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ECF22 - Loading and Environmental effects on Structural Integrity

Cruciform welded joints: hot-dip galvanization effect on the fatigue life and local energetic analysis.

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Abstract

Even in a well-controlled technological process, a certain variability in the final product is present and this is very well the case of welded joints, where each single joint is slightly different from the others in terms of fillet dimensions, distortion, notch opening angle and root radius and material properties. When the fatigue life assessment of a welded joint is carried out using the Notch Stress Intensity Factors, their dimensions, so their critical values, vary as a function of the notch opening angle, according to William's solution. This constitutes an adjunct level of complicacy in the implementation of the method, the most explicative case being the inability to use the same material property value in the same joint, this varying from weld toe to weld root. So considered, the local Strain Energy Density, averaged on a critical volume of carefully chosen radius on the base of the class of material and surrounding the notch's tip, has the great advantage of being a scalar value of relatively simple numerical computation, almost independent of mesh refinement and independent of the notch-opening angle. The aim of the paper is to adopt the local SED method to analyze the results of a series of tests executed on fillet welded galvanized and non-galvanized cruciform steel joints. The tests are performed in atmosphere at room temperature. The interest is particularly focused on the influence of the zinc layer on the fatigue life of the joint and on the fitness of the method for its prediction, regardless of coating thickness.

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Keywords: hot dip galvanization; strain energy density; welding; fatigue; structural steel; notch

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1. Introduction

The fatigue life of structures is heavily affected by environmental factors. Corrosion is one of the most important issues, causing a big safety and economy impact. Several techniques to prevent its detrimental effects have been developed, both as alloying and as surface treatment. Of these techniques, hot dip galvanizing is one of the most widely adopted and effective, generating a zinc layer on the surface of the structural member, which acts as a barrier for corrosive agents. Although having a positive effect on the resistance to environmental factors, the coating might change the response of the material to mechanical periodic excitation, diminishing the crack initiation life, according to technological parameters [1,2] and after a certain critical value of coating thickness [3]. Even though a negative effect on the fatigue life of un-notched specimens has been found [4], not all works agree with this conclusion [5]. A small amount of results is so far available in the case of notched components [6] and some of them regard hot dip galvanized welded steel joints [7]. The goal of the present work is to integrate the experimental results available and provide further considerations on the influence of the zinc coating on the fatigue life of the welded detail, providing an analysis of the results in terms of Nominal Stress [8] and Strain Energy Density [9,10].

2. Experimental procedure

The work summarizes the testing of a number of cruciform welded joints in two geometries, as in figure 1. The samples have been realized in three batches: 30 galvanized geometry 1, 5 non-galvanized geometry 1 and 15 galvanized geometry 2, being the geometry 1 load carrying and the geometry 2 non-load carrying as seen in figure 1. The base material consists of respectively 10 and 30 mm thick plates of S235 JRG2 structural steel. In the case of load carrying fillet, this has been made using S355 J2+N as filling material for the MAG welding process. The galvanization process generated a zinc layer of a thickness comprised between 470 and 500 μm . The samples have been then tested in as-welded condition, with no further thermal treatment to relieve the residual stresses, in order to better model a detail inserted in a real structure, case in which a thermal treatment is often unfeasible. Prior to clamping in the testing machine, each sample was measured and machined in order to minimize the distortion caused by the rigid clamping system. A servo hydraulic MTS 647 machine has been used to impose a cyclic axial load at the frequency of 10 Hz and a nominal load ratio $R=0.01$.

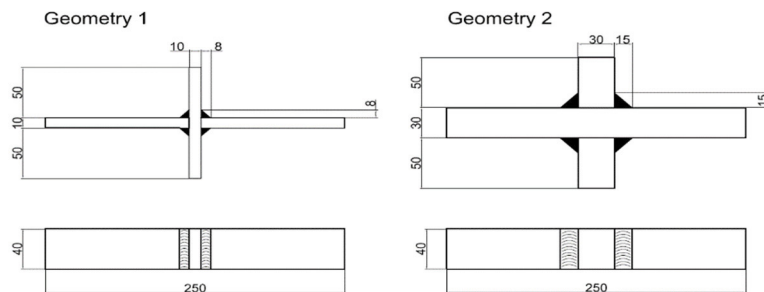


Fig. 1. Specimen geometries.

3. Fatigue curves

In the following figures, 2-6, the results of the testing in terms of nominal stress range are presented, in comparison with the S-N curves and averaged SED. Some effects are to be accounted for, mainly the thickness effect and the influence of the load ratio. The thickness of the plates constituting geometry 2, being of 30 mm, is major than the reference thickness of 25 mm suggested by Hobbacher for the use of the S-N curves. The document suggests then a factor to exponentially diminish the value of the FAT class in order to account for the loss of fatigue resistance experienced by a greater joint for a given nominal stress range. It is possible to observe in figure 4 a reduction of strength of the 30 mm thick galvanized non-load carrying geometry if compared to an analogous geometry, both galvanized and not, made by 10 mm thick plates. The document suggests an exponent of 0.3 for cruciform joints. The line for the FAT class in figure 5 has then been computed as follows:

$$FAT_{corr} = f(t)FAT = \left(\frac{t_{ref}}{t_{eff}}\right)^n FAT = \left(\frac{25}{30}\right)^{0.3} 80 = 76MPa$$

Another effect, besides that of the thickness, is the slight loss of fatigue strength due to the zinc coating at the crack initiation site, that is, the weld toe, leading to an early crack initiation compared to the uncoated samples.

For what concerns the load ratio, the testing was carried on at a nominal load ratio $R=0.01$, while Hobbacher suggests the families of S-N curves for each detail at $R=0.5$. The suggestion is, whereas no thermal stress relieving of the joints is performed, not to correct the allowable stress for $R<0.5$, providing a conservative estimate which accounts for the tensile residual stress caused by the thermal shrinking of the weld.

Figures 2 and 3 report the results of the testing, separately for the two geometries, in terms of nominal stress range. The two classes of detail are characterized by a very similar reverse slope k and present the same Stress Range of 79 MPa at a Probability of Survival of 50 %. Two mechanisms are contributing to lower the resistance of the non-load carrying detail, bringing it to the same level of geometry 1: the zinc coating affects the weld toe, but not the weld root and the greater thickness of the second geometry generates a more severe stress intensification at the weld toe, lowering then its fatigue life.

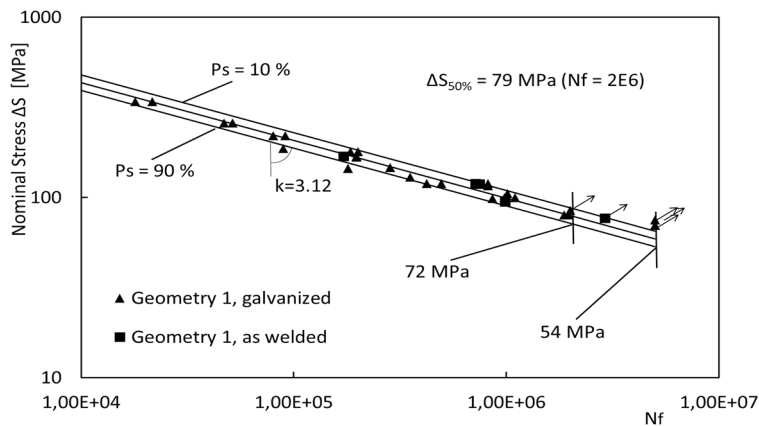


Fig. 2. Fatigue life for geometry 1.

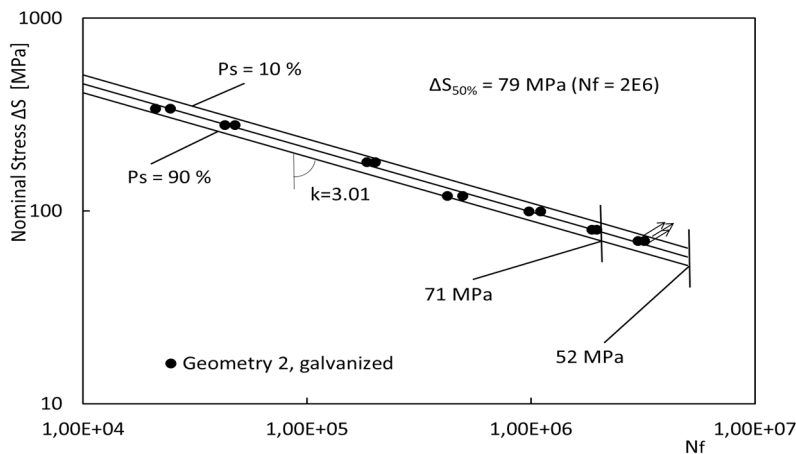


Fig. 3. Fatigue life for geometry 2.

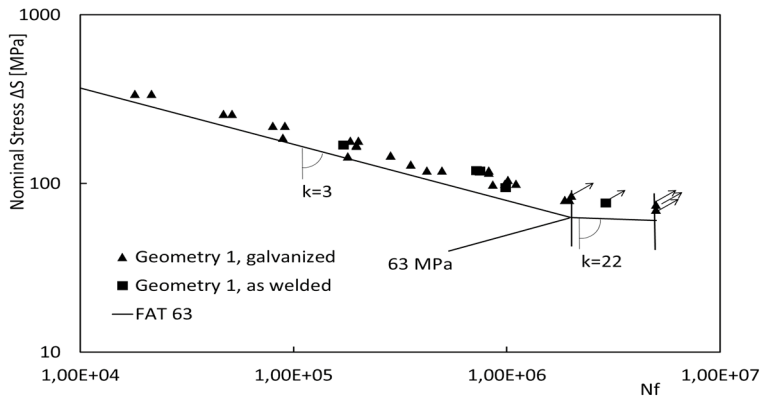


Fig. 4. Geometry 1 results and relative fatigue band [8]

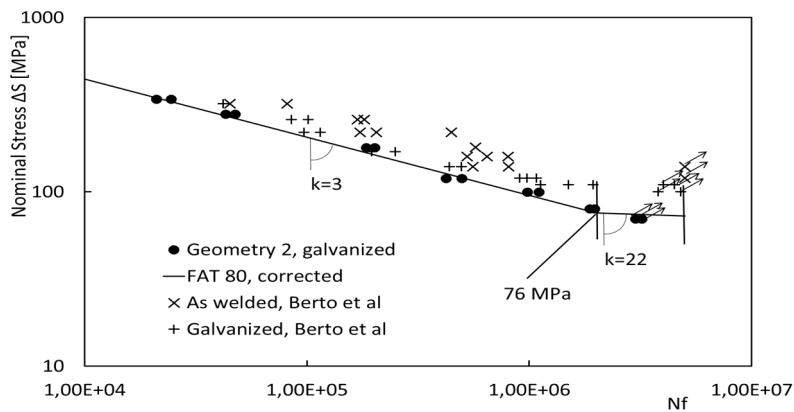


Fig. 5. Geometry 2 results and relative fatigue band, corrected for thickness [7,8].

Adopting the average SED to summarize the results and assess the performance of the joints, the effect of the thickness and of the difference of weak point, weld root and toe respectively for geometry 1 and 2, are automatically accounted for in the FEM analysis, obtaining a parameter that is solely dependent on the material and free from the necessity of characterizing every specific detail. The result is that the failure data are all aligned in a relatively narrow band, almost perfectly centered with the data already available in the literature for structural steels.

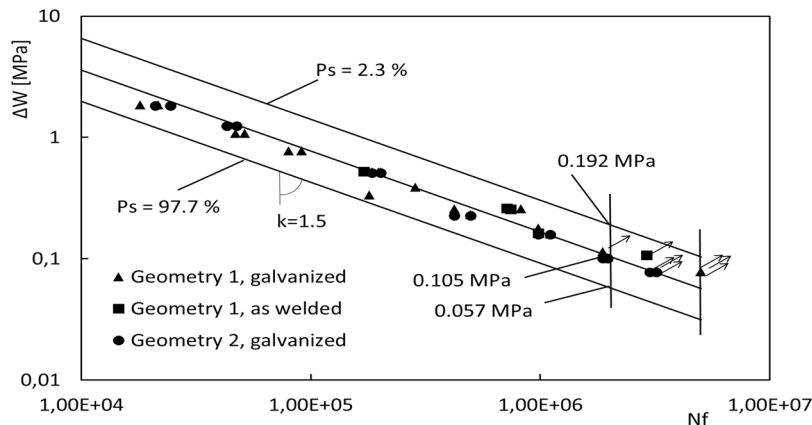


Fig. 6. Summary of the results as average Strain Energy Density.

The presence of the zinc coating influence differently the failures for the two geometries. In the case of geometry 2, being this non-load carrying, the weld toe has been the failing point for all the samples, just as in the case of the uncoated joints. More interesting, under the perspective of the investigation of the galvanization process on the failure dynamics, is the load carrying geometry 1. In this case, the crack generated by the lack of weld penetration at the root should be critical with respect to the weld toe. What actually observed is instead that, while most of the failures originate at the weld crack (figure 7, left), some of them show a concurrency of the two hot spots (figure 7, center) or even a prevalence of the weld toe (figure 7, right). The conclusion drawn is that while no strong average reduction in fatigue life for the coated geometry 1 is shown compared to the uncoated, this is because the bath does not penetrate to the root. An influence of the coating is present, and weakens the weld toe to the point of making it in concurrency with the weld root. To quantify the difference in SED between the weld toe and root for geometry 1, in the case on an applied nominal stress range of 100 MPa, the averaged SED range is equal to 0.153 and 0.180 Nmm/mm³ for toe and root respectively.

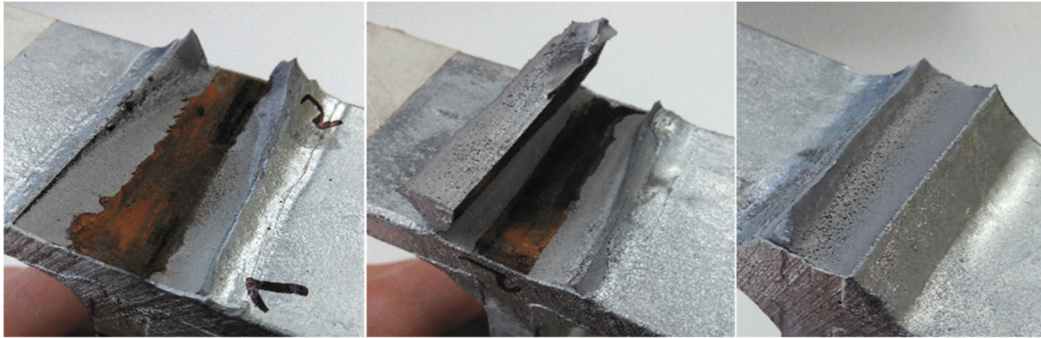


Fig. 7. Examples of the failure modes for geometry 1.

4. On the Strain Energy Density

Assessing the fatigue life of an open notch or a crack by the means of the Notch Stress Intensity Factors requires a detailed analysis of the stress-strain field. This requires a very refined mesh which, if not too problematic in a bi-dimensional linear elastic FEM analysis, becomes more difficult to handle both in preprocessing and in solving in the case of a three-dimensional structure or, even more, if a non-linear solution is required, as in the case of contact modelling. Also, the exponent of the NSIFs depends on the opening angle, according to the William's eigenvalues [11], that is, their measure and their critical values are depending on the opening angle, providing a more difficult material characterization. It is possible to overcome both these problems by evaluating the performance of the component or specimen, at the stress intensification point, by the means of the Strain Energy Density [9,10,12]. These properties of the SED are at the basis for its feasibility for a great variety of stress intensificator geometry, from cracks to butt joints [13]. Moreover, the majorly detailed modelling necessary if compared to other techniques as the Nominal Stress or the Hot Spot Stress, can provide more accurate results [14]. The SED is defined as the value of Strain Energy averaged on a critical volume of radius R , which is identified as a material property and quantified in 0.28 and 0.12 mm for steel and aluminum respectively. In the case of linear elastic isotropic behavior, the SED can be punctually expressed as:

$$W(r, \theta) = \frac{1}{2E} (\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - 2\nu(\sigma_{11}\sigma_{22} + \sigma_{11}\sigma_{33} + \sigma_{22}\sigma_{33}) + 2(1+\nu)\sigma_{12}^2)$$

where r and θ are the radius and angle from the notch or crack tip, E and ν are elastic modulus and Poisson's ratio. Integrating and averaging the function over a finite volume of radius R , considering the validity of the William's solution and after some passages which are well explained in the reference literature, the average SED can be written as:

$$\bar{W} = \frac{e_1}{E} \left[\frac{K_1}{R^{1-\lambda_1}} \right]^2 + \frac{e_2}{E} \left[\frac{K_2}{R^{1-\lambda_2}} \right]^2$$

Being e_1 and e_2 dependent on notch's opening angle and stress state and λ_1 and λ_2 the William's eigenvalues.

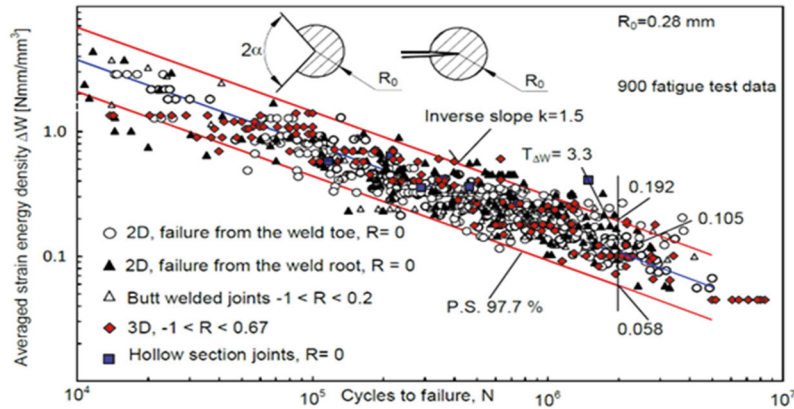


Fig. 8. SED fatigue band for welded steel joints [10]

4.1. SED rapid convergence

The accuracy of the SED solution for a very coarse mesh can be explained referring to the theory of the finite element method. For a generic element:

$\{d\}$ is the nodal displacements vector,

$[K]$ is the elemental stiffness matrix.

The basic formulation of the Finite Element Method, in linear elastic behavior assumption, leads to the following expression for the energy stored in an element:

$$E_e = \frac{1}{2} \{d\}' [k] \{d\}$$

The last step to obtain the averaged SED is then to divide it by the volume of the element. Avoiding the stresses and strains in the formulation, both lower than at convergence in the case of a coarse mesh, allows the computation of the energy to an almost immediate convergence, being the displacements lower and the elements of the stiffness matrix higher than at stress convergence, two effects balancing each other [10].

5. Conclusions

The work presents the results of a fatigue testing campaign on a series of cruciform welded joints. The joints have been realized by MAG welding, in two geometries, load carrying and non-load carrying using plates respectively 10 and 30 mm thick of S235 JRG2 structural steel. Most of the specimens so produced have then been hot dip galvanized up to a 500 μm thick zinc layer. The goal has been to investigate the influence of the zinc coating on the fatigue life of the welded details. The main conclusions drawn from the analysis of the results are:

- It is important to consider the presence of the zinc layer, because this affects the life of the component, even though not in a dramatic way. Observing the results, no difference in fatigue life is detected for geometry 1. This is due to the fact that the weak point for this geometry is the weld root, which is not affected by the coating. On the other hand, observing the results in figure 5 [7], the galvanization induces a slight reduction of fatigue life for the non-load carrying geometry.
- The thickness of the plate, as seen in figure 5 from the comparison with a previous work of Berto et al [7], affects the fatigue life. This can be easily quantified as an increase of Strain Energy Density range with an increase of plate thickness for a given nominal stress range.
- The effect of the thickness is observed also comparing the nominal stress range for the two geometries: they present very similar fatigue curves, while the geometry 1 fails at the weld root, a crack originated by the lack of penetration, while the geometry 2 fails at the weld toe, an open v-notch. In same thickness condition, geometry 2 should show a better performance than geometry 1.

- Recurring to the theory of the Strain Energy Density, it is possible to provide an analytical estimate of the variation of SED for similar joints of different thicknesses. This allows to a FEM characterization of a detail that can be scaled to different sizes without the necessity of new FEM analysis.
- Finally, since the tests do not show a strong, quantifiable reduction in the fatigue life, but rather a different failure mode for geometry 1 and a slight reduction in fatigue life, but still within the boundaries of the literature S-N curves, for geometry 2, the suggestion is, in design, to adopt the relative FAT class for detail in poor condition or a higher safety coefficient.

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