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Experimental investigation of the fatigue resistance of pipe-to-plate welded connections under bending, torsion and mixed mode loading

Leonardo Bertini [a], Alessandro Cera [b], Francesco Frendo [a,*]

[a] Department of Civil and Industrial Engineering, Largo Lucio Lazzarino, Pisa, Italy
[b] Trenitalia S.p.A. Direzione Tecnica, Ingegneria rotabili e Tecnologie di base, Italy

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ABSTRACT

The fatigue resistance of pipe to plate fillet welding connections was experimentally investigated. The specimens consisted of steel tubular elements, having 10 mm wall thickness and 64 mm external diameter, joined by seam welding to a plate of 25 mm thickness and were designed in order to reproduce a typical joint used in railway bogie frames. Tests were carried out under pure bending, pure torsion and under combined in-phase loading, with two different bending-to-torsion ratios. For each loading condition, tests were conducted with $R = 0$ (i.e. pulsating fatigue) and $R = -1$ (i.e. alternating fatigue). The results, obtained on the basis of the nominal stress method, show an almost independent behaviour on the load ratio R for the torsion loading and a significant effect of the load ratio R in case of bending loading. A modified equivalent stress, based on the results obtained under pure bending/torsion, is demonstrated to fit all the experimental results with a reduced scatter and a higher slope, with respect to the frequently used von Mises equivalent stress.

1. Introduction

Welding is an automated process that is widely used in many industrial areas (e.g. automotive, railway, offshore, cranes, bridges, etc.) in order to join different parts and obtain a desirable, even complex, geometry of components or frames. The fatigue strength of welded joints, then, represents a classical subject of the design of load carrying structures which is still subject of research. At the same time, the design or, alternatively, the analysis of a welded connection is very complex due to the influence that many factors have on the nucleation and propagation of defects. That is a consequence of the welding process itself, which produces the fusion of the filler material and subjects the base material to a severe thermal loading, leading to a locally inhomogeneous microstructure within adjacent material volumes having different mechanical properties. Among the factors influencing the fatigue strength are the local weld geometry, including possible misalignment and undercut, the presence of defects, such as inclusions and pores and cavities (see [1]), and the process parameters which determine the inhomogeneous microstructure and the residual stresses extent. Some post weld treatments for improving the fatigue strength of welded connections, grouped into improvement of shape, improvement of residual stress conditions and improvement of surface geometry [2], are suggested by the IIW.

The technical literature on this subject is really extended and there is not a unified analysis procedure yet. There are several, sometimes well established, procedures, which make use of different parameters and typically: the nominal stress, the "hot spot" stress, the notch stress or notch strain and the fracture mechanics method (see e.g. [3–13]).

The nominal stress method is usually adopted in design codes [14,15,6]. When the nominal stress concept cannot be employed, due to the fact that either the nominal stress cannot be defined or the detail under examination does not match anyone of the joint classes which are provided by standards, the "hot spot" or "structural stress" method [5,16,14,17] can be used. In this method the geometric stress acting at the weld toe is estimated on the basis of some strain determination obtained (by strain gauge measurement or FE simulations) at some distance from the weld toe. The reference hot spot stress, therefore, is no longer associated to any particular detail and in this way it is possible to take into account the joint geometry (and stiffness), while any local contribution due to the actual weld geometry is not considered. One of the drawbacks of this method is that only the stress at the weld toe is considered and then failure at the weld root is not covered. In local parameters methods, the stress acting at the weld toe or root is considered for the fatigue assessment. In order to overcome the

* Corresponding author. Tel.: +39 (0)502218074; fax: +39 (0)502210604.
E-mail address: frendo@ing.unipi.it (F. Frendo).

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singularity of the stress field two different approaches have been proposed: the fictitious radius, which is a well established procedure, and the notch stress intensity factor. In the fictitious radius method, a method proposed by Radaj [3–5], based on the original idea of the microsupport effect by Neuber, a finite radius is introduced at the toe or root and a notch stress (maximum principal stress or, alternatively, von Mises equivalent stress) is considered. A notch rounding radius of 1 mm or 0.05 mm have been established on the basis of the shell thickness ($t \geqslant 5$ mm and $t \leqslant 3$ mm, respectively) together with reference FAT lines, which depend on the employed material (steel or aluminum), on the adopted failure hypothesis (principal stress or VM equivalent stress) and on the kind of stress (normal or shear) acting on the weld [10]. According to the classical fracture mechanics approach the endurance of a welded joint is evaluated considering only the propagation phase of a given hypothesized existing crack (an initial crack of 0.15 mm is suggested by the IIW for a very conservative life estimation). On the other hand, in order to consider also the crack initiation, a Notch-SIF method has been proposed [18,19].

Recently, some additional methods have also been proposed, based on alternative parameters such as an integral average value of the stress component which is believed to be responsible for the failure or the local strain energy in a material volume in the surrounding of the critical area [20–22].

The subject is even more complicated under multiaxial loading conditions, especially in case of nonproportional loading [23,24]. Several methods have been proposed and the fatigue strength of welded joints in case of multiaxial loading is still an open problem [24–27]. In case of proportional loading the most commonly employed methods are based on the maximum principal or equivalent (von Mises) stress range, while in case of nonproportional loading the most promising methods seem to be those based on the critical plane concept or the effective equivalent stress (EESH) [11,25,28–30]. In [23] the author discuss the applicability of the maximum principal stress range, in case of in phase and out of phase loading, with reference to the FAT80/3 and FAT80/5 design curves. The analysis is based on data taken from the literature related to failures from the weld toe.

Material ductility is also demonstrated to have a significant effect on the fatigue endurance under nonproportional loadings [24]. Ductile material show a sensible reduction of the fatigue endurance in case of nonproportional loading, with respect to the case of proportional loading, while low ductility materials, such as aluminum, show an almost independent behaviour.

From a designer point of view, or when the theoretical background is not well known, simple and practical methods have to be considered. With this intention the Palmgren–Miner cumulative damage rule is recommended by both the Eurocode and the IIW [14,16] with no distinction. To this aim different *S–N* design curves are given for normal and shear stress and the damages due to normal and shear stress have to be separately evaluated:

$$\left(\sum \frac{n}{N}\right)_{\sigma} + \left(\sum \frac{n}{N}\right)_{\tau} \leqslant D \quad (1)$$

in which, the critical damage value D is set equal to 1 and 0.5 in the Eurocode and in the IIW recommendations, respectively. In case of constant amplitude loading the previous equation leads to a modified Gough–Pollard algorithm

$$\left(\frac{\Delta\sigma}{\Delta\sigma_E}\right)^{K_\sigma} + \left(\frac{\Delta\tau}{\Delta\tau_E}\right)^{K_\tau} \leqslant D \quad (2)$$

where in the Eurocode $K_\sigma = 3$ and $K_\tau = 5$.

In the present work the results of 71 experimental tests carried out on pipe-flange joint with fillet weld are presented and analysed with reference to nominal stress approach. The activity was carried out in the framework of a research contract between Trenitalia S.p.A., an Italian train manufacturer, and the Department of Civil and Industrial Engineering (University of Pisa) and the results will be shown in graphical format.

Tests were carried out at constant amplitude in bending, torsion and mixed mode in-phase loading, with two different bending to torsion combinations. It is discussed that the frequently used von Mises equivalent stress may result not fully appropriate for this kind of joints and a modified interaction equation is proposed. The presented data also extend the disposal of experimental data to different joint categories. Pipe-to-plate joints were also investigated [30,31], even if, in [30] a single bevel butt weld was used, while only bending loading was considered in [31] and a stress relieve heat treatment was applied before testing in both works. Another aspect which is worth of consideration is that failure originates in different regions (weld toe or root) according to different authors, even for very similar joint geometry. For single bevel butt welds, failures from the toe are described in [30], whereas failures from the root are described in [31]. In case of fillet welds, failure from both the toe and the root are described in [31], with a possible influence of after welding treatments (stress relieving and blast cleaning).

2. Specimen geometry and experimental tests

The analysed flange-tube connection is in some extent similar to that presented in [31] and typically employed in railway bogies as shown in Fig. 1. The specimen geometry is given in Fig. 2. The pipe (64 mm outer diameter and 10 mm thickness) and the plate (25 mm thickness) were made of S355JR steel ($\sigma_y = 360$ MPa and $\sigma_u = 520$ MPa) and were joined by fillet welding. A circular sleeve (10 mm thickness) was welded near both ends of the pipe, according to the construction design used in some real application, in order to increase the stiffness of the joint and avoid distortions.

Fig. 3 shows the weld cross section. As it can be seen, the weld is free from evident defects, with uniform grain size. The weld throat is about 6.1 mm. It can be also observed how, for fillet welding, a very small (almost zero) radius is present at the root of the weld. For this reason most of the failures were originated from the root, with the exception of bending tests where cracks originated from both the toe and the root.

Tests were carried out according to four different loading schemes (see Table 1 and Figs. 4 and 5) and and in particular: pure bending, pure torsion and combined bending/torsion with two

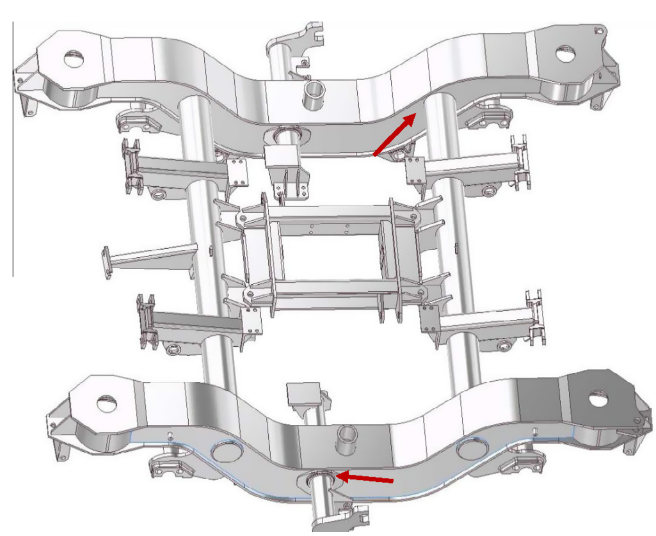

Fig. 1. Typical railway bogie.