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The structural effect of bolted splices on retrofitted transmission tower angle members

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

This paper examines the structural behavior of compound members used for transmission tower legs, constructed from steel angles that have been retrofitted by attaching additional parallel angle members. To study the load transfer mechanism between the original member and the reinforcing component as well as the influence of splice joints in the original tower structures, a group of static experimental tests have been conducted. A 3D non-linear finite element model was developed in ABAQUS after considering the clearance between bolts and holes and the contact interaction between bolts and member surfaces in all of the connections. The detailed 3D model was then simplified to a one dimensional model through the use of spring elements to simulate connectors and splices, and beam elements to represent original and reinforcing members. Numerical results based on the simplified model agreed well with those from the 3D model and experimental tests. A parametric study showed that the stiffness change and bolt-slip phenomenon in the splicing joint and the connectors play an important role in the structural behavior of the retrofitted system. Enhancement of the load-carrying capability and load-sharing rate for reinforcing members can be achieved by optimizing the connector joint parameters.

1. Introduction

Steel lattice transmission towers have been constructed for over 100 years. In Australia, there are approximately 150,000 steel lattice towers and most of them have been in service for more than 20 years, or even longer [1]. Many aging lattice transmission towers are considered to be structurally under-designed for current industrial requirements due to the additional demands from upgrades in wind load design codes and extra electricity/communication services. Rather than construct a series of new transmission towers, an ‘upgrading’ strategy has been recognized as an economic and practical way to strengthen existing tower structures and has been utilized for several years.

In order to retrofit existing/damaged steel structures, there are quite a few techniques described in current literature to increase the moment capacity of steel frames [2–10]. However, much of this work on steel framed buildings has limited application to tower structures, since the focus for towers is primarily on improving the axial load capacity of tower legs rather than the moment capacity. In comparison, the research on retrofitted steel towers is relatively limited. Two effective methods for upgrading critical tower members are the most widely adopted in practice and described in research. The first is to reduce the slenderness ratio of the long compression members (i.e. tower legs) by introducing additional bracing to existing tower leg segments [11,12], a method that is most suitable for members with high slenderness ratios. The second method is to increase the effective cross sections of critical members by attaching parallel reinforcing components. This method is more efficient than additional bracing for stocky structural members with slenderness ratios smaller than 80 [13] and is the method that is relevant to the current discussion.

In Australia, most transmission towers have been constructed using equal angle sections for the principal and bracing members. During upgrading using the parallel reinforcing method, the reinforcing member is normally also chosen as an equal angle section with the same size as the original member and they are connected corner to corner by bolted connections. Due to its practicality, this method has been recognized by industry as an effective solution for reinforcing lattice tower structures since the 1990s. However, the current Australian standard ‘Design of steel lattice towers and masts’ (AS 3995-1994) [14] has not included any guidelines for reinforcing steel lattice towers. To study the efficiency of different connectors in the retrofitted method, Zhuge et al. [1] conducted several experiments on steel angle members retrofitted with the same sized steel angle. The capacity increase and load-sharing rate were studied and compared with numerical models. In the study, several types of connectors were tested. In addition, detailed and simplified numerical simulations were proposed by using ABAQUS software. The bolt-slip phenomenon was considered by introducing a 2 mm size difference between the bolt and hole dimension in a 3D model. Meanwhile, a simplified clamping rim system was applied in the original bolt position to simulate the bolt-friction mechanism. The load-carrying capacity and load-sharing rate for the reinforcing and original members were obtained. The results concluded that a ‘cruciform’ connection type (Fig. 1), a bolted double steel angle cleat connector, provided the best capacity increase.

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* Corresponding author. Tel.: +61 8 83023109; fax: +61 8 83025082.
E-mail address: Xing.Ma@unisa.edu.au (X. Ma).

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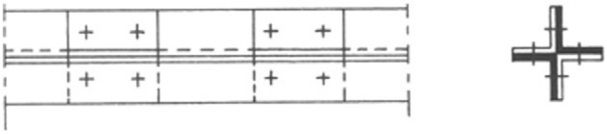

Fig. 1. A steel angle member retrofitted through cruciform connectors.

In actual towers, bolted splices are commonly used on the primary tower legs for construction and transportation convenience (Fig. 2). The stiffness change and bolt-slip effect at the splice joints will influence the load transfer and capacity increase of the retrofitted member and involve a different mechanism than that described for single continuous members by Zhuge et al. [1]. This paper therefore addresses the structural behavior and load transfer mechanism of spliced steel angle members retrofitted through additional parallel components. An experimental study and numerical modeling have been carried out. The internal mechanism between splice joints and connectors has been analysed through a series of parametric studies.

2. Experimental tests

2.1. Test specimens

The test specimens in this investigation were made from 65 mm × 65 mm × 5 mm equal angle steel with grade 300 (i.e. nominal yield strength of 300 MPa). As shown in Fig. 3, the specimens were composed of a main (original) member, a reinforcing member, two angle cleats at the top end, two angle cleats at the bottom end, and one bolted splice joint in the centre of the main member. The main member was cut in half then re-joined again by a bolted splice joint. The cross sections of the two re-joined members were not touching each other, but had a 10 mm gap between their ends. The test specimen was bolted to a bottom support which held the structure securely upright during loading. The upper main member and reinforcing member were connected by two angle cleats at the top end and each top angle cleat was designed to have six bolt holes per connection. The bottom main member and reinforcing member were connected by two angle cleats at the bottom, and each bottom angle cleat had four bolt holes for connection. The splice joint was composed of one splice angle and two splice plates with 12 bolt holes for connection. The reinforcing member was made from a steel angle with the same cross sectional area and yield stress as the main member. The length of the test specimen was 1107 mm including a 10 mm gap between the two main members at the splice joint. A slenderness ratio of 80 was chosen for the main member.

Grade 8.8 M16 (i.e. 16 mm diameter, 800 MPa nominal yield strength) high strength bolts and nuts were adopted as the fastener for all test specimens. The bolts and nuts were tightened with 150 Nm torque to reduce movements between the specimen components and to provide frictional forces between the surfaces in contact. The number of bolts at the top joint was 12, six per angle cleat, and the total number of bolts at the bottom joint was eight, four per angle cleat. The splice joint was 300 mm long, composed of two splice plates and one splice angle. There were 12 bolts, six bolts per connection face. These cleat and splice joints were important parts of this system to help in transferring forces between parts of the main member.

2.2. Test setup and procedures

The top support of the test specimen was a flat circular metal plate attached to the compression machine (Fig. 4). The contact surface between the top support and the test specimen acted as a semi-rigid joint to allow the metal plate to touch the member surface before and after the buckling occurred in the specimens.

The specimen was carefully positioned in the middle of the flat circular plate so that the centre of the top plate coincided with the centre of the main member. This system was designed to transfer forces from the top plate to the main member. The force in the main member is then shared with the reinforcing member by transfer through the top and bottom cruciform joints, replicating the situation in practice where load is already being carried by the main tower legs when the reinforcing members are attached to them.

The bottom parts of the test segments were fixed to the support to prevent translation and rotation in all directions, which allowed the main member and reinforcing member to behave as a compound member (and replicates the physical situation where the base of the tower legs are embedded in concrete footings). At the bottom section, the support was fabricated and attached to the bottom of the test specimen with a total of 8 Grade 8.8 M16 bolts to achieve sufficient rotational restraints during experimental tests.

In order to determine the load distribution behavior between the main members and reinforcing members, four pairs of strain gauges were attached at the assigned location as shown in Fig. 3. The load was applied to the top cross section of the main member of the test specimen at a speed of 2.5 kN/Sec. Hence, the top section of the loading machine was moving downward very slowly to allow the load to be transferred from the main member to the reinforcing member without causing any sudden failure.

Fig. 2. Bolted splice joint position in actual tower structures.