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Global fatigue life modelling of steel half-pipes bolted connections

S. Jovašević[a], J.A.F.O. Correia[a,b,*], M. Pavlović[c], C. Rebelo[a], A.M.P. De Jesus[b], M. Veljković[c], L. Simões da Silva[a]

[a] University of Coimbra, ISISE, Department of Civil Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal
[b] University of Porto, INEGI, Engineering Faculty, Rua Dr. Roberto Frias, 4200-465 Porto, Portugal
[c] Faculty of Civil Engineering and Geosciences, Delft University of Technology, Building 23, Stevinweg 1, 2628 CN Delft, Netherlands

Abstract

A steel hybrid structural solution for onshore wind turbine towers was proposed in the European project SHOWTIME. This solution is used in the lattice structure for the lower portion of the tower. Recently, a procedure for fatigue life estimation of steel half-pipes bolted connections applied in global structural models using multiaxial Smith-Watson-Topper (SWT) criteria was proposed by Öztürk et al. In this paper a procedure for design S-N curve modelling of steel half-pipes bolted connections is proposed. This procedure is based on a local approach using multiaxial fatigue criteria together with an elastoplastic analysis using the finite element method. The materials to be used in this analysis are the S355 and S690 steels. This evaluation to be performed is calibrated with experimental results of fatigue tests of the connection under consideration.

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Keywords: Half-pipes bolted connections; Finite element modelling; Fatigue crack initiation; Multiaxial damage criterion.

1. Introduction

Wind energy has been used for more than 3000 years. Today, when global warming has become one of the most serious environmental issues, the need for renewable energies is increasing. The high demand for wind energy is leading the development of more powerful wind energy converters that demand higher towers to reach zones of higher speed and less turbulent wind [1,2]. With the increase of the tower height also transportation, assembly, erection and maintenance of the tower becomes more difficult and costly. On the other hand, increase in height rises

* Corresponding author. Tel.: +351225082151; fax: +351225081584.
E-mail address: jacorreia@inegi.up.pt

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the generated energy. At the moment, the most commonly used type of tower for wind energy conversion (WEC) is steel tubular tower. However, for the heights above 100 m, this type of tower requires diameters at the tower base of more than 5 m which makes the usual assembling process unfeasible due to public road transportation limitations [3,4,5]. Some producers have proposed lattice solution. Comparing to tubular tower, lattice towers have many bolted connections that require frequent maintenance, do not provide protected area for workers and are aesthetically less appealing, but they are not affected by transportation limitations [6,7]. For the lattice tower, a Finnish steel manufacturer has developed a new concept using cold formed built up profiles. Cold formed pieces (Fig. 1-left) are connected together with preloaded bolts creating a hexagonal cross section. All joints of cross section are also bolted with preloaded bolts (Fig. 1-right) [1].

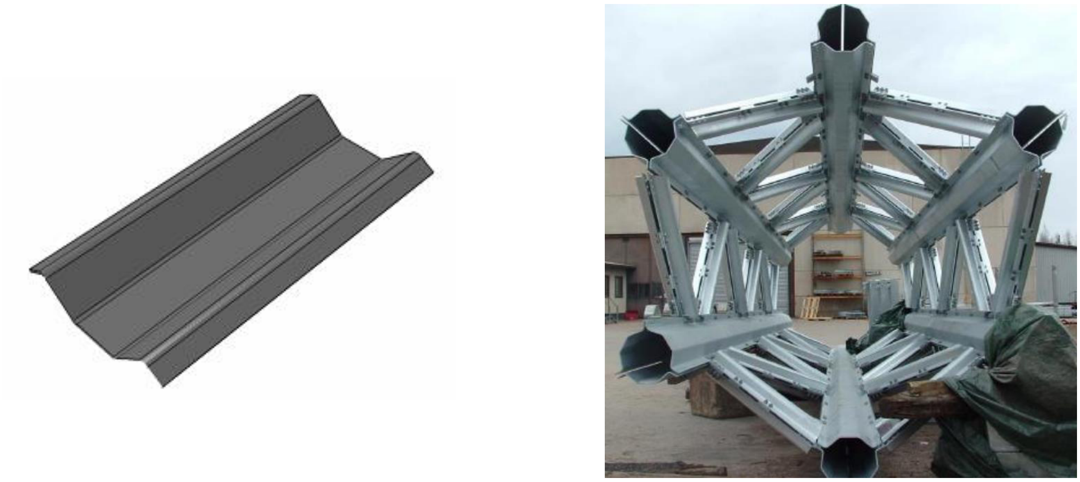

Fig. 1. Cold formed-plate for lattice towers (left), lattice steel tower (right)

Another type of tower construction that allows greater heights is the hybrid solution. This type of the tower is composed of three parts: the lower lattice part, tubular tower consisting of several parts bolted or welded together as in typical tubular tower solution, and transition piece which ensures the connection and transmission of forces between two main parts. The use of tubular tower for the upper portion beneficiates of all advantages of optimized technology for tubular steel towers with the diameters within public road transportation limitations, while the lattice portion enables the required extension of height [2,8]. Another advantage is that the lattice portion can be used to facilitate installation of the upper tubular portion and the turbine, therefore avoiding the need for very high cranes [3,8].

Lattice structures composed of hollow sections are widely used. They are used in buildings and halls, bridges, barriers, offshore structures, towers and masts. One main problem is the connections that can be used for tubular hollow sections. This has led to development of different types of welded and bolted connections between the sections. Within European project SHOWTIME [9] new type of tubular elements and connections are under development. These types of elements and connections will allow improvements in the way of construction as well as in the fatigue resistance and in the maintenance needs during service life.

The tower developed within SHOWTIME has hub height of 220m (120 m lattice part (Fig. 2), 100 m tubular part), supporting a 5 MW wind turbine. The lattice part is composed of 6 chord members placed with an angle of 120° and K braces with the angle of 45° from the horizontal. The materials to be used are S355 and S690 steels [10].

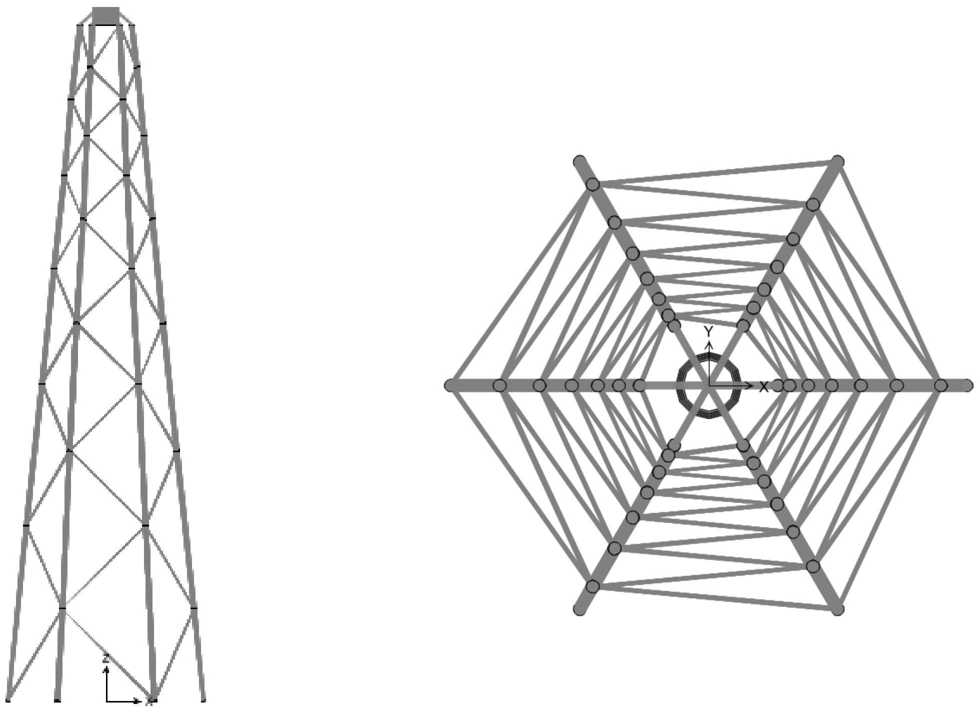

Fig. 2. Lattice structure of onshore wind turbine tower: side view (left), top plan view (right)

Connections with gusset plates are used for pylons which are connected in different directions to the bracing system. Preloaded bolts are used for the connection of gusset plates and the members. 3D and cross-section view are shown in the Fig. 3. In the application for structures of WEC, special attention has to be given to the fatigue behaviour of the connections as the towers are subjected to dynamic loads [11]. The fatigue behaviour of preloaded bolted connections is generally better than that of welds. They can carry higher fatigue loads then welded connections, meaning that in general bolted joints in shear are not the most critical components. Comparing preloaded with non-preloaded connections, preloaded bolted connections have a favourable fatigue behaviour and significantly better stress distributions [12,13].

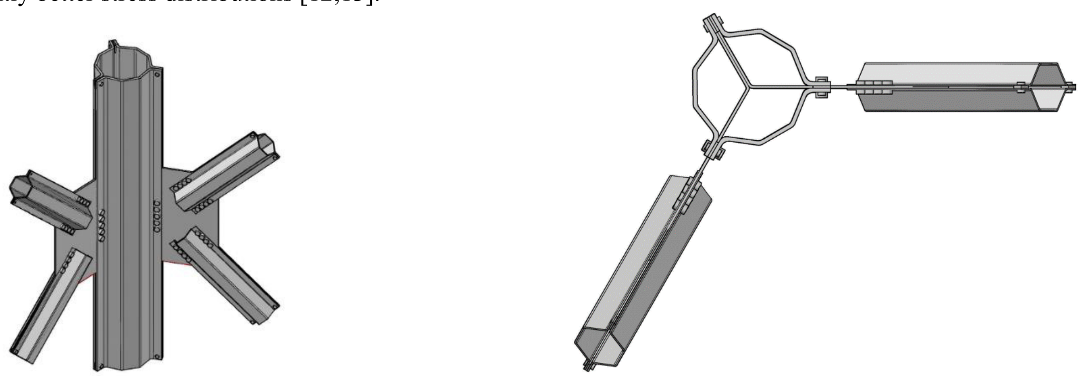

Fig. 3. 3D view and cross-section view of the bolted connection

Fatigue life evaluation of structural details may be carried out using different approaches. The global *S-N* approach was the first prediction technique developed [14]. This technique is generally used to predict the total life of a component. It is supported by experimental results and directly relates a global definition of stress range, $\Delta\sigma$, with total number of cycles to failure, N_f. Local approaches are associated with local failure models and could be described by strain-life and stress-life relations [15,16]. Strains and stresses are evaluated at a local hot spot. This approach considers only crack initiation life. Hence, it can be used only when crack initiation dominates the total fatigue life. On the other hand, Fracture Mechanics approach is based on fatigue crack growth models. Propagation of the crack is predicted from an initial crack size, to the final crack size which leads to the fracture of the structural detail or mechanical component [17,18]. When both, the crack initiation and propagation stage of a component are important, the local approaches combined with the Fracture Mechanics can be used to predict the total fatigue life of the structural detail [19,20]. Multiaxial fatigue models take into account the multiaxial strain or stress distributions at notches or crack tips and can be based on a stress or strain based approach, energy criteria and critical plane criteria [21]. Depending on the chosen criteria, fatigue crack initiation, propagation or total fatigue life can be predicted.

Eurocode 3 Part 1-9 [22] covers fatigue design/assessment of onshore steel structures. The fatigue assessment procedure essentially starts from a set of predefined constructional details. Different routes through the process are taken if the detail under consideration falls within the classification, or differs from any standard detail classified and/or is an unclassified detail. The route prescribes the type of fatigue stress range that can be used in the assessment along with the fatigue S-N curve to be applied. Constant amplitude and variable amplitude loading are addressed. In the latter case (the more general), assessment is based on cumulative damage (Palmgren-Miner rule) or equivalent constant amplitude. Normal stresses and shear stresses can be applied individually or in combination. Fatigue strength curves are bi-linear, or linear on log-log scales of fatigue strength (stress range) versus endurance, with some also having endurance limits (cut off levels).

The previously described connection (Fig. 3) is not classified by Eurocode 3 part 1-9. Taking into account the importance of the fatigue life evaluation of structural details in wind turbine towers, typified assessment route to derive a S-N curve is established. The aim is to find an *S-N* curve for the chosen typified structural detail.

2. Global fatigue analysis procedure of half-pipes bolted connections for onshore wind turbine towers

A procedure for multiaxial fatigue life estimation of steel half-pipes bolted connections is presented. This procedure is supported by global structural models based on beam elements. Local approaches to fatigue are proposed [23]. The procedure is summarized as follows (see Figure 4):

i) Linear-elastic analysis of the global structural model using beam elements;

ii) Definition of the global/local interface with the critical region identification and interpolation region specification;

iii) Local model definition of the connection in order to build the local model using linear-elastic analysis aiming at obtaining the stiffness of the joint;

iv) An elastoplastic analysis of the local model is also required to determine the maximum principal stresses and strains at the fatigue critical points;

v) Local multiaxial fatigue damage analysis at the critical point using a multiaxial damage criterion.

The proposed procedure for multiaxial fatigue life evaluation of steel half-pipe bolted connections of an onshore wind turbine tower would provide satisfactory results considering the reduced computational time of a global-local modelling approach. Computational time required to obtain internal forces in the global structural model is expected to be reduced using the local model for determination of the joint stiffness. The maximum principal stresses and strains taking into account fatigue loading can be determined from local model analysis of the joints. The use of the SWT parameter [24] as a multiaxial damage criterion can be used in the prediction of fatigue life of the steel half-pipe bolted connection [23].

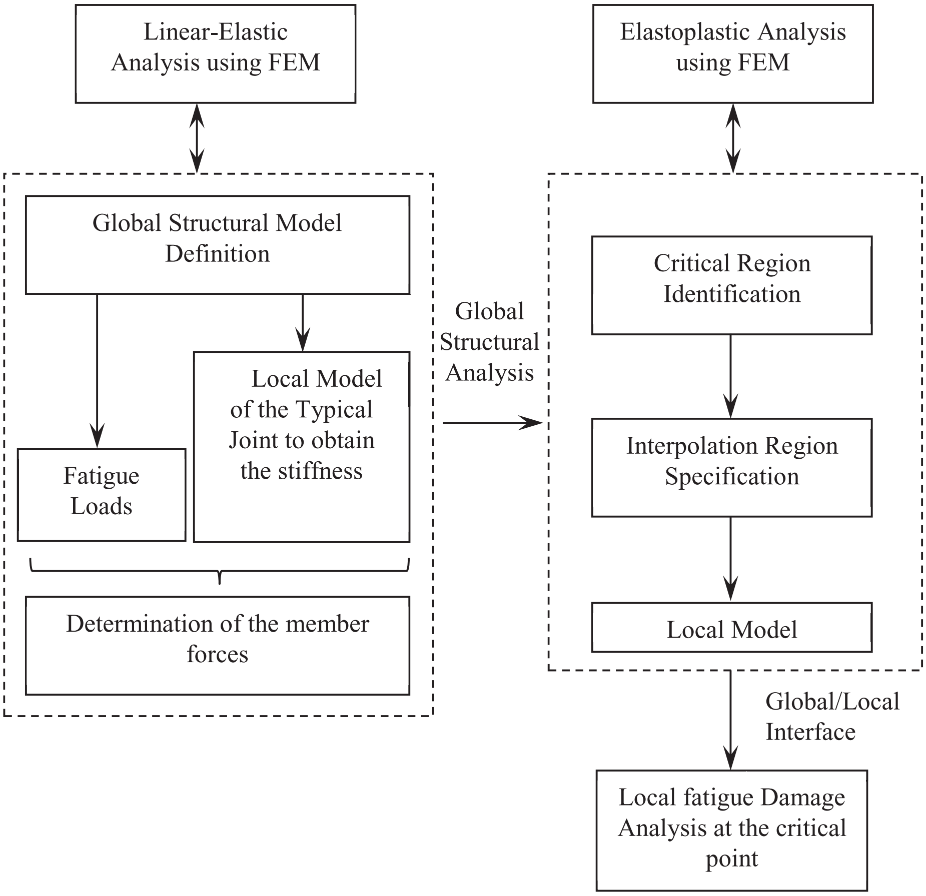

Fig. 4. Global fatigue analysis proposed by Öztürk et al. [23].

3. Proposed procedure for design S-N curve modelling of steel half-pipes bolted connections

A procedure for multiaxial fatigue assessment of a steel half-pipe bolted connection is to be proposed in the SHOWTIME project and some ideas are explored in this paper with this regard. The multiaxial fatigue life evaluations can be made using several approaches, such as based on strains [25,26,27], stresses [28] and energy [29,24]. The proposed approach (SWT) is a local energy-based type approach that will be explored to derive design S-N curves from plain material fatigue data.

This type of connections under analysis in this paper is subjected to complex loads. In this sense, the choice of a multiaxial damage criterion is required [23]. In order to apply a multiaxial/biaxial damage criterion it is necessary to carry out experimental tests of small-scale specimens to characterize the cyclic elastoplastic behavior under multiaxial/biaxial loading conditions of materials under study. A typified local model analysis is to be made based on an elastoplastic analysis using a finite element method taking into account loading conditions [30,31]. In this analysis the cyclic elastoplastic behavior under multiaxial/biaxial loading conditions of the material under study, taking into account stress state in the structural detail, is to be simulated. This analysis aims at obtaining design theoretical S-N curves taking into account various variations of local geometric and mechanical parameters.

A generalized probabilistic local model must be derived for the material under consideration from constant amplitude strain-based fatigue data, based on uniaxial and multiaxial loading conditions. For this purpose the generalized probabilistic Ψ-N model proposed by Castillo et al. [32,33] and Correia et al. [34,35] will be followed.

For the validation purpose fatigue tests on the connection shown in the Fig. 5 will be used performed. To evaluate the fatigue performance of double shear preloaded connections, axial fatigue testing applying tensile-tensile loads (R_σ=0) will be performed on the connections.

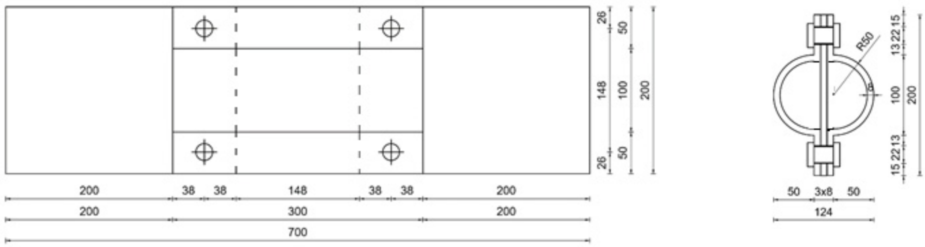

Fig. 5. Steel half-pipe bolted connection to be tested.

4. Conclusions

Eurocode 3 covers the fatigue assessment of a set of predefined constructional details. The connection described in this paper, that is to be used in the lattice part of a hybrid wind turbine tower, is not covered by the code. A typified connection for this type of structural detail has been established in the SHOWTIME project, but an appropriate fatigue assessment S-N curve is needed. A procedure for multiaxial fatigue assessment based on local energy-based approach is envisaged since complex loading histories are expected for these structures. Experimental tests are to be performed in order to characterize the cyclic elastoplastic behavior under multiaxial/biaxial loading. A local model will be used to obtain a theoretical S-N curve. The analysis is based on an elastoplastic analysis using a finite element method taking into account loading condition. Fatigue test results will be used for model calibration.

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