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Fatigue endurance of welded joints subjected to different blocks of bending and torsion loading

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Abstract

The fatigue strength of pipe-to-plate welded joints under bending, torsion and combined (in-phase and out-of-phase) bending and torsion has been already investigated in previous works by the authors. The specimen consisted of a pipe joined by seam welding to a plate. Both the pipe and the plate were made of S355JR steel. The test apparatus allows to apply any combination of proportional and non-proportional bending and torsion loads to the specimen.

For the analysed specimens failure originated mainly from the weld root, where a severe notch is present, even if some failure from the weld toe was observed in case of bending loading. However, the crack propagation and fracture surface under bending and under torsion were significantly different. For this reason, in order to investigate any possible influence of the loading order on the fatigue endurance, the effect of different loading blocks was analysed in this work. This subject has not been widely investigated in the technical literature about welded joints.

In a first series of tests, specimens were loaded in bending for a given fraction of the estimated endurance and then were loaded in torsion till failure. A similar series of tests was then conducted by varying the loading order: specimens were loaded in torsion for a given fraction of the estimated endurance, followed by a block of bending loading till failure. The whole test campaign was repeated for two different fractions of the estimated life, i.e. 0.3 and 0.45, respectively. The failure was intended as the presence of a through the thickness crack, whose presence was monitored by a drop in the internal pressure of the pipe. Results are discussed in terms of the Miner's rule based on nominal stresses and to the cumulative damage suggested by Eurocode and *IIW*.

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1. Introduction

Welded joints are widely used in engineering applications thanks to the possibility of obtaining complex geometries and to the possibility of automation of the process. The resistance of a welded joint is affected by many factors and the technical literature about the fatigue life assessment is wide; several approaches have been proposed both in codes (EN (1993); UNI (1988); BS7910 (1999)) and in scientific papers (see e.g. Radaj (1990); Radaj et al. (2009); Sonsino

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and Maddox (2001); Niemi (1995); Sonsino (2009); Verreman and Nie (1996); Lazzarin and Tovo (1998); Livieri and Lazzarin (2005); Fricke (2010); Tovo and Livieri (2007); Mikkola et al. (2014)).

Nomenclature

R	Load ratio
D	Cumulative damage
D_i	Block damage
n_i	Block length (number of cycles)
N_i	Expected endurance (number of cycles)
σ_n	Nominal normal stress
M_b	Bending moment
W_b	Bending strength modulus
d_e	Outside diameter
t	Weld throat size
τ_n	Nominal tangential stress
M_t	Twisting moment
W_t	Twisting strength modulus
F_1	Actuator 1 load
F_2	Actuator 2 load
a_1	Actuator 1 load amplitude
a_2	Actuator 2 load amplitude
ξ	Actuator 1 mean load
η	Actuator 2 mean load
ω	Load frequency
2γ	Phase angle between load 1 and 2

Dealing with variable amplitude loading, several cumulative damage theories have been proposed for the fatigue assessment of structural materials, some of them were reviewed by Fatemi and Yang (1998). However, the linear damage rule proposed by Miner et al. (1945) is probably the most widely used due to its simplicity (Gurney (2006)).

It is common practice to extend the use of Miner's rule to the fatigue life assessment of welded joints under multiaxial loads. Commonly tests are performed under proportional or non-proportional biaxial loadings, mainly bending and torsion, the damage components from normal and shear actions are assessed independently then combined together by means of the Miner's equation. Bäckström and Marquis (2001) reviewed a collection of experimental tests available in literature. They derived an average damage summation in good accordance with the value $D = 0.5$ proposed by the *International Institute of Welding* (*IIW*) (Hobbacher (1996)). Also Sonsino (2007) and Zhang and Maddox (2009) applied the Miner's rule to a number of variable amplitude loading tests performed on welded joints. They reported that the vast majority of the experimental results were under the classic $D = 1$ threshold, with worst case values ranging down to $D = 0.1$.

In previous works by the authors (Bertini et al. (2014), Frendo and Bertini (2015) and Bertini et al. (2016)) the fatigue strength of a pipe-to-plate fillet welded joint has been investigated covering a wide range of load conditions. Firstly, tests were performed under bending and under torsion with load ratios of $R = -1$ and $R = 0$. Then, combined bending and torsion loadings were applied both in-phase and out-of-phase, even in this case with load ratios of $R = -1$ and $R = 0$.

From those investigations it emerged that the Miner's rule appeared to overestimate the endurances in case of out-of-phase loading while it gave comparable results with experiments in case of proportional loading. It was also observed that, for the analyzed joint, the failure location was mainly at the weld root, where a severe notch is present, even if some failures from the weld toe were observed in bending tests.

The aim of this work is to investigate the fatigue endurance of the same pipe-to-plate joint when different loading blocks are applied. In case of homogeneous materials, Gladskyi and Fatemi (2014) studied the fatigue crack growth on tubular specimens with a through the thickness hole under different combinations of loading blocks in bending and torsion. They reported relevant differences in crack growth ratios due to sequence effects, but they did not present any evaluation of the damage to failure. To the authors' knowledge the sequence effect due to different loading blocks has not be investigated in the technical literature in case of welded joints.

Also in this case, if the Miner's rule is adopted the cumulative damage can be described by the following relationship:

$$D = \sum D_i = \sum \frac{n_i}{N_i} \tag{1}$$

where D_i is the damage produced by each load block, obtained as the ratio between the block's length, expressed in number of cycles n_i, and the expected fatigue endurance N_i at the block's load level.

The fatigue test data will be given in terms of nominal stresses, following the definitions given in the next section, considering that the fatigue endurances in bending and torsion were already obtained in terms of nominal stresses in previous experimental campaigns.

2. Nominal stress method

The use of nominal stress is among those recommended by both the *International Institute of Welding* (*IIW*) Hobbacher (1996) and by the Eurocode 3 EN (1993). The nominal stress is by far the most simple endurable stress used in fatigue life assessment and is the usually preferred one for engineers working in the industry.

The nominal stress on the weld section is calculated according to common stress formulas, based on beam theory. The nominal stress in bending can be evaluated by equation 2, where M_b is the bending moment and W_x is the strength modulus of the weld section, which is defined with reference to the pipe outside diameter d_e and to the weld throat size t:

$$\sigma_n = \frac{M_b}{W_b} \tag{2}$$

where

$$W_b = \frac{\pi\left((d_e + t)^3 - \frac{d_e^4}{d_e+t}\right)}{32} \tag{3}$$

The nominal stress in torsion, instead, is given by equation 4, where M_t is the twisting moment and W_0 is the strength modulus of the weld section in torsion, again referred to the pipe external diameter and to weld throat size:

$$\tau_n = \frac{M_t}{W_t} \tag{4}$$

where

$$W_t = \frac{\pi\left((d_e + t)^3 - \frac{d_e^4}{d_e+t}\right)}{16} \tag{5}$$

In the cited codes a wide range of structural details are grouped into classes and for each class a design S–N curve is provided, which is referred to a 97.7% probability of survival. Such reference curves could had been used in case that specific experimental fatigue data were not available.

3. Experimental set-up

The tested specimens were designed in order to reproduce a plate-to-tube joint (Fig. 1) typically found in railway boogie components. The tube had an external diameter of 64 mm and a thickness of 10 mm, while the thickness of the plate was 25 mm. The tube is connected to the plate by fillet welding with a seam weld having a nominal

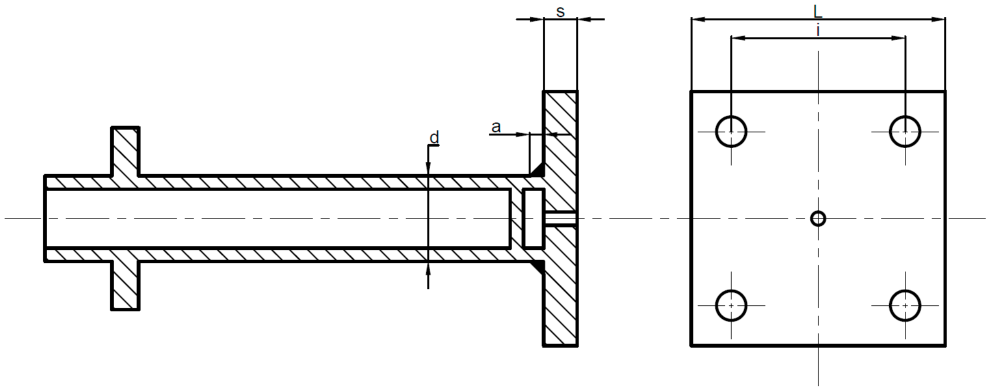

Fig. 1. Specimen geometry and dimensions.

dimension of 10 mm. The specimens were made of S355JR, a common structural steel, for which $\sigma_y = 360$ MPa and $\sigma_u = 520$ MPa. All the specimens were tested in as welded condition.

Tests were performed on the custom designed test bench shown in Fig. 2 described in Frendo and Bertini (2015). The bench is composed of two independently controlled hydraulic actuators connected on each side of the specimen by means of a lever arm with a length of $2b = 600$ mm. The lower plate of the specimen is fixed to the bench by four M20 bolts. The hydraulic actuators are controlled in order to produce sinusoidal forces with given amplitude, mean load and relative phase shift, i.e. $F_1(t) = a_1 \sin(\omega t) + \xi$ and $F_2(t) = a_2 \sin(\omega t + 2\gamma) + \eta$, in order to obtain the desired bending and twisting moments M_b and M_t:

$$\begin{aligned} M_b(t) &= [F_1(t) + F_2(t)]h \\ M_t(t) &= [F_1(t) - F_2(t)]b \end{aligned} \tag{6}$$

where the bending and torsion arms h and b are determined by the pipe and the lever arm lengths, respectively.

A prevalent bending load in the welded cross section is obtained imposing $a_1 = a_2$, $\xi = \eta$ and $\gamma = 0$. In this case also a shear stress is present; however, its value can be neglected, given the geometry of the test. Instead, a torsion load is obtained with $a_1 = a_2$, $\xi = -\eta$ and $\gamma = \frac{\pi}{2}$. A more detailed description of the experimental test apparatus can be found in Frendo and Bertini (2015).

Tests with different blocks of bending and torsion were carried out as described in the next section. The adopted failure criterion was the presence of a through the thickness crack. The occurrence of this kind of damage was easily detected by the sudden drop in air pressure imposed in the lower chamber trough a hole in the plate at the start of the test.

4. Experimental Tests

The current investigation consisted of four test series. In all cases tests were performed under constant amplitude loading and with a load ratio $R = 0$. Two series were designed so that the specimens were loaded in bending for two different fractions of the estimated fatigue endurance (i.e. $D_i = 0.3$ and $D_i = 0.45$). Subsequently they were loaded in torsion till failure. The fatigue endurance was estimated based on the results obtained from previous investigations by the authors (Bertini et al. (2014) and Frendo and Bertini (2015)), plus the results of some additional bending and torsion tests performed more recently in order to improve the statistical reliability of the fatigue life estimation. The resulting S–N curves for bending and torsion are given in Fig. 3.

For the bending block the load level corresponding to $\sigma_n = 64$ MPa was imposed, which corresponds to an expected fatigue life of $N_f = 9.2 \cdot 10^5$ cycles. Therefore, the fatigue life fractions of $D_i = 0.3$ and $D_i = 0.45$ resulted as bending blocks having lengths of $n_i = 2.8 \cdot 10^5$ and $n_i = 4 \cdot 10^5$, respectively. For the torsion block a load level corresponding

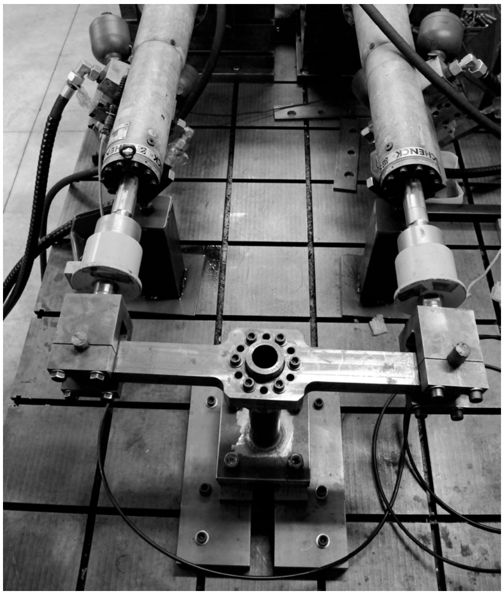

Fig. 2. Loading apparatus. The specimen is loaded by two hydraulic actuators attached at the extremities of a lever arm; this test rig was developed to have the possibility of applying complex combinations of bending and torsion (see Frendo and Bertini (2015)).

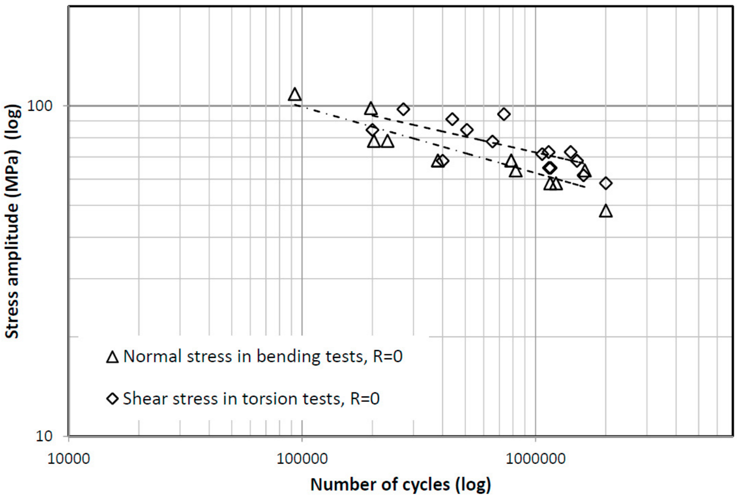

Fig. 3. Bending and torsion endurance data.

to $\tau_n = 72.5$ MPa was imposed; this value was selected in order to have the ratio between normal and shear stress $\sigma_n/\tau_n = 0.88$, which was investigated in previous works by the authors (Bertini et al. (2014) and Frendo and Bertini (2015)). The torsion load was applied till failure of the specimen.

Two additional test series were then carried out varying the loading order, in this case specimens were loaded in torsion for the selected fraction of the estimated fatigue endurance (i.e. $D_i = 0.3$ and $D_i = 0.45$) and, afterwards, they were loaded in bending till failure. The same load levels specified for the previous two series were considered. For the selected torsion load the expected endurance is equal to $N_f = 10.2 \cdot 10^5$ cycles (Fig. 3). Therefore, for the fatigue life fractions of $D_i = 0.3$ and $D_i = 0.45$ the torsion block length of $n_i = 3.1 \cdot 10^5$ and $n_i = 4.5 \cdot 10^5$ were obtained, respectively.

Table 1. Test series summary.

Test series	1^{st} Load block	D_1	n_1 (cycles)	2^{nd} Load block	n_2
1b	bending (σ_n = 64 MPa)	0.30	$2.8 \cdot 10^5$	torsion (τ_n = 72.5 MPa)	till failure
2b	bending (σ_n = 64 MPa)	0.45	$4 \cdot 10^5$	torsion (τ_n = 72.5 MPa)	till failure
1t	torsion (τ_n = 72.5 MPa)	0.3	$3.1 \cdot 10^5$	bending (σ_n = 64 MPa)	till failure
2t	torsion (τ_n = 72.5 MPa)	0.45	$4.5 \cdot 10^5$	bending (σ_n = 64 MPa)	till failure

The complete test plan is summarized in Tab. 1. Three tests were repeated for each condition for a total of 12 tests.

5. Experimental Results

The obtained experimental results are given in Tab. 2 and in Fig. 4. The first column of Tab. 2 refers to the tests series definitions given in previous Tab. 1, while the column n_2 refers to the 2^{nd} block length which was necessary to obtain a through the thickness fatigue crack. In the D_2 column the corresponding fatigue fraction calculated from the expected endurance in bending or torsion, respectively, is given. Finally, in the last column the total damage according to Miner's rule is given.

As it can be observed, in almost all the test resulted $D_2 > 1$. The cumulative damage to rupture resulted between 1 and 2 in 5 tests and greater than 2 in 5 five tests. In three cases $D_2 < 1$ and in particular $D_2 = 0.52$, $D_2 = 0.67$ and $D_2 = 0.94$. In the former two cases the total damage $D_1 + D_2 \approx 1$, while in the latter case resulted $D_1 + D_2 \approx 1.4$. The same results are illustrated in graphical form in Fig. 4, where the reference damage condition $D = 1$ is evidenced by a solid black horizontal line.

A comparison between the damage to rupture obtained for bending and torsion loading, for in-phase out-of-phase and loading blocks, is given in Fig. 5, where also the results obtained in Bertini et al. (2014) and Frendo and Bertini (2015) are reported.

Table 2. Test results.

Test series	n_2 (cycles)	D_2	$D_1 + D_2$
1b	$17.9 \cdot 10^5$	1.76	2.06
1b	$12.3 \cdot 10^5$	1.21	1.51
1b	$19.4 \cdot 10^5$	1.91	2.21
2b	$16.6 \cdot 10^5$	1.63	2.06
2b	$5.5 \cdot 10^5$	0.54	0.97
2b	$11.9 \cdot 10^5$	1.17	1.60
1t	$11.9 \cdot 10^5$	1.29	1.59
1t	$6.2 \cdot 10^5$	0.67	0.98
1t	$14.5 \cdot 10^5$	1.57	1.88
2t	$20 \cdot 10^5$ (run-out)	2.17	2.61
2t	$19.2 \cdot 10^5$	2.08	2.52
2t	$8.7 \cdot 10^5$	0.94	1.39

6. Conclusions

From the obtained experimental results the following conclusions can be drawn:

- the overall scatter observed in block tests is greater compared to that obtained in bending or torsion tests;
- almost all the tested specimens showed a cumulative damage greater than unity $D > 1$, with 5 tests having $D > 2$;

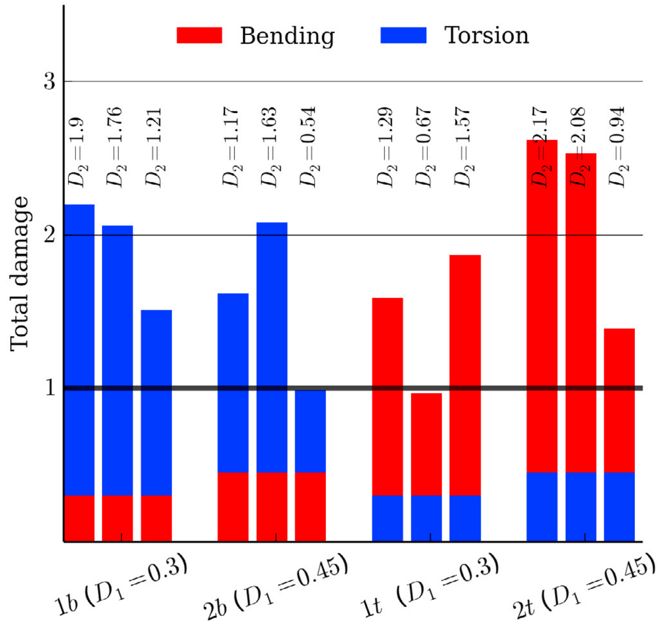

Fig. 4. Damage of each load block according to Miner's rule

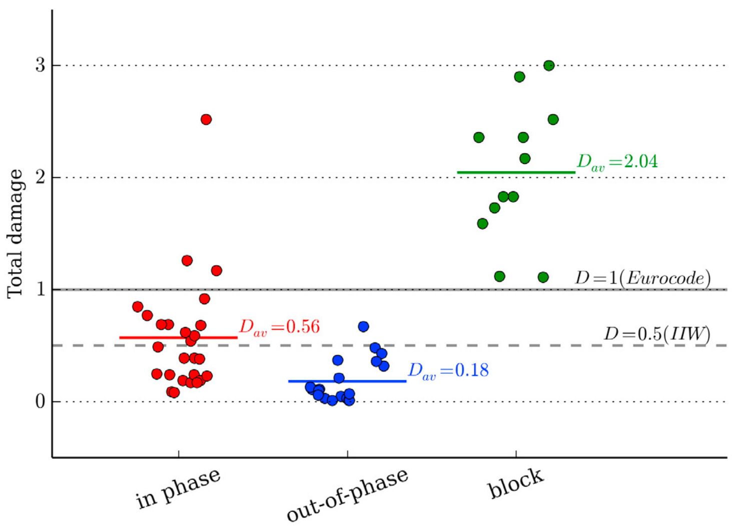

Fig. 5. Comparison of damages from in-phase, out-of-phase and block tests according to Miner's rule

- no clear sequence effects on the fatigue endurance emerged from the load block tests carried out in the present investigation.

From the comparison of the damages obtained in in-phase, out-of-phase and block tests (Fig. 5) the following conclusions can also be drawn:

- the damage summation for in-phase and out-of-phase tests, with the exception of three tests, resulted $D < 1$, in accordance with the results of several references found in literature;
- the damages for the in-phase tests are in good agreement with the damage summation $D = 0.5$ suggested by the *IIW*;
- out-of-phase tests showed an average damage summation $D \approx 0.2$, confirming a lower endurance in case of non proportional loading;
- for loading blocks tests the average damage summation resulted $D \approx 2$; this result support the idea that the damage in torsion and bending are almost independent for the considered joint and block loadings.

References

Bäckström, M., Marquis, G., 2001. A review of multiaxial fatigue of weldments: Experimental results, design code and critical plane approaches. Fatigue and Fracture of Engineering Materials and Structures 24 (5), 279–291.

Bertini, L., Cera, A., Frendo, F., 2014. Experimental investigation of the fatigue resistance of pipe-to-plate welded connections under bending, torsion and mixed mode loading. International Journal of Fatigue 68, 178–185.

Bertini, L., Frendo, F., Marulo, G., 2016. Effects of plate stiffness on the fatigue resistance and failure location of pipe-to-plate welded joints under bending. International Journal of Fatigue.

BS7910, B. S., 1999. Guide on methods for assessing the acceptability of flaws in fusion welded structures. British Standards Institutions.

EN, 1993. Eurocode3: design of steel structures. Fatigue.

Fatemi, A., Yang, L., 1998. Cumulative fatigue damage and life prediction theories: A survey of the state of the art for homogeneous materials. International Journal of Fatigue 20 (1), 9–34.

Frendo, F., Bertini, L., 2015. Fatigue resistance of pipe-to-plate welded joint under in-phase and out-of-phase combined bending and torsion. International Journal of Fatigue 79, 46–53.

Fricke, W., 2010. Guideline for the fatigue assessment by notch stress analysis for welded structures. International Institute of Welding 13, 2240–08.

Gladskyi, M., Fatemi, A., 2014. Load sequence effects on fatigue crack growth in notched tubular specimens subjected to axial and torsion loadings (69), 63 –70.

Gurney, T. R., 2006. Cumulative damage of welded joints. Woodhead Publishing.

Hobbacher, A., 1996. Fatigue design of welded joints and components: Recommendations of IIW Joint Working Group XIII-XV. Woodhead Publishing.

Lazzarin, P., Tovo, R., 1998. A notch intensity factor approach to the stress analysis of welds. Fatigue & fracture of engineering materials & structures 21 (9), 1089–1103.

Livieri, P., Lazzarin, P., 2005. Fatigue strength of steel and aluminium welded joints based on generalised stress intensity factors and local strain energy values. International Journal of Fracture 133 (3), 247–276.

Mikkola, E., Murakami, Y., Marquis, G., 2014. Fatigue life assessment of welded joints by the equivalent crack length method. Procedia Materials Science 3, 1822–1827.

Miner, M. A., et al., 1945. Cumulative damage in fatigue. Journal of applied mechanics 12 (3), 159–164.

Niemi, E., 1995. Stress determination for fatigue analysis of welded components. Woodhead Publishing.

Radaj, D., 1990. Design and analysis of fatigue resistant welded structures. Elsevier.

Radaj, D., Sonsino, C., Fricke, W., 2009. Recent developments in local concepts of fatigue assessment of welded joints. International Journal of Fatigue 31 (1), 2–11.

Sonsino, C., 2007. Fatigue testing under variable amplitude loading. International Journal of Fatigue 29 (6), 1080–1089.

Sonsino, C., 2009. Multiaxial fatigue assessment of welded joints–recommendations for design codes. International Journal of Fatigue 31 (1), 173–187.

Sonsino, C., Maddox, S., 2001. Multiaxial fatigue of welded structures–problems and present solutions. In: Proceedings of the sixth international Conference on Biaxial/Multiaxial fatigue and Fracture. pp. 3–15.

Tovo, R., Livieri, P., 2007. An implicit gradient application to fatigue of sharp notches and weldments. Engineering Fracture Mechanics 74 (4), 515–526.

UNI, C., 1988. 10011steel structures. Instructions of design, construction, testing and maintenance. UNI, Italy.

Verreman, Y., Nie, B., 1996. Early development of fatigue cracking at manual fillet welds. Fatigue & Fracture of Engineering Materials & Structures 19 (6), 669–681.

Zhang, Y.-H., Maddox, S., 2009. Investigation of fatigue damage to welded joints under variable amplitude loading spectra. International Journal of Fatigue 31 (1), 138–152.