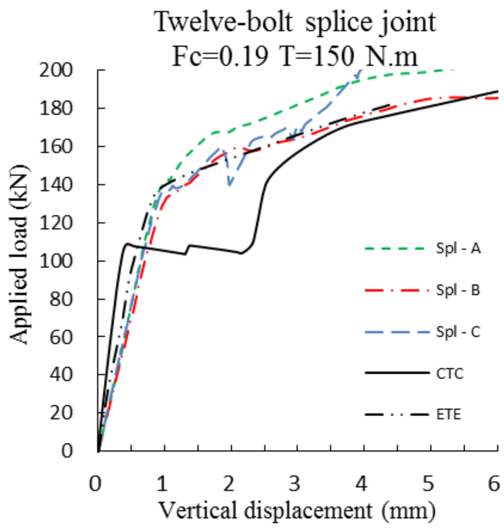
The ABAQUS models with different assembly configurations indicated different load-displacement behaviours. It is clear that three stages can be distinguished in the load-displacement curve of the CTC assembly type – a friction resistance stage, bolt-slip stage and bearing stage. In the first stage, the applied bolt pretension developed the frictional resistance, which provided the initial stiffness for the bolted connections. Once the applied loads were larger than the frictional resistance, connections started to slip as shown by the flat line. Then, the bolted connections started to shear and stopped with material failure. Whereas, the ETE assembly type skipped the first two stages and directly entered into the last stage. Its results matched the experimental results well. This is because the assembly process of the experimental specimens meant they were more likely to be in the ETE configuration rather than the CTC assembly type and/or some bolts were already in the ETE condition before applying loads.

Two types of failure modes were observed for these two types of connections. As shown in Figure 6.a, local buckling was the typical failure mode for the top and bottom members of the splice joints. This distinctive failure type confirms that the top main member carried and transferred loads to the bottom main members through the splice joints. The buckling failure was found in side-cleat members in twelve-bolt cruciform connections, which again verified that the main member carried and transferred loads to the reinforcing member through side-cleats in cruciform connections (Figure 6.b).

Although the ETE assembly configuration agreed well with the experimental results, it is an extreme assembly case and might not always occur in real construction. In addition, since the load-displacement curves of the CTC type were theoretically closer to the load-displacement curve developed by Ungkurapinan, et al. (2003), the parametric study was carried out based on the CTC assembly type.

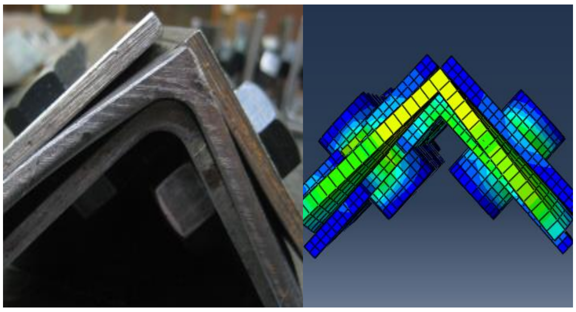


(a) Twelve-bolt cruciform connector

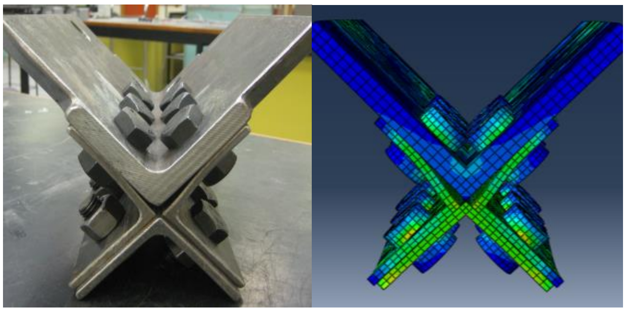


(b) Twelve-bolt splice joint

Figure 5. Load-displacement curve



(a) Twelve-bolt splice joints



(b) Twelve-bolts cruciform joints

Figure 6. Failure mode of specimens (CTC type)

PARAMETRIC STUDY

From the experimental and numerical results above, it is clear that connection properties play an important role in the load-displacement behaviour of splice and cruciform connections. Hence, a parametric study was carried out to analyse the influence parameters including friction coefficients, torque values, and bolt numbers. The details of the study will be the subject of a later paper but the important findings were:

- the load-carrying capacity was not significantly influenced by varying the friction coefficient
- higher torque values did not improve the load-carrying capacity of either connection
- adding extra bolts on the connections increased the ultimate load-carrying capacity.

CONCLUSIONS

This paper presented the load-displacement behaviour of cruciform and splice connections on retrofitted transmission tower legs. ABAQUS was used to develop numerical models to simulate experimental tests and the verified numerical models were then used in a parametric study. Based on results from both experimental tests and numerical models, it was noted that the assembly configuration influenced the load-displacement behaviors. A subsequent parametric study showed that the friction coefficient and torque values have a limited effect on the load-displacement behavior of both cruciform and splice connections and do not greatly enhance the ultimate load-carrying capacity. Increasing the number of bolts in connections is the most effective approach to enhance the load-displacement behavior and ultimate load carrying capacity for both cruciform and splice connections.

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