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Cyclic performance of bolted cruciform and splice connectors in retrofitted transmission tower legs

Chenghao Lu, Xing Ma*, Julie E. Mills

School of Natural and Built Environments, University of South Australia, SA 5095, Australia

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ABSTRACT

Aging transmission towers are increasingly being found to have insufficient strength to meet increased design wind loads and additional electricity demands. One potential solution is to strengthen old tower members through adding new structural components. The bolted cruciform connector is an effective load-transferring component for members that combine new and old components. This paper addresses the cyclic performance of bolted cruciform and splice connectors in retrofitted transmission towers through a series of experimental tests. One type of 12-bolt splice connector and one type of 8-bolt cruciform connector were designed and two groups for each type were tested under monotonic and cyclic loading conditions. Key parameters including bolt pretension, bolt-slip load and dynamic stiffness with varying load amount, frequency and cycle number were investigated. Experimental results showed that the cyclic loadings reduce bolt-slip load and static structural stiffness of cruciform and splice connectors due to the surface smoothening and bolt pretension loss. The bolt pretension and bolt-slip load continuously reduced with the increase of loading cycle numbers and loading magnitudes. However, the static bolt-slip load was not found to be sensitive to varying loading frequencies. Finally, practical prediction equations were developed in terms of cyclic loading parameters for both connectors. The prediction equations showed strong agreement with experimental results in both low and high loading magnitudes under varying loading conditions.

1. Introduction

Lattice transmission towers are important infrastructure elements for electricity supply in modern society. In Australia and elsewhere, most lattice transmission towers are constructed from equal angle steel members. To form structural elements, equal angles are connected by one/multi-bolt connectors (Fig. 1). In recent years, to address the increasing wind design loads and electricity demands, cruciform connectors (Fig. 2) have been used on aged transmission towers to retrofit their critical leg elements by adding additional angle members. Recent research has verified the effectiveness of this kind of connector in retrofitted towers [1–3].

The structural performance of bolted connectors has attracted research interest for many years. Besides the investigations of moment-resistance joints in steel frame structures [4–9], many works have been conducted on the axial loading capacity of bolted connectors subject to monotonic loads. The early experiments were conducted to study the load-displacement behaviour of butt-splice connectors and the relationship between the 'slip resistance' and the influencing factors such as bolt arrangements, bolt torques, material surface properties and material strength [10]. Ungkurapinan et al. [11] studied bolted connectors constructed by equal angle steel members through experimental tests and developed a theoretical load-displacement function, which was further applied on failure analysis of unreinforced lattice transmission towers in current industrial practise [12,13]. Most of the above research [10–13] focused on the bolt-slip effect on connectors with pretensioned bolts.

The cruciform connection has been employed as the main loading transfer component in retrofitted towers [1]. The structural behaviour of bolted cruciform connectors was investigated recently. Experimental studies verified that bolted cruciform connectors could provide high load-transferring capability in retrofitted transmission tower leg segments and tower systems. The bolt-slip load and joint stiffness of the cruciform connectors are the controlling factors on the load-transferring effectiveness between original tower members and reinforcing members [2,14] and govern the load carrying capacity of the reinforced tower systems [1]. Recent study on bolted end-plate joints and splice connectors under dynamic loads showed that repeating friction between contact surfaces might cause local shear deformation and sudden stiffness change [15–18]. Meanwhile, bolt pretension tended to

* Corresponding author.
E-mail address: Xing.Ma@unisa.edu.au (X. Ma).

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Fig. 1. Single/Multi-bolt connector.

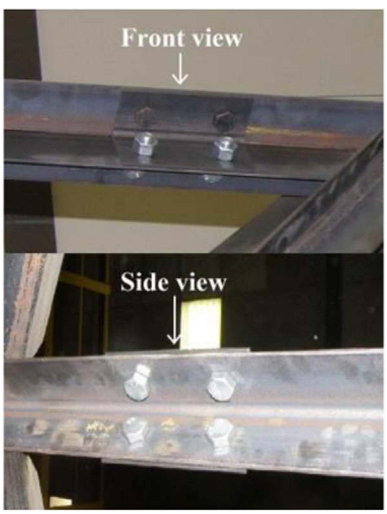

Fig. 2. Cruciform connector.

decrease during the dynamic loading process [19–21]. Studies on the dynamic performance of cruciform connectors in existing literature are quite rare. A numerical study based on a 3D FEM model indicated that the dynamic stiffness of cruciform connectors decreased due to the bolt-pretension reduction during the cyclic loading process [22].

However, the above research mainly focused on the overall static and dynamic behaviour of bolted cruciform connectors. There is still a research gap on their dynamic performance such as bolt pretension and bolt-slip load degrading due to cyclic loading procedure as well as the influence of loading history and loading types. This paper therefore addresses the dynamic structural behaviours of bolted cruciform and splice connectors through a series of experimental studies on 8-bolt cruciform and 12-bolt splice connectors under a specific loading sequence. Two groups of prediction equations of friction coefficient and bolt pretension reduction in relation to the cyclic loading parameters for both cruciform and splice connections were developed and compared with experimental results.

2. Experimental tests

In this paper, one 12-bolt splice and one 8-bolt cruciform connector were designed and tested under cyclic loads. The relationship between structural behaviours and: (a). number of loading cycles; (b). loading frequencies; (c). loading magnitudes were studied.

2.1. Description of test specimens and bolts

Two types of connectors were constructed in this study. Details of specimens are summarised in Table 1, Figs. 3 and 4. In these tests, the main member and side cleats of the cruciform connector were constructed with 65 mm × 65 mm × 5 mm equal angle steel, while 125 mm × 125 mm × 12 mm equal angle steel was adopted as the reinforcing member for the cruciform connector to avoid the potential premature failure. The top/bottom and inside cleats of the splice connector were also constructed with 65 mm × 65 mm × 5 mm equal angle steel. The outside cleats were constructed with 65 mm × 5 mm flat steel plates. All steels were grade 300 (nominal yield strength in MPa). In 8-bolt cruciform connectors, the main members were attached to the thick reinforcing member through two side cleats (Fig. 3). In the splice connector, the two separate main members were constructed with a 10 mm gap between their ends (Fig. 4). The detailed material properties are also listed in Table 1.

Grade 8.8 M16 high strength bolts and nuts were adopted for all test specimens. A torque of 150 N*m was applied to develop an effective friction resistance. To further obtain the details of bolt pretension relaxation and consequence of structural behaviour variations, the bolts in this study were specially designed with a built-in strain gauge (Fig. 5). The high strength bolts were drilled with a hole along their centroid line and a strain gauge with a data collection cable was attached to the hole surface (Fig. 6). Calibration checks were conducted for the specially designed bolts before commencing experiments. Hence, the bolt pretension force could be accurately monitored and the collected data could be post-analysed for the bolt pretension relaxation phenomenon. The bolts were reused for all tests in the study.

2.2. Test procedures and explanation

Because this experimental study was designed at load values that did not result in damage to the connection components, the specimens were re-used in a sequence of tests. The accumulating reduction in friction coefficient on surfaces between connectors and members was investigated in test result analysis. As shown in Table 2, four specimens were designed and tested in a specific sequence. The numbers in the 'Experimental sequence' column indicate the experimental order of each specimen. Each group represents a parametric combination from the loading frequencies, loading magnitudes and the number of loading cycles. The force control loading manner was adopted for all tests to obtain the potential bolt-slip phenomenon. The loading curves for

Table 1
Summary of test specimens and material properties.

Test specimen	Test specimen	Nominal yield strength of member (MPa)	Bolt grade	Bolt diameter (mm)	Bolt hole (mm)	Nominal yield strength of bolts (MPa)	Torque (N*m)
8-bolt cruciform connectors	Cru A, B (8 bolted)	300	8.8 M16	16	18	800	150
12-bolt Splice connectors	Sp C, D (12 bolted)	300	8.8 M16	16	18	800	150