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Procedia Structural Integrity 1 (2016) 118–125

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XV Portuguese Conference on Fracture, PCF 2016, 10-12 February 2016, Paço de Arcos, Portugal

Fatigue assessment of steel half-pipes bolted connections using local approaches

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Abstract

This paper proposes a multiaxial fatigue assessment of a steel half-pipe bolted connection using a local energy-based approach. This bolted connection has been proposed for onshore wind turbine towers. A global linear-elastic model with beam elements for the onshore wind turbine tower was developed taking into account the stiffness of the joint. Damage equivalent fatigue loads were applied in global beam model. To assess the stiffness of the joint a linear-elastic model considering the preload on the bolts was made. A local elastoplastic model was built to obtain the maximum principal stresses and strains. Using this analysis was possible to determine the *SWT* damage parameter and the number of cycles to failure for the steel half-pipes bolted connection under investigation.

Keywords: Elastoplastic analysis; Half-pipes bolted connections; Finite element modelling; Local approaches; Multiaxial fatigue.

1. Introduction

Recently, a steel hybrid solution for onshore wind turbine towers using a lattice structure for the lower portion of the tower and a tubular upper portion was proposed. This solution targeted tall onshore applications supporting multi megawatt wind turbines. Previous developments focused on conceptual design and structural predesign of one case study based on equivalent load tables and using S355 steel grade: hub height 150 meters (40 meters lattice part, 110

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10.1016/j.prostr.2016.02.017

meters tubular part) supporting a 5 MW wind turbine. This paper develops a finite element (FE) model of a steel half-pipes bolted connection for multiaxial fatigue behavior assessment. The finite element model is a solid model that applies contact elements to simulate the contact between the bolts and the plates. In this paper, a multiaxial fatigue assessment using a local energy-based approach to fatigue is presented. Stress distributions around the bolts holes (critical locations) are investigated. Derived stresses are used to assess the fatigue crack initiation using available experimental strain-life fatigue data. Fatigue life estimation for the half-pipe bolted connection is performed.

2. Multiaxial fatigue life assessments

The multiaxial fatigue life evaluations can be made using several criteria, such as, criteria based on stresses, strains and energy. There are a number of multiaxial damage parameters being proposed in the literature covering low-cycle fatigue, high-cycle fatigue, proportional and non-proportional loading conditions. The multiaxial fatigue approaches used currently in the design codes are based on nominal normal and shear stresses. The multiaxial fracture mechanics approaches are defined using the three cracks deformation modes.

2.1. Stress-based criteria

Gough and Pollard (1935, 1937) proposed for ductile metals under combined in-phase bending and torsion the following equation for the fatigue limit under combined multiaxial stresses:

$$\left(\frac{\sigma_b}{\sigma_{FL}}\right)^2 + \left(\frac{\tau_t}{\tau_{FL}}\right)^2 = 1 \tag{1}$$

Sines (1959) proposed an alternative criterion in high-cycle fatigue regime, which became very popular:

$$\sqrt{J_{2,a}} + k\sigma_{H,m} \leq \lambda \tag{2}$$

A similar criterion was proposed by Findley (1959), Matake (1977) and McDiarmid (1991) using the shear stress amplitude and the maximum normal stress on the critical plane as parameters:

$$\tau_{a,cr} + k\sigma_{n,cr} \leq \lambda \tag{3}$$

McDiarmid (1991) defined k and λ as follows:

$$k = \frac{t_{A,B}}{2\sigma_u}, \lambda = t_{A,B} \tag{4}$$

Papadopoulos (2001) proposed a fatigue limit criterion which could be used in constant amplitude multiaxial proportional and non-proportional loading in high-cycle fatigue regime:

$$\tau_{a,cr} + k\sigma_{H,max} = \lambda \tag{5}$$

2.2. Strain-based type criteria

Findley and Tracy (1956, 1973) proposed a fatigue life equation in low-cycle fatigue regime about the influence of normal stresses to the maximum shear stress plane, with the following form:

$$\left(k \cdot \sigma_n + \frac{\Delta\tau}{2}\right)_{max} = \tau_f^*\left(N_f\right)^b \tag{6}$$

where k is a material constant, $\Delta\tau/2$ ($=\tau_a$) is the alternating shear stress, $\sigma_{n,max}$ is the maximum normal stress, and variable τ^*_f is determined using the torsional fatigue strength coefficient, τ_f', in the equation:

$$\tau_f^* = \sqrt{1 + k^2} \cdot \tau_f' \tag{7}$$

Brown and Miller (1973) defined the damage critical plane and proposed the following equation:

$$\left(S \cdot \Delta\varepsilon_n + \frac{\Delta\tau}{2}\right)_{max} = A\frac{\sigma_f'}{E}\left(2N_f\right)^b + B\varepsilon_f'\left(2N_f\right)^c \tag{8}$$

with

$$A = 1.3 + 0.7S \; and \; B = 1.5 + 0.5S \tag{9}$$

where S is a Brown and Miller constant.

Fatemi and Socie (1988) proposed a modified equation which was originated from Brown and Miller's relationship as follows:

$$\gamma_{max}\left(1 + n\frac{\sigma_n^{max}}{\sigma_y}\right) = (1+\nu_e)\frac{\sigma_f'}{E}\left(2N_f\right)^b + \frac{n}{2}(1+\nu_e)\frac{\left(\sigma_f'\right)^2}{E\sigma_y}\left(2N_f\right)^{2b} + (1+\nu_p)\varepsilon_f'\left(2N_f\right)^c + \frac{n}{2}(1+\nu_p)\frac{\sigma_f'\varepsilon_f'}{\sigma_y}\left(2N_f\right)^{b+c} \tag{10}$$

Where n is an empirical constant, ν_e and ν_p are Poisson's ratio in the elastic and plastic region, respectively.

2.3. Energy-based criteria

Smith et al. (1970) proposed a damage parameter, known as *SWT* parameter, to account for mean stress effects updating existing strain-based fatigue models. In multiaxial fatigue conditions the SWT parameter is determined for the critical plane which corresponds to the maximum principal stress and strain as follows:

$$SWT = \max\left(\sigma_n \cdot \frac{\Delta\varepsilon_1}{2}\right) \tag{11}$$

$$\sigma_n \cdot \frac{\Delta\varepsilon_1}{2} = \frac{\left(\sigma_f'\right)^2}{E}\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c} \tag{12}$$

where σ_n is the maximum principal stress during the cycle and $\Delta\varepsilon_1/2$ is the principal strain amplitude. Socie (1987) modified the *SWT* parameter taking into account the parameters that control the damage, such as:

$$SWT = \Delta\varepsilon_1^{max} \cdot \Delta\sigma_1 + \Delta\gamma_1^{max} \cdot \Delta\tau_1, for\ tensile\ mode \tag{13}$$

$$SWT = \Delta\gamma_{max} \cdot \Delta\tau \quad + \Delta\varepsilon_n \cdot \Delta\sigma_n, for\ shear\ mode \tag{14}$$

Other approaches for the *SWT* parameter were proposed by *Chu et al.* (Chu et al. (1993)), *Liu* (Liu (1993)) and *Glinka et al.* (Glinka et al. (1995)). *Ellyin* (Ellyin (1997)) proposed a model based on the energy density associated to each cycle, ΔW^t, which is composed by two parts: plastic strain energy, ΔW^P, and the positive elastic strain energy, ΔW^{E+}. In the case of proportional or biaxial non-proportional loading, the total energy density associated to a cycle may be computed as:

$$\Delta W^t = \Delta W^P + \Delta W^{E+} = \int_t^{t+T} \sigma_{ij} d\varepsilon_{ij}^P + \int_t^{t+T} H(\sigma_i)H(d\varepsilon_i^e)\sigma_i d\varepsilon_i^e \tag{15}$$

where σ_{ij} and ε^P_{ij} are the stress and plastic strain tensors, σ_i and ε_i^e are the principal stresses and the principal elastic strains, T is the period of one cycle and $H(x)$ is the Heaviside function. The fatigue failure criterion is defined according to the following expression:

$$\psi = \Delta W^t = \frac{\Delta W^P}{\bar{\rho}} + \Delta W^{E+} = \kappa\left(2N_f\right)^\alpha + C \tag{16}$$

where κ, α and C are material parameters to be determined from appropriate tests and $2N_f$ is the number of reversals to failure. The multiaxial constraint ratio, $\bar{\rho}$, can be determined using the following expression:

$$\bar{\rho} = (1+\bar{\nu})\frac{\hat{\varepsilon}_{max}}{\hat{\gamma}_{max}} \tag{17}$$

with

$$\hat{\varepsilon}_{max} = max[\varepsilon_a, \varepsilon_t] \tag{18}$$

$$\hat{\gamma}_{max} = max[|\varepsilon_a - \varepsilon_r|, |\varepsilon_t - \varepsilon_r|] \tag{19}$$

where ε_a and ε_t are principal in-plane strain (axial and transversal) parallel to the free surface, ε_r is the radial strain (perpendicular to the free surface), and $\bar{\nu}$ is an effective Poisson's ratio.

2.4. Nominal stress approach

The calculation of nominal normal ($\Delta\sigma_{nom}$) and shear ($\Delta\tau_{nom}$) stress ranges using the theory of elasticity are typical when applied with design codes. The fatigue assessment using the nominal stress approach for several joints is shown in fatigue classes where the relation between applied stress range, $\Delta\sigma_{nom}$ or $\Delta\tau_{nom}$, and fatigue life, N, is given by the following relations:

$$N \cdot \Delta\sigma_{nom}^{m} = C \tag{20}$$

$$N \cdot \Delta\tau_{nom}^{m_\tau} = C_\tau \tag{21}$$

where C, C_τ, m and m_τ are material constants. The material constants m and m_τ describe the slope of the fatigue strength curves.

The normal and shear stresses effects must be combined in the multiaxial fatigue assessment. The Eurocode 3 part 1-9 present three different alternatives to take into account their effects:

i) The effects of the shear stress range may be neglected, if the $\Delta\tau_{nom}<0.15\Delta\sigma_{nom}$;

ii) For proportional loading, the maximum principal stress range may be used, in the situation in that the plane of the maximum principal stress doesn't change significantly in the course of a loading event;

iii) For non-proportional loading events, the components of damage for normal and shear stresses should be assessed separately using the interaction equation or the Palmgren-Miner rule:

$$\left(\frac{\Delta\sigma_{eq,nom}}{\Delta\sigma_c}\right)^3 + \left(\frac{\Delta\tau_{eq,nom}}{\Delta\tau_c}\right)^5 \leq 1 \tag{22}$$

where $\Delta\sigma_c$ and $\Delta\tau_c$ are the reference values of the fatigue strength at 2 million cycles.

$$D_\sigma + D_\tau \leq 1 \tag{23}$$

The computation of the equivalent normal and shear stress ranges are presented, as a function of the normalized stress cycles, N_{ref}:

$$\Delta\sigma_{eq,nom} = \sqrt[m]{\frac{\sum_{i=1}^{k}\left(\Delta\sigma_{nom,i}^{m} \cdot n_i\right)}{N_{ref}}} \tag{24}$$

$$\Delta\tau_{eq,nom} = \sqrt[m_\tau]{\frac{\sum_{i=1}^{k}\left(\Delta\tau_{nom,i}^{m_\tau} \cdot n_i\right)}{N_{ref}}} \tag{25}$$

2.5. Fracture Mechanics criteria

The Fracture Mechanics is based on three cracks deformation modes. These deformation modes are the following: opening mode or tension mode or mode I; in-plane shear or mode II; and out-of-plane shear or mode III.

A simple power law relationship between the rate of the crack growth per cycle (da/dN) and the range of stress intensity factor (ΔK_I) to describe the tension mode for mode I in constant or variable amplitude loading conditions was developed by *Paris and Erdogan* (Paris et al. (1963)):

$$\frac{da}{dN} = C(\Delta K_I)^m \tag{26}$$

where C and m are material constants.

The crack growth rates in multiaxial fatigue loading may be determined using an equivalent stress intensity range, ΔK_{eq}. The multiaxial fatigue evaluations are conducted with *Paris* simple power law by replacing ΔK_I with ΔK_{eq} (Tanaka (1974), Socie et al. (2000)):

$$\Delta K_{eq} = \left[\Delta K_I^4 + 8 \cdot \Delta K_{II}^4 + \frac{8 \cdot \Delta K_{III}^4}{1-\nu}\right]^{0.25} \text{ [20]} \tag{27}$$

$$\Delta K_{eq} = [\Delta K_I^2 + \Delta K_{II}^2 + (1+\nu) \cdot \Delta K_{III}^2]^{0.5} \text{ [21]} \tag{28}$$

where ν is the Poisson's ratio.

The numerical automatic crack-box technique was developed to perform fine mixed-mode fracture mechanics calculations. This technique was proposed by *Lebaillif et al.* (Lebaillif et al. (2007)) and consists of the following steps: i) meshing of the three regions for the initial crack; ii) performing finite element method calculations associated with crack extension criterion in order to determine the crack extension angle; iii) taking a crack growth increment in the direction corresponding to the crack extension angle; iv) updating of local crack tip region mesh and connecting it by the use of transition zone to the whole structure.

Another technique based on a two-step approach was proposed in order to compute the stress intensity factors of the mixed mode crack propagation tests using modified CT geometries (Da Silva (2015), Correia el al. (2016)). The experimental data assessment for the mixed mode tests is performed using Digital Image Correlation (DIC). DIC is used with two purposes: i) crack path evaluation and ii) stress intensity factors computation.

3. Proposed procedure for fatigue life estimation of half-pipes bolted connection

The proposed procedure to multiaxial fatigue life estimation of steel half-pipes bolted connections applied in global structural models with beam elements using local approaches can be summarized as follows:

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 to obtain 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, for example one of the criteria described in Section 2.

4. Wind turbine towers using steel half-pipes bolted connections - application of the proposed procedure

4.1. S355 steel behavior

The fatigue behavior of the S355 mid steel to use in this study was evaluated by De Jesus et al. (De Jesus et al. (2012)), based on experimental results from fatigue tests of smooth specimens. The fatigue tests of smooth specimens were carried out according to the ASTME606 standard, under strain controlled conditions and are summarized in Tabs. 1 and 2. The Poisson's ratio, ν, equal to 0.30 was used in this study.

Table 1. Monotonic and cyclic elastoplastic properties of the S355 mid steel.

E	f_u	f_y	K'	n'
GPa	*MPa*	*MPa*	*MPa*	-
211.60	744.80	422.000	595.85	0.0757

Table 2. Morrow constants of the S355 mid steel.

σ'_f	b	ε'_f	c
MPa	-	-	-
952.20	-0.0890	0.7371	-0.6640

4.2. Steel half-pipes bolted connection – local linear-elastic model to evaluate the joint stiffness

A 3D finite element model was developed in order to calculate stiffness of the joint (Fig. 1). Only one half of the KK joint was modelled. The finite element model is composed by quadratic C3D20R and linear C3D8R elements for gusset plates and other parts, respectively. To extract more accurate results, mapped meshes with sufficiently fine mesh around the hole of the plates has been used in finite element analyses. The friction effect between the surfaces of the bolt head and plates was included in the finite element model using the elastic Coulomb model, where the average value of the friction coefficient is equal to 0.35.

A simple calculation was made by finding a relation between rotation and moment in order to validate the obtained results in joint stiffness model analysis. This simple method allowed obtaining the joint stiffness using three different finite elements, such as, C3D20R, C3D10, and C3D10M, with second order accuracy elements for gusset, and C3D8R elements for other parts. The relationship between the moment and rotation for these models is shown in Fig. 2. The result of the model with C3D20R elements was used. This last model is suggested because of the good balance between computational time and accuracy given by such elements.

Calculation of the bolts preload was made according to EN 1993-1-8. A simple preload model was made in order to validate the value obtained according to the EC3-1-8 (Fig. 3).

The preload value was used in the finite element model of the connection in order to obtain the stiffness of the joint. The stiffness was taken into account in the global structural model.

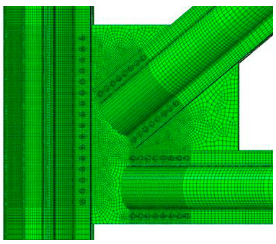


Fig. 1. Finite element model in order to calculate the joint stiffness.

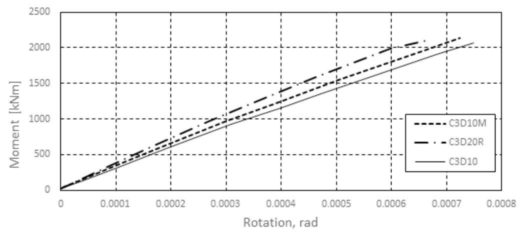


Fig. 2. Elastic joint stiffness.

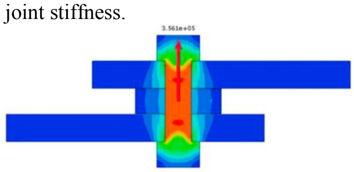


Fig. 3. Preload validation (356.1 kN).

4.3. Onshore wind turbine tower – global structural model

The global structural model of the onshore wind turbine tower is composed of 8 chord members with a length of 54.83 m placed with an angle of 66º. The tower height is approximately 50 m, with 64 braces and 72 horizontal members.

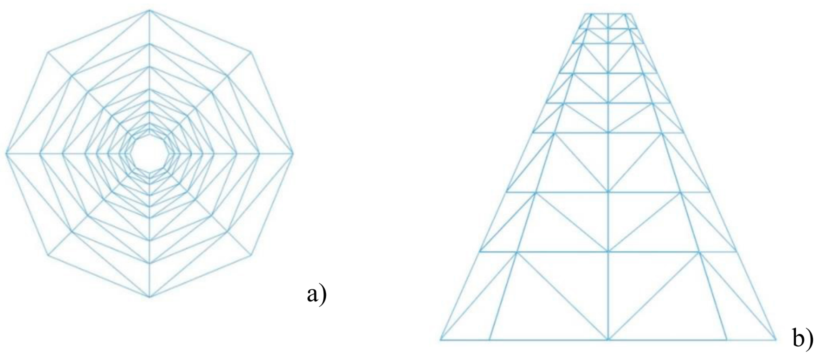


Fig. 4. Global structural model of the onshore wind turbine tower: (a) Top plan view; (b) Side view.

The global linear-elastic analysis of the wind turbine tower was carried out in Abacus commercial software. A 3D global structural model was built with beam elements and combined with the joint stiffness in order to obtain member forces (Fig. 4). Boundary conditions of the lattice tower were applied directly to bottom nodes. Bottom nodes of the lattice tower were restrained in all translational directions while their rotations kept free. Moreover, loads were applied through a reference point at the center of the top octagon. The cross-section and members length used in the analysis are given in Table 3. The global structural model was analyzed under fatigue load conditions. The fatigue loads were determined in previous studies (Figueiredo (2013)). Damage equivalent fatigue loads used in the analysis are shown in Table 4.

Table 3. Cross-section properties of members.

Member	Cross-section	Length
Chords	CHS 559 × 32 mm	6000 mm
Braces	CHS 406.4 × 32 mm	5000 mm
Horizontal bars	CHS 406.4 × 32 mm	5000 mm

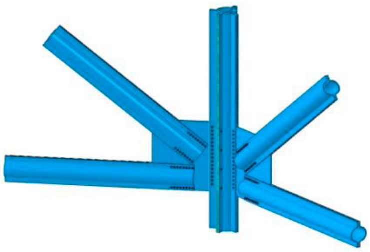
Table 4. Damage equivalent fatigue loads applied in global beam model.

ΔF_x	ΔM_x	ΔM_y	ΔM_z
kN	*kNm*	*kNm*	*kNm*
203	781	4065	3950

4.4. Steel half-pipe bolted connection – local elastoplastic model

A local elastoplastic model of the steel half-pipe bolted connection of the lattice tower under investigation was built (see Fig. 5). The numerical model is composed of chord, horizontal and diagonal members, which are connected by gusset and filler plates. In this analysis the same elements described for the joint stiffness model were used. The plasticity model based on multilinear kinematic hardening for the S355 steel was used (Correia et al. (2015)). A mesh convergence study was carried out on a double lap joint representing two horizontal members and gusset plate connection using same thickness and bolt diameter in order to obtain an optimum solution between result accuracy and computational time. Mesh convergence criteria was considered to be 5% difference from previous analysis in maximum stress under preloading of bolt. Based on the local elastoplastic analysis for the half-pipes bolted connection taking into account the results achieved in the global structural model, was possible to obtain the principal stresses and strains for the fatigue loading conditions presented in Table 4.

The multiaxial fatigue life estimation was made using the proposed procedure in section 3. This analysis is carried out using an energy-based criterion, based on *SWT* parameter. The *SWT* parameter was determined for the critical plane which corresponds to the maximum principal stress, $\sigma_{\perp,max}$ equal to 323.42MPa and strain range, $\Delta\varepsilon$, equal to 1.29×10^{-3}. Applying the equations (11) and (12) it was possible to obtain the number of cycles to failure, N_f, equal to 2.375×10^{7} for fatigue load conditions used in this study.


a)

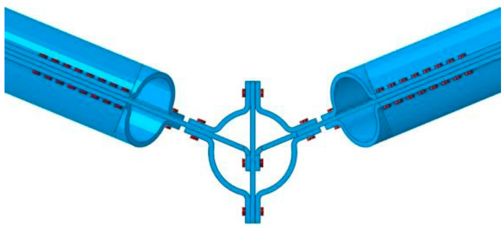

b)

Fig. 5. 3D and cross-section views of the bolted joint.

5. Conclusions

The proposed procedure to multiaxial fatigue life evaluation of the steel half-pipe bolted connections of an onshore wind turbine tower conducted to satisfactory results considering the reduced required computation time. The local model used for determination of the joint stiffness in study is important to reduce the computation time for obtaining the efforts of the global structural model of the onshore wind turbine tower. Based on elastoplastic analysis used in the local model of the connection under study the maximum principal stresses and strains taking into account the fatigue efforts were determined obtained od the global structural analysis of the tower. The use of the *SWT* parameter as a multiaxial damage criterion proved to be efficient in getting of the fatigue life of the steel half-pipe bolted connection.

Acknowledgements

The authors acknowledge Portuguese Science Foundation (FCT) by the financial support through the post-doctoral grant SFRH/BPD/107825/2015.

References

Gough, H.J., Pollard, H.V., 1935. The strength of metals under combined alternating stress. Proc Inst Mech Engrs 1935;131:3–18.

Gough, H.J., Pollard, H.V., 1937. Properties of some materials for cast crankshafts, with special reference to combined alternating stresses. Proc Inst Automobile Engrs 1937;31:821–93.

Sines, G., 1959. Behaviour of metals under complex stresses. In: Sines G, Waisman JL, editors. Metal fatigue. New York: McGraw-Hill; 1959. p. 145–69.

Findley, W.N., 1959. A theory for the effect of mean stress on fatigue of metals under combined torsion and axial load or bending. J Eng Ind, Trans ASME 1959;81:301–6.

Matake, T., 1977. An explanation on fatigue limit under combined stress. Bull JSME 1977;20:257–63.

McDiarmid, D.L., 1991. A general criterion for high cycle multiaxial fatigue failure. Fatigue Fract Eng Mater Struct 1991;14:429–53.

Papadopoulos, I.V., 2001. Long life fatigue under multiaxial loading. Int J Fatigue 2001;23:839–49.

Findley, W.N., 1956. Theories relating to fatigue of materials under combinations of stress. Colloquium on Fatigue, Stockholm (1955), Springer-Verlag, Berlin, 35.

Findley, W.N., Tracy, J.F., 1973. The Effect of the Intermediate Principal Stress on Triaxial Fatigue of 7075-T6 Aluminum Alloy. Journal of Testing and Evaluation, Volume 1, Issue 5.

Brown, M.W., Miller, K.J., 1973. A theory for fatigue failure under multiaxial stress–strain conditions. Proc Inst Mech Engrs 1973;187:745–55.

Fatemi, A., Socie, D.F., 1988. A critical plane to multiaxial fatigue damage including out-of-phase loading. Fatigue Fract Eng Mater Struct 1988;11(3):149–65.

Smith, K.N., Watson, P., Topper, T.H., 1970. A Stress-Strain Function for the Fatigue of Metals. Journal of Materials 1970; 5(4): 767-78.

Socie, D.F., 1987. Multiaxial fatigue damage models. J Eng Mater Tech 1987;109:293–8.

Chu, C.C., Conle, F.A., Bonnen, J.J., 1993. Multiaxial stress–strain modeling and fatigue life prediction of SAE axle shafts. In: McDowell DL, Ellis R, editors. Advances in multiaxial fatigue, ASTM STP 1191. Philadelphia: ASTM; p. 37–54.

Liu, K.C.,1993. A method based on virtual strain-energy parameters for multiaxial fatigue life prediction. In: McDowell DL, Ellis R, editors. Advances in multiaxial fatigue, ASTM STP 1191. Philadelphia: ASTM; p. 37–54.

Glinka, G., Plumtree, A., Shen, G., 1995. A multiaxial fatigue strain energy parameter related to the critical plane. Fatigue Fract Eng Mater Struct;18(1):37–46.

Ellyin, F., 1997. Fatigue damage, crack growth and life prediction. Chapman & Hall.

CEN (2005c) 1993-1-9:2005, Eurocode 3 - Design of steel structure - Part 1-9: Fatigue, European Committee for standardization, Brussels.

Paris, P.C., Erdogan, F., 1963. A critical analysis of crack propaga-tion laws. Transactions of the ASME Series E: Journal Basic Engineering, Vol. 85, pp.528–34.

Tanaka, K., 1974. Fatigue crack propagation from a crack inclined to the cuclic tensile axis. Engineering Fracture Mechanics; 6:493-507.

Socie, D.F., Marquis, G.B., 2000. Multiaxial fatigue. USA: SAE International. ISBN 0 7680 0453 5.

Lebaillif, D., Rechob, N., 2007. Brittle and ductile crack propagation using automatic finite element crack box technique. Engineering Fracture Mechanics, Volume 74, Issue 11, Pages 1810–1824.

Da Silva, A.L.L., 2015. Advanced methodologies for the fatigue analysis of representative details of metallic bridges. Ph.D. Thesis, University of Porto, Portugal (in English).

Correia, J.A.F.O., De Jesus, A.M.P., Tavares, S.M.O., Moreira, P.M.G.P., Tavares, P.J.S., Calçada, R.A.B., 2016. Mixed-mode fatigue crack propagation rates of currents structural steels applied for bridges and towers construction. Bridge Maintenance, Safety and Management (IABMAS'16), Foz do Iguaçu, Brazil, 26-30 June 2016.

De Jesus, A.M.P., Matos, R., Fontoura, F.C.B., Rebelo, C., da Silva, L.S., Veljkovic, M., 2012. A comparison of the fatigue behavior between S355 and S690 steel grades. Journal of Constructional Steel Research 79 140–150.

ASTM E606: Standard Practice for Strain-Controlled Fatigue Testing, Annual Book of ASTM Standards, ASTM, West Conshohocken, PA, USA, 03.01 (1998).

CEN (2005b) 1993-1-8:2005, Eurocode 3 - Design of steel structures - Part 1-8: Design of joints, European Committee for Standardization, Brussels.

Figueiredo, G.G., 2013. Structural behavior of hybrid lattice – tubular steel wind tower. MSc. Thesis, University of Coimbra, Portugal (in English).

Correia, J.A.F.O., De Jesus, A.M.P., Fernández-Canteli, A., Calçada, R.A.B., 2015. Modelling probabilistic fatigue crack propagation rates for a mild structural steel. Frattura ed Integrita Strutturale, Vol. 31, 80-96.