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Effect of damaged circular flange-bolted connections on behaviour of tall towers, modelled by multilevel substructuring

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ABSTRACT

The paper deals with non-linear analysis of a telecommunication tower with circular flange-bolted connections (CFBCs). They are composed of two flanges, welded to the structural tubes, and then connected together with pre-tensioned bolts. A rigorous FEM analysis is performed for finding the connection stiffness in two cases. One deals with all bolts undamaged and the second one with one or more bolts broken.

The analysis, which includes contact and friction forces, shows that when joints are under tension, the bolts are not only subjected to axial forces, but also to bending moments due the prying effect. The value of stresses caused by bending depends strongly on the bolt pre-tension and flange thickness. Removing one of the six connection bolts significantly increases stresses in the remaining bolts. Knowing the behaviour of the connection, it is possible to study the behaviour of the whole structure. This is achieved by applying the multilevel substructuring approach. The first levels is related to the flanges and bolts, whereby the connection model is simplified, and compared with the rigorous one, the second level is related to the assembly of the whole tower.

The paper is illustrated with several examples of connections of different thicknesses, and different bolt pre-tensions. The considered tower comes from a real design.

1. Introduction

Bolted connections have been used widely for several decades, in many fields of engineering design. Most often, they are applied in the beam-to-column connections. Recently, extensive studies have been devoted to their behaviour, taking into account both static and dynamic states [1–4].

Joints with bolts have also often been used in the form of flange connections, of different shapes. Circular flange-bolted connections (CFBC) are applied in pressure pipe systems and aircraft engines [5]. In civil engineering structures, CFBCs are mostly used in all kinds of tubular structures.

Circular tubes are widely applied in many structures, such as telecommunication towers, guyed masts and windmills. Usually, these are structures of very large dimensions, which have to be divided in sections owing to assembly constraints. Each section is fabricated (welded) separately, and then, on site all sections are connected together, applying the CFBCs. This is the reason why relatively a lot of attention has been paid to the mechanical behaviour of CFBC and their impact on whole structure response. Cao and Bell [6] discussed widely, among others, the prying effect occurring in these types of joints. Schaumann and Seidel [7] and Schaumann and Kleineidam [8] presented FE modelling and failure analysis of CFBC. Recently, Pavlovic et al. [9] proposed a new design of assembling joints, applying a single overlapping friction connection with long opened slotted hole. The flexural rigidity of bolts and its influence on the behaviour of steel joints has been shown by Abidelah et al. [10].

In engineering design, tubular connections are usually assumed to be pinned or rigid. It was shown by Gutkowski [11] that, such an assumption can lead to significant errors in structural response. Moreover, recent investigations of bolted circular joints showed their complex, non-linear nature, arising mostly from contact forces, friction and bolt pre-stressing. Research in the field over the past two decades deals with several important problems, mostly connection rigidity and its influence on the dynamic behaviour of the total structure. Investigations cover design models, numerical studies, as well as experimental approaches.

Swiercz et al. [12] applied Virtual Distortion Method for identification of bolted joint characteristics in frame structures. In another paper, Blachowski et al. [13] presented a method to localize damage in a frame structure with one loosened bolted

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connection. Bogacz et al. [14] investigated bolt connections in railway engineering. Stocki et al. [15] discussed the reliability problem of spot weld joints important for most of automotive industry structures.

The behaviour of the bolted flange connections under monotonic and cyclic loadings is discussed in [16]. The connections were subjected to axial tension forces applied monotonically, for low-cycle and high-cycle fatigue tests. The tests allowed the characterization of the behaviour of connections for this type of loading.

CFBCs play an important role in aircraft engines. Schwingshackl et al. [5] found that the flange model depends strongly on the steady stress/load distribution across the joint and on non-linear elements.

Luan et al. [17] found, by static mechanical investigation, that the axial stiffness of the bolted flange joint is different in tension and compression.

Heinisuo et al. [1] applied the component method for the structural modelling of steel joints in three dimensions. The results of investigation are presented in terms of local and global analysis. The proposed method is verified, for a beam-to-column joint, by a detailed 3D non-linear finite element analysis. Validation of the results is performed with experiments on the end-plate splice joints of rectangular tubular structures.

Couchaux et al. [18] discussed the global behaviour of CFBCs, subjected to complex loadings of bending moment and axial forces. Elastic and elastic–plastic states of the flange material were taken into account.

An important group of papers deals with CFBC defects. Yang et al. [19] proposed the application of a reduced-order modelling technique in damage detection. Numerical results were supported with interesting experiments performed on a shaking table of a 1:3-scale six-storey steel frame structure. The damages of joints are simulated by loosening the connection bolts. Another approach for location of damage in structural connections was presented by Pnevmatikos [20]. He applied Discrete Wavelet Transform to detect plastic hinges within a frame structure subjected to earthquake excitation.

He et al. [21] discussed a lightning mast composed of two pipes, connected together with a bolted flange connection. They proposed applying the global vibration approach, in which models of damaged and undamaged are compared. By introducing a logistic function transformation an unconstrained problem was obtained, which allowed the damage and its magnitude to be localized. The theoretical considerations were in a good agreement with experiments.

Perttola et al. [22] investigated the flanged joint of tubular members experimentally. The joint was subjected to different relative positions of the bending moment and bolts. The test data were compared with a mechanical 3D model.

Hanson et al. [23] evaluated practical, hand formulae for the design of bolted joints in launch vehicles. The formulae, which are based on idealized models, were compared with numerical results, obtained using FEM. Applying the flange model it is possible to observe the non-linear behaviour of a joint under external forces and temperature change.

Patrakkos and Tizani [24] investigated the behaviour of a new kind of anchored blind-bolt connection for concrete-filled hollow profiles. Experimental results showed the forms of the damaged connection through pull-out testing. Degree of dispersion based approach to investigate damage and the loss of stiffness in laboratory-scale beam with flexible connections was presented in the paper by An et al. [25].

All of the above works, theoretical and experimental, show that the mechanical properties of joints are crucial in the design of structures. Among these are CFBCs, which play an important role in the behaviour of the whole structure, in both static and dynamic cases.

In the present paper, a rigorous FEM analysis of CFBCs, applied in tubular towers, is presented. The analysis contains such effects as, contact and friction, together with pre-stressing of connecting bolts. Parametric studies are conducted to show the non-linear effect of the rigidity, compared with a variation of bolt tightness. Additionally, the stress distribution is found, not only in the flange itself, but also in the bolts. It is interesting to note that under the tension of the connection, the bolts are subjected to bending. Next, a damaged connection with a broken or loose bolt is considered.

In the last part of the paper, the behaviour of the complex structure, composed of tubular beams and bolted connections, is investigated. The discussion includes the influence of a damaged connection on the tower deflection. The problem is solved by applying a multilevel substructuring approach, and a reduction of DOFs using static condensation method.

2. The structure under consideration

The paper deals with a telecommunication tower, composed of four truss/frame segments (Fig. 1), together assembled with CFBC. The tower is of a triangular cross section. It is composed of tubular, longitudinal members and tubular bracings. All of them constitute a truss like structure. However, on the contrary to the pin joints assumed in the truss design, here the connections joining longitudinal elements are considered to be elastic. They are composed of circular flanges and pre-stressed bolts (Fig. 2).

Due to a very large number of degrees of freedom in FEM analysis, a two level of substructuring to the whole tower is applied. The substructuring of the connection consists on dividing it in components, which are modelled separately, and then combined together. The substructuring of the tower consists on separate analyses of tower sections and connections, and then joining all of them in one structural system.

First of all, in Section 3, the non-linear FEM analysis of the connection is considered. As the result, CFBC rigidity, in the form of force–deformation relation is obtained. Additionally, results of the analysis show the bolt bending due to the prying effect.

An extended FEM analysis allows, moreover observing the behaviour of the connection with one or more bolts failed.

At the end of general consideration, the substrucuring and the condensation of tower segments and connections is discussed. This gives practical formulae allowing to find the response of the tower to external loads.

3. The dependence of the CFBC rigidity on bolt pre-tension

The discussed CFBC is presented in Fig. 2. It is composed of two similar flanges, each welded to a structural tube. The flanges are connected together with six bolts. The bolts, acting through washers, are pre-tensioned with prescribed forces. The material of flanges, bolts and pipes is steel, with Young modulus 205 GPa and Poisson ratio 0.3. The friction coefficient is assumed to be 0.5.

Owing to the non-linearity, the connection rigidity is understood as a ratio of the force variation Δf to the displacement variation Δu, between places where flanges are welded to the tubes. It means that tubes are not included in defining the connection rigidity. They are only needed for a proper modelling of place where the connection is linked to the tube.

The connection is modelled using 3D FEM in Abaqus/Standard (Fig. 3), with the finite-sliding, surface-to-surface contact formulations. The master and slave nodes are automatically assigned to surfaces by the program.