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Procedia Structural Integrity 5 (2017) 761–768

Structural Integrity Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Structural Integrity, ICSI 2017, 4-7 September 2017, Funchal, Madeira, Portugal

Fatigue strength of welded joints under multiaxial non-proportional loading

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Abstract

Fatigue behaviour of a fillet-welded tubular T-joint in the so-called H structural component of an agricultural sprayer is examined by using experimental strain measurements found in the literature and linear elastic finite element analyses. Two stress-based critical plane criteria are applied at a verification point located near the intersection between the end of brace and chord of the above-mentioned T-joint, where crack initiation and growth is experimentally observed.

Peer-review under responsibility of the Scientific Committee of ICSI 2017

Keywords: agricultural sprayer; critical plane-based criteria; multiaxial fatigue; non proportional loading; T-joint.

1. Introduction

Herbicides and fungicides used in Brazilian agriculture to protect the crops against harmful insect and herbs are applied through a pulverisation process performed by agricultural sprayers. Let us consider the arm sprayer consisting of a metal truss structure (named bar) equipped of spray nozzles. The bar is raised and lowered in vertical direction by a structural component, named H component due to its shape (Fig. 1). The H component consists of tubular elements fillet-welded as T-joints. Each T-joint, made of C25E steel, is composed by a chord (with rectangular hollow cross-section) and a brace (with cylindrical hollow cross-section).

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2452-3216
Peer-review under responsibility of the Scientific Committee of ICSI 2017
10.1016/j.prostr.2017.07.167

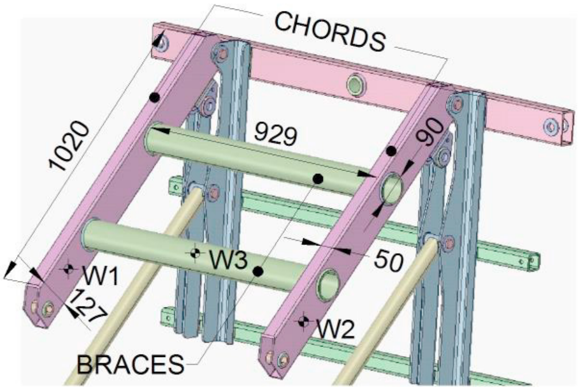

Fig. 1. H structural component of an agricultural sprayer: sizes of the H component (in mm) and positions of the control points W1, W2 and W3.

The above T-joints are the weakest links of the structural component, because high stresses are concentrated in the vicinity of the weld, and cracks are frequently observed after few hours of sprayer service condition. Welding is an efficient technique to obtain strong joints, but welded joints are prone to fatigue failure due to manufacturing defects, notches at both weld toe and root, and tensile residual stresses.

Three approaches can be used for the fatigue assessment of welded joints**:** (i) the nominal stress approach (global approach) **[1-5]**, (ii) the hot spot stress approach (intermediate between global and local approach) **[1,3,6,7]**, and (iii) the notch stress approach (local approach) **[1,3].**

The above approaches were developed for uniaxial fatigue, while welded joints often experience a multiaxial fatigue stress state. Therefore, a remarkable research activity aims to revise multiaxial fatigue criteria in terms of either nominal, or hot spot, or notch stresses **[8-11]**.

In the present paper, two multiaxial critical plane-based criteria **[12-17]** are revised in terms of notch stresses. According to the critical distance approach by Taylor **[18-20]**, such criteria are applied to a material verification point at a certain distance from the weld toe, measured along the experimental crack paths developed in the H structural component after 2000 hours of typical sprayer service condition.

2. Experiments and numerical model

An experimental campaign was performed to determine the strain/stress field in the H structural component of an agricultural sprayer used to apply herbicides in crops of a Brazilian city **[21]**. Such a H component consists of fillet-welded tubular T-joints in as-welded condition. The strain field in the H component was measured at points W1, W2, and W3 (Fig. 1), named control points in the following, under service condition consisting of several maneuvers during 2000 hours of sprayer operation time, after which fatigue damage appeared in the equipment.

By using the strain signals coming from the control points, the principal stress sequences related to the above-mentioned maneuvers were determined at points W1, W2, and W3 **[21]**. The most meaningful stress sequences obtained were those related to the maximum principal stress, being the minimum stress equal to about zero. Therefore, the stress field at the control points W1,W2, and W3 is almost uniaxial: one sequence was determined by averaging the strain signals coming from points W1 and W2 (such a sequence is named σ_{1c} in the following, where c stands for chord) and another sequence (named σ_{1b} in the following, where b stands for brace) was determined by the strain signals coming from point W3. An example of such load histories is shown in Fig. 2, where both σ_{1c} and σ_{1b} related to a given maneuver (named 'Travel on unpaved road – empty fuel tank') are plotted over a time interval of 210.0 sec.

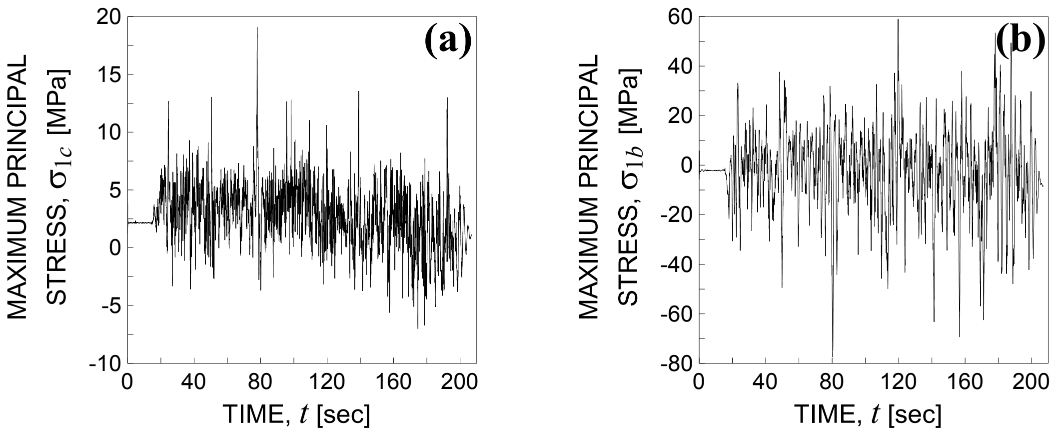

Fig. 2. Load histories over a time interval of 210.0sec for the maneuver named 'Travel on unpaved road – empty fuel tank': (a) σ_{1c} ; (b) σ_{1b} .

The rainflow counting procedure is then applied to both σ_{1c} and σ_{1b} time history, and the value of damage accumulated is computed by using both the Palmgren-Miner rule and the fatigue properties of the H component material (C25E steel). The fatigue properties of welding are also taken into account. Note that each fatigue parameter, listed in Table 1, has been computed through the procedure proposed by Hanel e Haibach **[22]**.

Now a linear elastic finite element analysis is performed on the H components through the Commercial Package Ansys 14.5 (Workbench 15.0) **[23]**, by using SOLID185 finite elements, both prismatic (8 nodes) and tetrahedral (10 nodes). The finite element mesh is selected after a convergence analysis, with the minimum finite element size equal to about 0.7mm. The loading condition consists in the forces (F_c and F_b in Fig. 3) transferred by the sprayer bar to the H component.

Table 1. Fatigue properties for the C25E steel and welding.

MATERIAL	$\sigma_{af,-1}$ [MPa]	k	$\tau_{af,-1}$ [MPa]	k^*	N_0 [cycles]	N_0^* [cycles]
C25E steel	141.0	5	86.0	8	10^6	10^6
Welding	29.0	3	18.0	5	$5\,(10)^6$	10^8

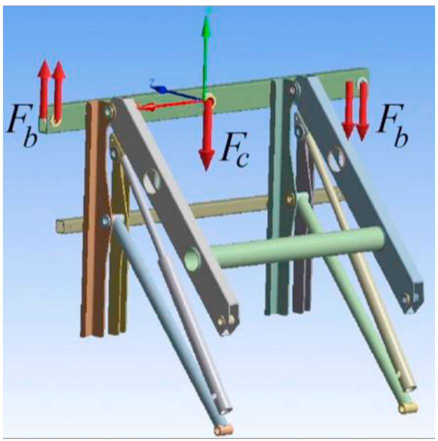

Fig. 3. Schematization of the forces transferred by the sprayer bar to the H component in the finite element model.

Since such forces were not measured during the experimental campaign, the actual loading condition can be simulated through deterministic procedures. A first attempt was made by the authors in Ref.**[24].** A new proposal is presented here by defining deterministic time histories (for both F_c and F_b) able to accumulate the damage value $D_c = 5.109 \cdot (10)^{-3}$ at the control points W1, W2, and $D_b = 1.214 \cdot (10)^{-6}$ at the control point W3 (deterministic procedure). Such values of damage due to 2000 hours of sprayer service condition have been computed by using both the Palmgren-Miner rule and the fatigue properties of the H component material (C25E steel).

Such a new proposal is based on the following assumptions:

(1) The time histories of F_c and F_b are modelled through constant amplitude cyclic loading, the amplitudes of which are $F_{c,a}$ and $F_{b,a}$, respectively;

(2) The amplitude of the maximum principal stress at points W1,W2 (named $\sigma_{1c,a}$ in the following) and that at point W3 ($\sigma_{1b,a}$ in the following), produced by the above forces, are computed by imposing that the accumulated damage at the control points is equal to D_c and D_b , respectively.

Therefore, the unknown quantities are $F_{c,a}$, $\sigma_{1c,a}$, and $F_{b,a}$, $\sigma_{1b,a}$.

By taking into account that the Wöhler curve is representative of the fatigue failure (that is, such a curve is associated to a damage value equal to the unity), the amplitude $\sigma_{1c,a}$ can be computed by both applying the Basquin relationship and assuming a given reference number ($N_{ref,c}$) of loading cycles:

$$\sigma_{1c,a} = \sigma_{af,-1}\left(\frac{N_0}{N_{ref,c}}\right)^{\frac{1}{k}} \tag{1}$$

$\sigma_{af,-1}, N_0$, and k being values for C25E steel. Note that such a stress amplitude represents the amplitude of a cyclic stress that, acting at either point W1 or point W2 for $N_{ref,c}$ times, produces a damage value equal to 1.

Since the damage value is equal to D_c at the above control points, the reference number of loading cycles is recalculated according to the Miner rule:

$$n_c = D_c \cdot N_{ref,c} \tag{2}$$

Finally, the value of $F_{c,a}$ can be numerically determined by a finite element analysis, so that the amplitude of the maximum principal stress at control points W1,W2 is equal to $\sigma_{1c,a}$. Analogous procedure is followed to compute $\sigma_{1b,a}$ and $F_{b,a}$.

Point C_1 (see Fig. 4, where the experimental crack paths are also plotted) located along a crack path

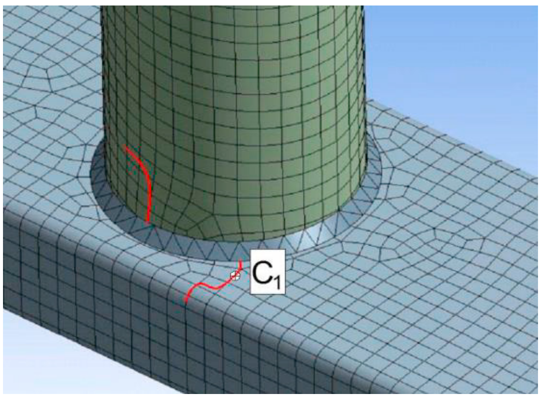

Fig. 4. Digitalisation of the crack paths experimentally observed and localisation of the material verification point C_1 .

experimentally observed in the chord, near the welding that joints the chord and the brace, is assumed as the verification point by following the philosophy of the critical distance approach proposed by Taylor **[18-20]**, that is, the criterion is applied to a material point at a certain distance from the weld toe. Such a point is characterised by a damage value equal to the unity.

A shifting of the shear stress with respect to the normal stresses can be noticed at point C_1 from the experimental campaign and, therefore, an analogous shifting is also taken into account for the deterministic stress state at point C_1, so that the stress field at such a point can be described as follows:

$$\sigma_x(t) = \sigma_{x,a} \sin(\omega t) \tag{3a}$$

$$\sigma_z(t) = \sigma_{z,a} \sin(\omega t) \tag{3b}$$

$$\tau_{xz}(t) = \tau_{xz,a} \sin(\omega t - \gamma) \tag{3c}$$

where ω is the pulsation, t is the time, and γ is the angle of phase shifting. Different values of γ are assumed: 0, 15, 30, 45, 60, 75 and 90 degrees.

3. Fatigue strength assessment

Now two multiaxial critical plane-based criteria are employed to perform the fatigue assessment of the H component: the classical criterion proposed by Findley **[12]**, and a more recent one presented by Carpinteri et al. **[13-17]**.

According to the Findley criterion, the orientation of the critical plane (identified by the spherical coordinates φ_c and ϑ_c) is determined by maximising a linear combination of the shear stress amplitude, C_a, and the maximum value of the normal stress N_{max}, both acting on the critical plane:

$$(\varphi_c, \vartheta_c): \max_{(\varphi,\vartheta)} \{C_a(\varphi,\vartheta) + K \cdot N_{\max}(\varphi,\vartheta)\} \tag{4}$$

where the parameter K is a sensitivity factor taking into account the influence of the normal stress component related to the critical plane. According to Socie and Marquis **[25],** such a factor varies from 0.2 to 0.3 for ductile materials, whereas its value increases for fragile materials. Let us consider $K = 0.3$ hereafter. The equivalent shear stress amplitude, related to the critical plane, according to the Findley criterion is given by:

$$\tau_{eq,a} = C_a(\varphi_c, \vartheta_c) + K \cdot N_{\max}(\varphi_c, \vartheta_c) \tag{5}$$

The number of loading cycles to failure, N_f, is determined by solving the following equation:

$$[C_a(\varphi_c, \vartheta_c) + K \cdot N_{\max}(\varphi_c, \vartheta_c)] = \tau_{af,-1}\sqrt{K^2+1}\left(\frac{N_f}{N_o^*}\right)^{m^*} \tag{6}$$

where $\tau_{af,-1}, N_0^*$ and k^* being values for welding ($m^* = -1/k^*$).

According to the Carpinteri criterion, the orientation of critical plane is determined as follows. Firstly, the averaged principal Euler angles, $\hat{\phi}, \hat{\theta}, \hat{\psi}$, are computed, which coincide with the instantaneous ones at the time instant when the maximum principal stress σ_1 (being $\sigma_1(t) \geq \sigma_2(t) \geq \sigma_3(t)$) achieves its maximum value during the loading cycle. By means of the angles $\hat{\phi}, \hat{\theta}, \hat{\psi}$, the averaged principal stress directions ($\hat{1}, \hat{2}, \hat{3}$) are identified. Then, the normal $\mathbf{w}$ to the critical plane is linked to the averaged principal direction $\hat{1}$ through an off-angle δ, which is defined as follows ($\mathbf{w}$ belongs to the principal plane $\hat{1}\hat{3}$, and the rotation is performed from $\hat{1}$ to $\hat{3}$):

$$\delta = \frac{3}{2}\left[1 - \left(\tau_{af,-1}/\sigma_{af,-1}\right)^2\right]45° \tag{7}$$

The equivalent stress amplitude related to the critical plane, according to the Carpinteri criterion, is given by:

$$\sigma_{eq,a} = \sqrt{N_{a,eq}^2 + \left(\frac{\sigma_{af,-1}}{\tau_{af,-1}}\right)^2 C_a^2} \tag{8}$$

where $N_{a,eq}$ is expressed by:

$$N_{a,eq} = N_a + \sigma_{af,-1} \left(N_m / \sigma_u\right) \tag{9}$$

being N_m and N_a the mean value and the amplitude of the normal stress to the critical plane, respectively, σ_u is the ultimate tensile strength of the material, and C_a is the amplitude of the shear stress acting on the critical plane, computed according to the procedure proposed by Araujo et al. **[16]**.
The number of loading cycles to failure, N_f, is determined by solving the following equation:

$$\sqrt{N_{a,eq}^2 + \left(\sigma_{af,-1}/\tau_{af,-1}\right)^2 \left(N_f/N_0\right)^{2m} \left(N_0^*/N_f\right)^{2m^*} C_a^2} = \sigma_{af,-1}\left(N_f/N_0\right)^m \tag{10}$$

By employing the fatigue life N_f results obtained from Eqs (6) and (10), the value of damage D at the verification point C_1 is computed applying both the Basquin relationship:

$$N_{ref,C1} = \left(\frac{S_{af,-1}}{S_{eq,a}}\right)^{k_S} N_{0S} \tag{11}$$

and the Miner rule:

$$D = \frac{N_f}{N_{ref,C1}} \tag{12}$$

being $S_{af,-1} = \tau_{af,-1}$, $S_{eq,a} = \tau_{eq,a}$, $k_S = k^*$, and $N_{0S} = N_0^*$ when the Findley criterion is applied, whereas $S_{af,-1} = \sigma_{af,-1}$, $S_{eq,a} = \sigma_{eq,a}$, $k_S = k$, $N_{0S} = N_0$ when the Carpinteri criterion is applied.

The damage values according to the Findley criterion are constants since D is independent of both n and γ: D = 1.22 by employing the welding fatigue properties, and D = 1.37 by employing the C25E steel fatigue properties. The damage values according to the Carpinteri criterion depends on n (Fig. 5).

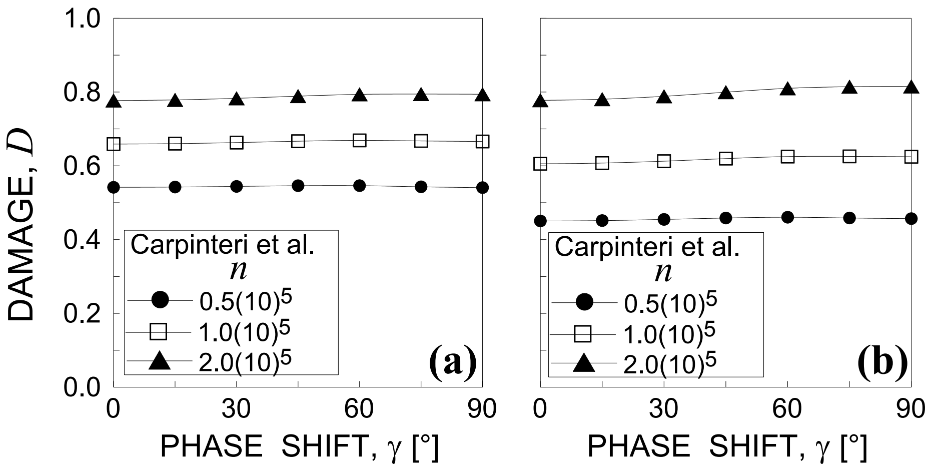

Fig. 5. Damage determined by employing (a) the welding fatigue properties, and (b) the C25E steel fatigue properties.

The Findley criterion provides damage values dependent on the fatigue properties employed, whereas an opposite trend is noted by applying the Carpinteri criterion. D values determined employing the Findley criterion are far from the unity (value expected at the verification point C_1), but such results are always conservative ($D>1$). The Carpinteri criterion provides quite satisfactory values of D especially for $n=2\cdot(10)^5$ using the fatigue properties of welding and steel, but such results are always non-conservative.

4. Conclusions

In the present paper, the fatigue assessment the T-joint named H component of an agricultural sprayer has been discussed, because it is the weakest link of the sprayer with respect to the failure. Such a component is subjected to random loading condition. An equivalent deterministic cyclic loading has been defined in order to perform the fatigue assessment by using rather simple criteria formulated for cyclic loading. Two multiaxial fatigue criteria have been employed: the classical criterion proposed by Findley, and a more recent criterion presented by Carpinteri et al. The Carpinteri criterion produces quite satisfactory results in terms of damage, even if the results are non-conservative, being the damage values lower than the unity for all the cases examined.

Acknowledgements

The authors gratefully acknowledge the financial support of the Italian Ministry of Education, University and Research (MIUR), the National Council for Scientific and Technological Development (CNPq - Brazil) and the Coordination for the Improvement of Higher Education Personnel (CAPES – Brazil).

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