WELDED JOINTS UNDER MULTIAXIAL NON-PROPORTIONAL LOADING

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ABSTRACT

The present paper examines the fatigue behaviour of a fillet-welded tubular T-joint in the so-called H structural component of an agricultural sprayer. Since the experimental measurements, performed in some control locations of the equipment, have highlighted a stress/strain field of random nature, an equivalent deterministic cyclic loading is here defined in order to simplify the fatigue analysis. Such an equivalent loading is able to accumulate damage values equal to the experimental ones in correspondence of the above control locations. The present study shows that it is possible to neglect the actual nature of loading provided that a suitable equivalent deterministic cyclic loading is taken into account.

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

NOMENCLATURE

C_a	shear stress amplitude acting on the critical plane
D	damage value at the verification location C_1 (Figure 7)
D_b	damage value at the control location W3 (Figure 1(c))
D_c	damage value at the control locations W1 and W2 (Figure 1(c))
F_b, F_c	random or deterministic loading acting on the H structural component
$F_{b,a}, F_{c,a}$	amplitudes of deterministic loading acting on the H structural component
K	sensibility factor
$m = -\frac{1}{k}$	slope of the S-N curve for fully reversed normal stress
$m^* = -\frac{1}{k^*}$	slope of the S-N curve for fully reversed shear stress
n	reference number of loading cycles for F_b and F_c , producing a damage value equal to D_b at location W3 and D_c at locations W1 and W2
N_a	normal stress amplitude acting on the critical plane
$N_{a,eq}$	equivalent normal stress amplitude
N_m	normal stress mean value acting on the critical plane
N_{max}	maximum value of the normal stress acting on the critical plane
N_f	finite life fatigue strength, expressed in loading cycles
$N_{ref,b}$	reference number of loading cycles for F_b , producing a damage value equal to 1 at location W3
$N_{ref,c}$	reference number of loading cycles for F_c , producing a damage value equal to 1 at locations W1 and W2
N_0	reference number of loading cycles under fully reversed normal stress
N_0^*	reference number of loading cycles under fully reversed shear stress

t	time
$\mathbf{w}$	normal unit vector perpendicular to the critical plane
δ	angle between the averaged direction $\hat{\mathbf{l}}$ and the normal $\mathbf{w}$ to the critical plane
γ	phase angle
φ_c, ϑ_c	spherical coordinates identifying the orientation of critical plane according to Findley criterion
$\hat{\phi}, \hat{\theta}, \hat{\psi}$	averaged Euler angles
σ_{1b}	maximum principal stress at the control location W3
σ_{1c}	maximum principal stress at the control locations W1 and W2
$\sigma_{1b,a}$	amplitude of the maximum principal stress at the control location W3
$\sigma_{1c,a}$	amplitude of the maximum principal stress at the control locations W1 and W2
σ_{af-1}	fully reversed normal stress fatigue limit
$\sigma_{eq,a}$	equivalent uniaxial normal stress amplitude
σ_u	ultimate tensile strength
τ_{af-1}	fully reversed shear stress fatigue limit
$\sigma_{eq,a}$	equivalent shear stress amplitude
ω	pulsation

1. INTRODUCTION

Herbicides and fungicides are commonly used in Brazilian agriculture to protect the crops against harmful insect and herbs. Such substances are applied by means a pulverisation process, performed by systems named agricultural sprayers.

One of the most common systems is the arm sprayer, that consists of a metal truss structure (named bar), equipped of spray nozzles (**Figure 1(a)**). The bar is raised and lowered in vertical direction by a structural component, that is named H component due to its shape (**Figure 1(b),1(c)**). The H component consists of tubular elements fillet-welded as T-joints (**Figure 1(c)**). 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).

Figure 1.

The present paper examines one of the above T-joints, which are the weakest links of the structural component with respect to the failure. As a matter of fact, high stresses are concentrated near the welds, and cracks are frequently observed after relatively few hours of sprayer service condition (**Figure 2**).

Note that each maneuver (i.e. shifting the tractor, application of the herbicide on the perimeter of the uncultivated field, application of the herbicide on the cultivated area, braking) was performed twice a day: one when the tractor fuel tank was full, and the other one when the fuel tank was empty.

Figure 2.

As is well-known, welding is considered an efficient technique to obtain strong joints, since it ensures loading transfer between steel structural components [1,2]. However, welded joints are

prone to fatigue failure. Such a failure type, produced by cyclic loading, may be due to manufacturing defects, notches at both weld toe and root, and tensile residual stresses [3].

Three approaches can be used for the fatigue assessment of welded joints: (i) the nominal stress approach (global approach) [4-8], (ii) the hot spot stress approach (intermediate between global and local approach) [4,6,9,10], and (iii) the notch stress approach (local approach) [4,6]. The nominal stress approach is adopted in many codes due to its simplicity. The notch stress approach is considered to be more accurate than the other ones, but difficult to be applied. The hot spot stress approach is widely used in engineering practice.

The above approaches were developed for uniaxial fatigue, while welded joints often experience a multiaxial fatigue stress state. Therefore, in recent years, a remarkable research activity has aimed to revise multiaxial fatigue criteria in terms of either nominal, or hot spot, or notch stresses [11-19].

The T-joint here examined is characterized by a multiaxial stress/strain field of random nature. To the best knowledge of the authors, the solutions proposed in the literature to solve similar problems are based on revised multiaxial criteria specifically formulated for random loading.

In the present paper, instead, a suitable equivalent deterministic cyclic loading is firstly defined according to damage concepts, in order to simplify the fatigue assessment of such a T-joint.

Then, two multiaxial critical plane-based criteria proposed for constant amplitude loading [20-25] are revised in terms of notch stresses. According to the critical distance approach by Taylor [26-28], such criteria are applied to a material verification location characterised by a certain distance from the weld toe. Such a distance is measured along the experimental crack paths (**Figure 2**) developed in the H structural component after 2000 hours of typical sprayer service condition.

The present study shows that, even in presence of a random stress/strain field, the fatigue assessment of a metallic structural component can be performed by considering a suitable equivalent deterministic cyclic loading. Such a conclusion can be interesting in industrial applications: as a matter of fact, the nature of random loading is often non-Gaussian, and that makes the problem even more complex.

In details, the paper is organised as follows. In Section 2, an experimental campaign carried out for the H component under sprayer service condition is described. Section 3 is dedicated to the finite element analysis of the H component. In Section 4, multiaxial critical plane-based criteria employed for fatigue assessment of the H component are briefly presented, and the results are discussed in Section 5. Final conclusions are drawn in Section 6.

2. EXPERIMENTAL CAMPAIGN

An experimental campaign aimed to determine the strain/stress field in the H structural component of an agricultural sprayer under the following typical service condition: application of herbicides in crops of a Brazilian city (Jaboticabal, São Paulo). Details may be found in Ref. [29,32].

Such a H component consists of fillet-welded tubular T-joints in as-welded condition. The welding is performed by means a metal inert gas process. The thickness of the tubular components is equal to 4.75mm. The leg length of the fillet welding is equal to 5mm.

2.1 Loading condition

The strain field in the H component was measured at locations W1, W2, and W3 (shown in **Figure 1(c)**), named control locations in the following.

The service condition investigated consists of the maneuvers listed in **Table 1**. In more detail:

(a) Shifting the tractor, dragging the agricultural sprayer from the farmhouse to the crops on unpaved road. The tractor left the farmhouse with the herbicide-tank full and came back with the tank empty;

(b) Application of the herbicide on the perimeter of the uncultivated field. Only the spray nozzles located on one side of the bar with respect to the H component were opened in such an operation;

(c) Application of the herbicide on the cultivated area. The tractor wheels remained between the planting rows and, when the machine reached the end of the row, it performed a U-curve crossing the planting rows;

(d) Braking: this occurred about five times each travel.

Note that each maneuver was performed twice a day: one when the tractor fuel tank was full, and the other one when the fuel tank was empty.

Table 1 lists the duration of each maneuver described above, with reference to the time (2000 hours of sprayer operation under typical service condition) after which fatigue damage appeared in the equipment (see **Figure 2**).

Table 1.

Note that, although the damage numerically computed at locations W1, W2 and W3 after 2000 hours of sprayer operation is lower than the unity, the experimental campaign showed fatigue damage in regions near welding (**Figure 2**), that is, some material locations along the crack paths were characterized by a damage value equal to the unity.

2.2 Results

This Section describes the experimental data and their treatment.

The strain field in the ``H'' component was measured at locations W1, W2, and W3, shown in **Figure 1(c)**. More precisely,

two tee rosettes mounted on a complete-bridge Wheatstone circuit were arranged on each chord (circuits W1 and W2), whereas two fishbone strain gages mounted on a complete-bridge Wheatstone circuit were arranged on the brace (circuit W3) (**Figure 1(d)**).

By using the strain measurements coming from the control locations, the principal stress sequences related to the maneuvers listed in **Table 1** were determined at the material locations W1, W2, and W3 [29]. The acquisition frequency was equal to 1kHz and the cutoff frequency, in the low pass filter used, was equal to 20Hz. As is indicated in **Figure 1(d)**, the measurements at the above material localizations are not influenced by the stress/strain field in the welding regions.

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 locations W1, W2, and W3 is almost uniaxial. More precisely, one sequence was determined by averaging the strain measurements coming from locations W1 and W2 (such a sequence is named σ_{lc} in the following, where c stands for chord) and another one (named σ_{lb} in the following, where b stands for brace) was determined by the strain measurements coming from location W3. An example of such load histories is shown in **Figure 3**, where both σ_{lc} and σ_{lb} , related to the maneuver named 'Travel on unpaved road - empty fuel tank' in **Table 1**, are plotted over a time interval of about 210.0 sec.

The rainflow counting procedure is then applied to both σ_{lc} and σ_{lb} time history, and the value of damage accumulated is computed for each of the maneuvers listed in **Table 1** by using both the Palmgren-Miner rule and the fatigue properties of the H component material (C25E steel) listed in **Table 2**.

The fatigue properties of welding are also listed in **Table 2**. Note that each fatigue parameter in such a Table has been computed through the procedure proposed by Hanel e Haibach [30].

Figure 3.

Table 2.

3. NUMERICAL MODEL

A linear elastic finite element analysis is performed on the H components through the Commercial Package Ansys 14.5 (Workbench 15.0) [31], by using SOLID185 finite elements, both prismatic (8 nodes) and tetrahedral (10 nodes). The adopted discretization is shown in **Figure 4**, where the finite element mesh is derived from a convergence analysis, being the minimum finite element size equal to about 0.7mm.

Figure 4.

The sprayer bar transfers the forces F_c and F_b to the H component (**Figure 5**). The material locations of the H-components (numbered from 1 to 12 in **Figure 5**) are characterised by both zero displacements along x-, y-, z-axis, and rotations equal to zero except around x-axis.

Figure 5.

The contour maps of normal stresses σ_x , σ_y and σ_z in the H-component under the forces $F_c=1000\text{N}$ and $F_b=500\text{N}$ are shown in **Figure 6(a)-(c) and 6(d)-(f)**, respectively.

Figure 6.

It was numerically proved [29] that, when only the force F_c is applied to the model, the maximum principal stresses in the braces are significantly lower than those in the chords (up to about 110

times lower) and, therefore, such stresses in the chords can be assumed to be linked to the force F_c only. Further, it was numerically proved that, when only the forces F_b are applied to the model, the maximum principal stresses in the braces are greater than those in the chords (up to about 10 times greater) and, therefore, such stresses in the braces can be assumed to be linked to the forces F_b only.

Since such forces were not measured during the experimental campaign, two different procedures can be applied to simulate the actual loading condition:

- (i) Definition of random time histories for both F_c and F_b , able to produce the random time history σ_{1c} at the control locations W1, W2 and σ_{1b} at the control location W3 (random procedure);
- (ii) Definition of deterministic time histories for both F_c and F_b , able to accumulate the damage value $D_c=5.109(10)^{-3}$ at the control locations W1, W2 and $D_b=1.214(10)^{-6}$ at the control location W3 (deterministic procedure). Such values of damage are reported in last line of Table 1.

Regarding the random procedure, **Figure 7** shows some results referred to the stress field at a material location C_1 along a crack path experimentally observed in the chord (**Figure 2**), near the welding that joints the chord and the brace. Such a location is shown in **Figure 8**, where the whole crack paths determined through a digitalisation procedure performed on the pictures shown in **Figure 2** are also plotted.

It can be observed that shear stress (**Figure 7(c)**) is shifted with respect to the normal stresses (**Figs 7(a)** and **(b)**). The same trend is observed for all maneuvers.

Figure 7.

Figure 8.

Regarding the deterministic procedure, a first attempt was performed by the authors in Ref. [32], and a different proposal is presented in the following Section 4.

4 NEW PROPOSAL BASED ON DETERMINISTIC LOADING COMPUTATION

In order to compute the deterministic loading to implement in the numerical model, let us take advantage of the damage values D_c and D_b (**Table 1**). More precisely, the following assumptions are made here:

- (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 locations W1, W2 (named $\sigma_{lc,a}$ in the following) and that at location W3 ($\sigma_{lb,a}$ in the following), produced by the above forces, are computed by imposing that the accumulated damage at the control locations is equal to D_c and D_b , respectively.

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

Firstly, 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 $\sigma_{lc,a}$ is computed by both applying the Basquin relationship and assuming a given reference number ($N_{ref,c}$) of loading cycles:

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

$\sigma_{lc,a}$, N_0 , and k being values listed in Table 2 for C25E steel. Note that such a stress amplitude represents the amplitude of a cyclic

stress that, acting at either location W1 or location W2 for $N_{ref,c}$ times, produces a damage value equal to the unity.

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

$$n_c = D_c \cdot N_{ref,c} \quad (2)$$

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 locations W1,W2 is equal to $\sigma_{1c,a}$.

Analogous procedure is followed to compute $\sigma_{1b,a}$ and $F_{b,a}$. The results are listed in **Table 3**, for different values of $N_{ref,c}$ and $N_{ref,b}$.

Table 3.

The frequency for both the forces F_c and F_b is arbitrarily assumed to be equal to 1HZ. The above forces are in-phase. Time histories of the stress tensor components at location C_1 are plotted in **Figure 9** for $n=n_c=n_b=50000$ cycles (**Table 3**).

Figure 9.

Because a shifting of the shear stress with respect to the normal stresses is observed at location C_1 by employing the random procedure (see **Figure 7**), let us consider an analogous shifting also for the deterministic stress state at location C_1 , so that the stress field at such a location can be described as follows:

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

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

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

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.

4. FATIGUE STRENGTH ASSESSMENT

According to the results shown in the previous Section, a multiaxial fatigue criterion has to be employed to perform the fatigue assessment of the H component.

Location C_1 is assumed as the verification location according to the critical distance approach proposed by Taylor [26-28]. More precisely, the criterion is applied to a material location at a certain distance from the weld toe. Such a location is characterised by a damage value equal to the unity, because it is located along the crack path experimentally observed in the chord (**Figure 2(b)**).

Two multiaxial critical plane-based criteria are examined: the classical criterion proposed by Findley [20], and a more recent one presented by Carpinteri et al. [21-25].

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:

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

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 [33], 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:

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

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

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

where $m^* = -1/k^*$.

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 $\hat{3}$):

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

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

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

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

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

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, calculated according to the procedure proposed by Araujo et al. [24].

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

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

5. RESULTS AND DISCUSSION

The results in terms of fatigue life, N_f , obtained by employing both the Findley criterion and the Carpinteri criterion are listed in **Tables 4** and **5**, for different values of γ (0, 15, 30, 45, 60, 75 and 90 degrees) and reference number n of loading cycles (50000, 100000, and 200000 cycles). More precisely, the results in **Table 4** are determined using the fatigue properties of welding (**Table 2**), whereas those in **Table 5** are derived using the fatigue properties of C25E steel (**Table 2**).

Table 4.

Table 5.

By employing the results listed in **Tables 4** and **5**, the value of damage D at the verification location C_1 is computed applying both the Basquin relationship:

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

and the Miner rule:

$$D = \frac{N_f}{N_{ref,C1}} \quad (12)$$

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 are listed in **Tables 6** and **7**.

Table 6.

Table 7.

It can be observed that, by applying the Findley criterion, the value of damage is independent of both n and γ , whereas D depends on n by applying the Carpinteri criterion.

However, the Findley criterion provides damage values quite dependent on the fatigue properties employed, whereas an opposite trend is noted by applying the Carpinteri criterion.

D values determined employing the above criteria fall in the range 0.45 - 1.37, whereas a value equal to 1 is expected at the verification location C_1 .

These results can be considered acceptable if we take into account the level of uncertainties related to the material fatigue properties and the assumption to consider a deterministic equivalent stress history in order to represent the random one. Furthermore, note that the equipment fatigue failure after 2,000

hours is only an estimation, that is, such a value should not be considered as a value with statistical consistency.

Figure 10 shows the damage D , averaged on the different values of γ (for a given value of n), against the reference number of loading cycles, n , by employing the fatigue properties of both welding (**Figure 10(a)**) and steel (**Figure 10(b)**), with the damage computed through the Carpinteri criterion.

Figure 10.

The above results are well fitted by logarithmic curves, the equations of which are given by:

$$D = 0.1757 \cdot \ln(n) - 1.3578 \quad (13)$$

employing the welding fatigue properties(**Figure 10(a)**), and:

$$D = 0.2467 \cdot \ln(n) - 2.217 \quad (14)$$

employing the steel fatigue properties(**Figure 10(b)**).

Using Eq.(13), the reference number of loading cycles to produce a damage equal to 1.0 at the verification location should be equal to 672976, whereas it should be $n=460528$ if Eq.(14) were used.

6. CONCLUSIONS

In the present paper, the fatigue assessment of an agricultural sprayer has been discussed. More precisely, the T-joint named H component has been examined, because it is the weakest link of the sprayer with respect to the failure.

The experimental measurements, performed in some control locations of the equipment, have highlighted a stress/strain field of random nature. By using such experimental data, an equivalent deterministic cyclic loading has been defined, which is able to

accumulate damage values at the above control locations equal to the experimental damage values. Such a procedure has been developed by performing a linear finite element analysis.

According to the above assumption, the H component is characterized by a multiaxial constant amplitude stress field. Therefore, two multiaxial fatigue criteria have been employed to carry out the fatigue assessment of such a structural component: the classical criterion proposed by Findley, and a more recent one presented by Carpinteri et al.

The results in terms of damage D fall in the range 0.45 - 1.37. Such values can be considered acceptable by taking into account both the high level of uncertainties on the material fatigue properties and the assumption related to a deterministic equivalent stress history representing the random one.

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**WELDED JOINTS UNDER MULTIAXIAL NON-PROPORTIONAL
LOADING**

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FIGURES AND TABLES

Figure 1. (a) Agricultural sprayer; (b) H structural component;
(c) sizes of the H component (in mm) and positions of the control
locations W1, W2 and W3; (d) Wheatstone circuits.

Figure 2. Fatigue crack paths experimentally observed in one T-
joint of the H component under sprayer service condition: (a)
brace; (b) chord. Crack sizes in mm.

Table 1. Maneuvers duration and accumulated damage at locations
W1 or W2 on the chord, and at location W3 on the brace, after 2000
hours of sprayer operation.

Figure 3. Load histories over a time interval of 210.0sec related
to the maneuver named 'Travel on unpaved road - empty fuel tank'
in Table 1: (a) σ_{lc} ; (b) σ_{lb} .

Table 2. Fatigue properties for the C25E steel and welding.

Figure 4. Discretization adopted for the finite element analysis.

Figure 5. Schematization of the forces transferred by the sprayer bar to the H component in the finite element model, and locations of the boundary conditions in terms of fixed displacements/rotations.

Figure 6. Normal stress contour maps in the H-component under the force $F_c=1000\text{N}$: (a) σ_x , (b) σ_y , (c) σ_z . Analogous maps under the force $F_b=500\text{N}$: (d) σ_x , (e) σ_y , (f) σ_z .

Figure 7. Stress field over a time interval from 90 to 140 sec., produced at point C_1 by the maneuver named 'Travel of unpaved road - full fuel tank' in Table 1: (a) $\sigma_x(t)$; (b) $\sigma_z(t)$; (c) $\tau_{xz}(t)$. The reference frame XYZ is shown in Figure 5.

Figure 8. Digitalisation of the crack paths experimentally observed and localisation of the material verification point C_1 .

Table 3. Values numerically determined for: $\sigma_{lc,a}$, $F_{c,a}$ and $\sigma_{lb,a}$, $F_{b,a}$, for different values of $N_{ref,c}$ and $N_{ref,b}$.

Figure 9. Time histories of the stress tensor components at point C_1 , by considering $n_c=n_b=50000$ cycles (Table 3).

Table 4. Results in terms of N_f , determined using the welding fatigue properties.

Table 5. Results in terms of N_f , determined using the C25E steel fatigue properties.

Table 6. Damage D determined by employing the welding fatigue properties.

Table 7. Damage D determined by employing the C25E steel fatigue properties.

Figure 10. Damage against reference number of loading cycles by using the fatigue properties of: (a) welding; (b) steel.

Figure 1.

Figure 2.

Table 1.

MANOUVERS	FUEL TANK	DURATION [h]	DAMAGE W1 or W2	DAMAGE W3
Travel on unpaved road	Full	100	$4.689 (10)^{-7}$	$3.749 (10)^{-8}$
	Empty	100	$1.683 (10)^{-7}$	$7.100 (10)^{-9}$
Application of the herbicide (perimeter)	Full	200	$2.250 (10)^{-6}$	$1.332 (10)^{-8}$
	Empty	200	$3.095 (10)^{-6}$	$4.266 (10)^{-9}$
Application of the herbicide (cultivated area)	Full	450	$8.443 (10)^{-5}$	$2.379 (10)^{-9}$
	Empty	450	$1.535 (10)^{-6}$	$8.423 (10)^{-10}$
U - curves	Full	100	$1.242 (10)^{-6}$	$4.676 (10)^{-7}$
	Empty	100	$1.261 (10)^{-3}$	$5.273 (10)^{-7}$
Perimeter curves	Full	100	$5.038 (10)^{-6}$	$9.502 (10)^{-9}$
	Empty	100	$2.280 (10)^{-3}$	$1.275 (10)^{-7}$
Braking	Full	50	$1.920 (10)^{-4}$	$1.451 (10)^{-8}$
	Empty	50	$3.704 (10)^{-5}$	$2.339 (10)^{-9}$
Σ		2000	$5.109 (10)^{-3}$	$1.214 (10)^{-6}$

Figure 3.

Table 2.

MATERIAL	REF.	$\sigma_{af,-1}$ [MPa]	k	$\tau_{af,-1}$ [MPa]	k^*	N_0 [cycles]	N_0^* [cycles]
C25E steel	[29]	141.0	5	86.0	8	10^6	10^6
Welding	[29]	29.0	3	18.0	5	$5 (10)^6$	10^8

Figure 4.

Figure 6.

Figure 7.

Figure 8.

Table 3.

POINT	DAMAGE	$N_{ref,c}$ [cycles]	$\sigma_{1c,a}$ [MPa]	n_c [cycles]	$F_{c,a}$ [N]	$N_{ref,b}$ [cycles]	$\sigma_{1b,a}$ [MPa]	n_b [cycles]	$F_{b,a}$ [N]
W1 or W2	$5.109 \cdot 10^{-3}$	$50000 / D_c$	89.0	50000	10410.0				
		$100000 / D_c$	77.0	100000	9273.0				
		$200000 / D_c$	68.0	200000	7888.0				
W3	$1.214 \cdot 10^{-6}$					$50000 / D_b$	17.0	50000	19964.0
						$100000 / D_b$	15.0	100000	17080.0
						$200000 / D_b$	13.0	200000	15080.0

Figure 9.

Table 4.

	FINDLEY			CARPINTERI ET AL.		
n [cycles]	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$
γ [°]	N_f			N_f		
0	4207	8834	17040	6806	12905	22592
15	3963	8322	16052	6864	13021	22805
30	3718	7810	15064	7024	13339	23389
45	3968	8570	16538	7247	13793	24233
60	4425	9536	18408	7449	14219	25053
75	5102	10800	20700	7520	14403	25461
90	5213	11052	21100	7518	14426	25542

Table 5.

	FINDLEY			CARPINTERI ET AL.		
n [cycles]	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$
γ [°]	N_f			N_f		
0	26700	87400	249900	55362	155973	387047
15	24325	79608	227691	56215	158400	393286
30	21950	71816	205483	58488	165119	410642
45	25735	84201	241100	61793	174963	436426
60	30471	99702	285600	64998	184732	462746
75	35900	117504	336702	66349	189625	477249
90	36608	119808	343304	66545	190598	480777

Table 6.

	FINDLEY			CARPINTERI ET AL.		
n [cycles]	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$
γ [°]	D			D		
0	1.22	1.22	1.22	0.54	0.66	0.78
15	1.22	1.22	1.22	0.54	0.66	0.78
30	1.22	1.22	1.22	0.54	0.66	0.78
45	1.22	1.22	1.22	0.55	0.67	0.79
60	1.22	1.22	1.22	0.55	0.67	0.79
75	1.22	1.22	1.22	0.54	0.67	0.79
90	1.22	1.22	1.22	0.54	0.67	0.79

Table 7.

	FINDLEY			CARPINTERI ET AL.		
n [cycles]	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$	$5 \cdot (10)^4$	$1 \cdot (10)^5$	$2 \cdot (10)^5$
γ [°]	D			D		
0	1.37	1.37	1.37	0.45	0.61	0.78
15	1.37	1.37	1.37	0.45	0.61	0.78
30	1.37	1.37	1.37	0.45	0.61	0.79
45	1.37	1.37	1.37	0.46	0.62	0.80
60	1.37	1.37	1.37	0.46	0.63	0.81
75	1.37	1.37	1.37	0.46	0.63	0.81
90	1.37	1.37	1.37	0.46	0.62	0.81

Figure 10.