Journal of Constructional Steel Research 121 (2016) 253–260

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Experimental and numerical analysis of a bolted connection in steel transmission towers

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 21 January 2016
Accepted 12 February 2016
Available online 26 February 2016

Keywords:
Lattice transmission tower
Topic:
Bolted connection
Splice connection
Steel angle
Bolt slip
Finite element analysis
Tension member

ABSTRACT

This paper presents an integrated numerical and experimental study on a bolted splice connection used in main legs of steel lattice transmission towers. At specific locations, where the number of angle sections in built-up cross section of main leg members changes, the complex geometry around the connection region results in eccentricities in the load path and indirect load transfer. Such complex configurations and uncertainties in the load path have led to overdesigned connections with increased number of bolts and redundant connection reinforcing members. The current study was conducted in an attempt to gain a better understanding of the load-flow mechanism at this specific location where the cross section of main leg members changes. The experimental part included tensile load testing of six specimens with different connection details. The main parameters used in the testing program were the number of bolts used in the connection as well as the presence of connection reinforcement angles and tie plate. For all connection configurations studied, the failure occurred due to net section fracture of upper main member angle near leading bolt holes. The calculated load capacity based on the measured material strength closely predicted the measured load capacity of specimens. The experimentally determined response of each connection configuration was better predicted by the FE model that incorporates bolt slip as compared to the model that assumes no slip. The experimental and numerical results also indicate that major differences among the investigated connection details do not cause any appreciable difference in behavior under tensile loading.

1. Introduction

Steel lattice towers have been extensively used worldwide as an important component of power transmission networks. These towers are usually constructed using equal leg angle section members and bearing type bolted connections. Depending on the magnitude of conductor and environmental loads as well as the geometric constraints of the transmission line, the axial force in main members at lower parts of the tower could get so large that built-up sections have to be used at these locations. These built-up sections are usually made of two, three, or four steel angle sections connected corner-to-corner, depending on the level of axial force in the member. At higher locations along the height of tower, axial force level in main legs decreases and this allows a reduction in the cross-sectional area of these members. Such reduction in the cross-sectional area of main legs is usually achieved by reducing the number of steel angle sections in the built-up cross section. At the specific locations, where the number of angle sections in the built-up cross section changes, the complex geometry around the connection region results in eccentricities in the load path and indirect load transfer between several components. Such complex configurations and the uncertainties in the load path have led to overdesigned connections with increased number of bolts and redundant connection reinforcing members. The current study was conducted in an attempt to gain a better understanding of the load-flow mechanism at this specific location where the cross section of main leg members changes. The overall goal was to simplify the connection geometry by identifying the redundant members that can be eliminated from the connection without significantly affecting the structural behavior. An experimental study integrated with numerical analyses was conducted in order to achieve this goal.

Numerical analysis of steel lattice towers has recently been performed by many researchers [1–4]. These numerical analyses were conducted using finite element models constructed using either one-dimensional beam–column elements or two-dimensional shell and plate elements. Eccentricity of connections and flexibility of joints were also considered in some of the studies. In majority of the cases, results obtained from the models were compared to the observed response from full-scale proof-load tests or smaller scale laboratory tests of the towers. These studies indicate that the maximum load capacity and the distribution of member failures can be predicted with a fair accuracy using numerical models. Based on the analysis of transmission

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http://dx.doi.org/10.1016/j.jcsr.2016.02.009
0143-974X/

line tower failures during prototype load testing, the possible reasons for tower failures are given as incorrect design assumptions, improper detailing, material defects, fabrication errors, force fitting during erection, and variation in bolt strength [1]. Several studies have also focused on the effect of bolt slip on nonlinear behavior of lattice towers [5–7]. Results from these studies indicated that the joint slip would be expected to affect the tower displacement, but have no major influence on the failure mode and ultimate strength of the tower.

Another current area of research related with overhead transmission line towers is on strengthening of existing towers. Various strengthening methods to improve the load capacity of existing lattice towers so that they can tolerate the increase in conductor loads have recently been studied both experimentally and numerically [8–12]. These studies revealed that upgrading of existing towers could be achieved by providing additional bracing for members or by increasing the total cross-sectional area of individual members by reinforcement.

Experimental and numerical studies on bolted splice connections of different types of metallic members are also available in the current literature [13–18].These studies revealed information regarding many aspects of bolted connections that can be useful in design of various bolted connections in steel lattice towers. The main phenomena investigated with these studies are the influence of connection geometry on the extent of shear lag effect on steel angles, the influence of the amount of edge distance as well as the level of bolt pretension on the behavior of plate connections, and the influence of connection eccentricity on the behavior of T-section tension members.

2. Experimental program

The experimental part of the study included tensile load testing of six specimens with different connection details. The main parameters used in the testing program were the number of bolts used in the connection as well as the presence of connection reinforcement angles and tie plate. The specimens were fabricated at the production facility of a local manufacturer of transmission line towers, and were tested at Atilim University Structural Mechanics Laboratory.

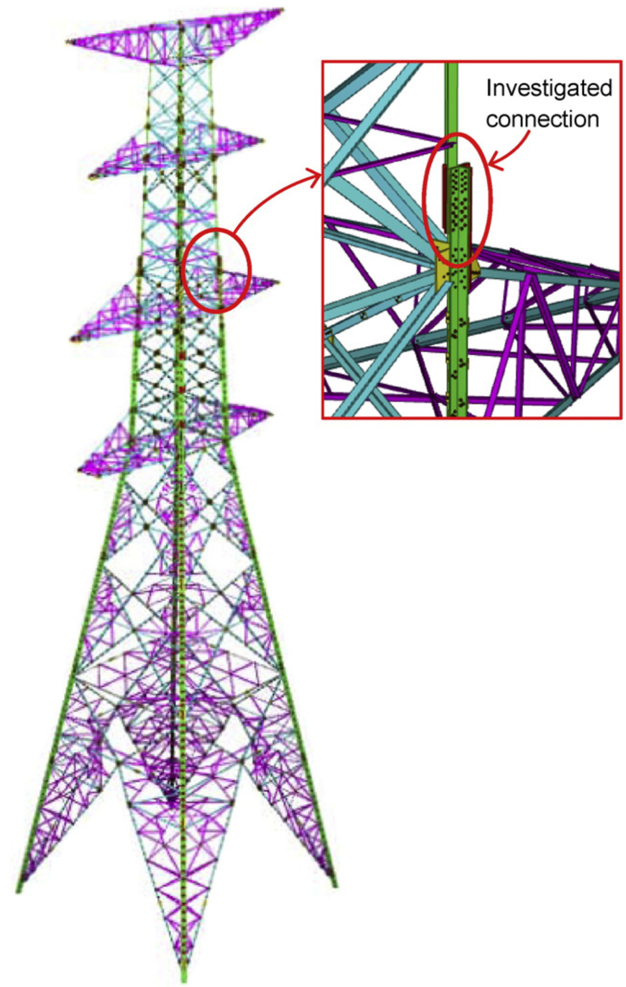

Fig. 1. Prototype design of 75 m tall 500 kV capacity tower.

2.1. Test specimens

A prototype latticed transmission tower was designed, and the splice connection at main legs of this prototype structure was used as a basis for the test specimens. General geometry of the prototype tower and the location of the investigated splice connection along the length of the tower are shown in Fig. 1. The loads considered during design of the 75 m tall 500 kV prototype tower included wind, ice, equipment, conductor, broken wire, and earthquake loads. A commercial computer program called PLS-Tower [19] was used to create the tower geometry, to apply the loads on the tower, to analyze the tower under loads, and to specify the member sizes. In the prototype design, S355 grade steel ($F_y = 355$ MPa) was used for the angle sections, and 20 mm diameter grade 8.8 bolts ($F_y = 640$ MPa, $F_y = 800$ MPa) were used for the connections. Each main leg in the prototype tower has two L150x16 angle sections positioned corner-to-corner below the investigated connection, while a single L160x17 angle section is used above this connection. Due to the limitations on the load capacity of the test setup, the test specimens used in the study were fabricated with a scale factor of 1:2.7, resulting in L60x6 angle sections and 8 mm diameter bolts. Testing of transmission tower subassemblies with scaled down models has previously been adopted by several researchers [8–10,20,21]. For the 8 mm diameter bolts, holes of 10 mm in diameter were used in members. The test specimens were fabricated by a local manufacturer of overhead transmission line tower supplier following the manufacturing methods conventionally used for the manufacturing of these towers.

The connection detail that is currently used for the transition from a double-angle section to a single angle section is shown in Fig. 2, together with the other details considered in this study. The original configuration (configuration A in Fig. 2) includes an interior and an exterior reinforcement angle, as well as a tie plate and two filler plates placed between the reinforcement angles and the main members. There are 16 bolts on each leg of the two lower main members, resulting in a total of 64 bolts in the connection. The two angle sections forming each main leg in the prototype tower are connected intermittently by 8 mm thick batten plates. Such an application results in an 8 mm gap between the angle sections of the main legs. To accommodate this gap, two 8 × 55 × 315 mm filler plates were used in the test specimens for configurations A–E. Each filler plate was replaced with two 8 mm thick plate washers for configuration F, as indicated in Fig. 2. The original connection detail also includes an 8 × 128 × 315 mm tie plate that is bolted to one leg of each of the two lower main member angles with 16 bolts. The tie plate was eliminated from the connection for configurations B, C, and F. Details of the investigated connection configurations are provided in Table 1 and the geometric details of angle members are given in Fig. 3.

In Specimens A through E the bolts were tightened with an air impact wrench. The experience gained during fabrication of the test specimens indicates that the tightness of the bolts obtained with the air impact wrench approximately corresponded to that obtained by the full effort of a person using a hand wrench. Such application was adopted in order to reflect the bolt installation practice that is usually used in erection of steel lattice transmission towers. In Specimen F, on the other hand, the air impact wrench was used only on the four bolts that were located where plate washers were used. Because there is a gap of 8 mm between the legs of the upper and lower main member angles at other bolt locations, these bolts were left as “finger tight”.