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Fatigue strength of a common steel welded detail through Eurocode 3 and local strain energy values

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Abstract

This paper investigates the influence of the main geometrical parameters of a welded detail, common for structures having various applications, providing a comparison between the recommendations given by the Eurocode 3 and the results achievable through the application of a local approach, such as the Strain Energy Density method. The effect of a complete weldment versus a weldment presenting lack of penetration is investigated as well. Indeed, a full penetration weldment, involving higher costs, is not always needed to ensure failure from the weld toe, a condition to be preferred for monitoring purposes. The fatigue strength estimated for the joint though the local approach showed that the Eurocode 3 significantly overestimates the influence of some geometrical parameter describing the joint, neglecting other important parameters. The results of this study highlight the limitations of a global approach in accounting for different geometrical parameters and show instead the power of a local approach in determining the parameters that may severally influence the fatigue strength. Thus, it allows fatigue assessment through ad hoc experimental campaigns, reducing in this way the costs of such kind of investigations.

Keywords: Fatigue strength; Welded Joints; Local Approaches, SED.

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1. Introduction

Welded components constitute one of the most utilized kind of joints in different industrial and civil engineering field such as shipbuilding, bridge bents, trains, and many others (Corigliano et al., 2019; Fricke et al., 2014; Lazzarin et al., 2013; Saiprasertkit et al., 2012; Wu et al., 2016). The increasing complexity of the geometry in the welded structures makes clear the need for accurate and cheaper tools for the design of these components whose behaviour can be also more deeply investigated by simulating the entire process of welding (Leoni et al., 2021, 2020b, 2020a)

These components are subjected to fatigue loads during their operational life; therefore, they must be carefully dimensioned to avoid unexpected fatigue failures. Different standards (1993-1-3:2009, 2011; A. Hobbacher, 2008; British Standards Institution, 2014; DNV GL AS, 2016) are available for the fatigue assessment of these components depending mostly on the field of application.

The fatigue failure in welded components is usually determined by the geometrical discontinuities created during the realization of the weldment, i.e., the weld root and the weld toe. These geometrical discontinuities and notches lead to a localized stress concentration that could lead to the generation of a crack and to the final failure of the component over time (Pietro Foti et al., 2020b). Other imperfections and defects determined by the welding process can also have an effect of the fatigue strength of these components.

Regardless of the local nature of the fatigue failures, the fatigue assessment approach suggested by the codes is the nominal stress approach. It is a global approach that considers nominal stresses in the critical cross-section and compares them with S-N curves, which correlate the fatigue strength of the component with the number of cycles to failure. The nominal stress approach results in a S-N curve that depends on the geometrical parameters of the tested joint and that considers local phenomena only statistically so that its rigorous application should be done only dealing with details having the same geometry and loading conditions of the one utilized to realize the design curve. This is not a usual case in real industrial applications having complex geometries and loading conditions whose fatigue assessment lacks, in this sense, of a clear experimental validation. Besides, the standard misses to account for parameters that have been shown to have an influence on the fatigue strength of the component (Pietro Foti et al., 2021b).

Fatigue assessment methods able to overcome this issue are represented by the so-called local approaches, that consider a local quantity for the fatigue assessment. The results are generally independent on the global geometry and loading conditions of the component, considering the fatigue strength of a detail equal to that of any other components having locally similar conditions. However, the use of these methods usually requires expertise and the use of finite element (FE) software.

The main objective of the present work is to highlight the main discrepancies found, in designing against fatigue a common welded detail, between the nominal stress approach, considering the recommendation of the Eurocode 3 and the strain energy density (SED) method, a local approach. The SED method is also employed to study the lack of penetration in welded details with the determination of conditions of equiprobability of failure from the weld root and weld toe.

2a	length of the partial penetration crack
E	Young's modulus
FE	finite element
FAT classes	fatigue strength at 2 million of cycles in terms of nominal stress range
h	weld leg height
l	intermediate plate thickness
P.S.	probability of survival
R_0	control volume characteristic length.
SED	strain energy density
w	weld length
$\overline{W}$	averaged strain energy density
$\overline{W_c}$	critical averaged strain energy density

Greek

ΔF	amplitude of the remote applied force
$\Delta\sigma_i$	remote nominal tensile stress amplitude
$\Delta\sigma_L$	fatigue limit of the component in terms of remote nominal tensile stress amplitude
$\Delta\bar{W}$	cyclic averaged strain energy density
$\Delta\bar{W}_i$	strain energy density value due to the application of $\Delta\sigma_i$
$\Delta\bar{W}_L$	fatigue strength at 2 million of cycles in terms of cyclic averaged strain energy density

2. Theoretical background

2.1. Fatigue Assessment by Eurocode 3

The fatigue assessment of steel or aluminium welded joints is explained in the ninth section of the Eurocode 3 (1993-1-3:2009, 2011)

The standard suggests the use of the nominal stress approach that considers the nominal stress in the component critical cross-section that, through the proper S-N curve, allows the calculation of the fatigue life of the component.

The standard defines the fatigue curve to be used for each detail classified by defining two different parameters: the inverse slope of the fatigue curve, common for all the details and equal to 3 in the case of steel welded joints, and the FAT class, i.e. the fatigue strength at 2 million of cycles. The consideration of different possible geometrical parameters combinations for each detail are accounted by the standard defining the FAT class only for a specific set of geometrical parameters from which it is possible to obtain all the others through simple rules. The fatigue curves defined by the standard are intended for as-welded joints under normal atmospheric conditions treated only for stress relief and with enough corrosion protection and regular maintenance.

The FAT classes of cruciform joints having different geometrical parameters are defined by the Eurocode 3 through ranges of their main geometrical parameters, i.e., the intermediate plate thickness l and the attached load carrying plate thickness t reported in Figure 1a; while the welding height is accounted only when dealing with the assessment of failures from the welding root and peculiarities such as the welding bead shape cannot be analysed. In the case of partial penetration conditions, the standard also requires that both the weld root and toe are assessed: the weld toe through the FAT classes established for the full penetration joint; the weld root through a FAT class of 36 MPa to be compared with the stress $\Delta\sigma_W$ evaluated in the throat of the weldment as:

$$\Delta\sigma_W = \frac{\Delta F}{\sum(a_w \cdot w)} \tag{1}$$

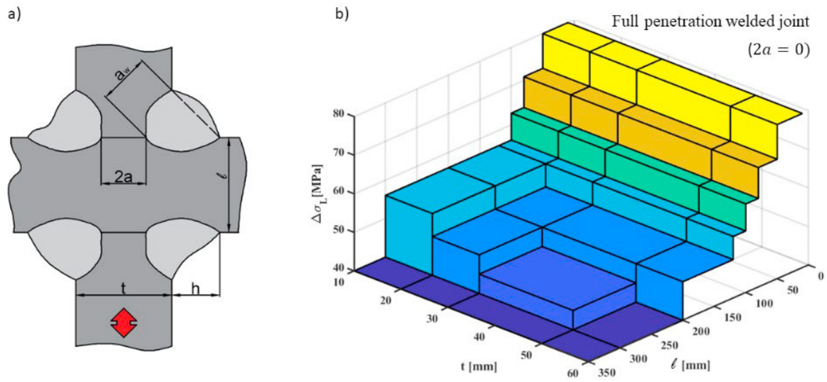


Figure 1: a) main geometrical parameters for cruciform joint; b) FAT classes as a function of the main geometrical parameters of cruciform joint according to the Eurocode 3 under full penetration conditions

Where w is the weld length while a_w is the throat thickness as shown in Figure 1a.

The result of this classification in terms of FAT classes as a function of the main geometrical parameters of the joint is reported in Figure 1b, in the case of full penetration weld, i.e., 2a= 0.

However, the fatigue assessment of this welded detail by the standard is subjected to some conditions related to the geometry of the joint that must be inspected and adhere to the tolerance of EN 1090.

2.2. Fatigue Assessment by Eurocode 3

The averaged strain energy density (SED) is a local approach that has been proved to be suitable to assess both fracture in static condition and fatigue failure (Aliha et al., 2017; Berto and Barati, 2011; Lazzarin et al., 2008; Lazzarin and Zambardi, 2002, 2001; Razavi et al., 2018; Torabi et al., 2015). The assumption that brittle fracture occurs when the local SED, $\overline{W}$, averaged in a given control volume reaches a critical value represent the basic idea of the method. The independence of the method on the local geometry and on the loading conditions (Lazzarin et al., 2008; Lazzarin and Zambardi, 2002, 2001) is reflected on the unicity of the critical value of the averaged SED, $\overline{W} = \overline{W}_C$, that must be considered a material property as well as the size of the volume in which $\overline{W}$ is evaluated. The SED critical value under static loading condition can be evaluated for a material that behaves as ideally brittle exploiting its conventional ultimate tensile strength σ_{UTS}:

$$\overline{W}_C = \frac{\sigma_{UTS}^2}{2E} \quad (2)$$

The averaging of the SED value must be carried out in a so-called control volume. This control volume has a characteristic length R_0 that is assumed to be a material property (Lazzarin and Berto, 2005a, 2005b; Lazzarin and Zambardi, 2001; Yosibash et al., 2004). On the other hand, the local geometry affects the shape of the control volume that is a sector-shaped cylinder for sharp notches and a crescent moon-like shape in the case of blunt notches. The loading conditions instead act on the control volume position: sharp notches have the control volume centre on the notch tip; blunt notches have the control volume axis of symmetry oriented in a way that the centre of curvature of the notch and the first principal stress maximum belongs to it. The conditions enlisted above can be appreciated graphically through Figure 2. Considerations about the analytic frame of the SED method can be found in (Berto and Lazzarin, 2014; Radaj, 2015; Radaj and Vormwald, 2013).

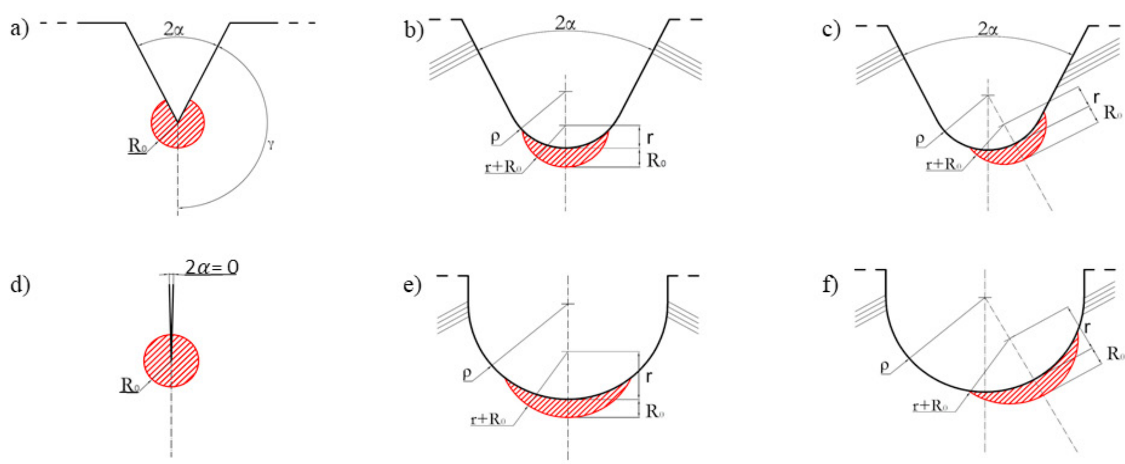


Figure 2: Control volume for a) Sharp V-notch; b) blunt V-notch under mode I loading; c) blunt V-notch under mixed mode loading; d) Crack; e) U-notch under mode I loading; f) blunt U-notch under mixed mode loading (Pietro Foti et al., 2021a)

It is worth underlining that the application of the SED method presented a major drawback in having to create in the finite element (FE) model the control volume in which averaging the SED. Regarding this topic, different solutions have been proposed in literature to overcome this limitation (Campagnolo et al., 2020; Fischer et al., 2016; P. Foti et al., 2020; Pietro Foti et al., 2021a, 2020a).

The application of the SED method for the fatigue assessment in the high-cycle fatigue regime is based on two assumptions: the failure happens in the linear elastic regime; the failure has a brittle nature. For the fatigue assessment the method considers the cyclic averaged SED, $\Delta\overline{W}$, in a control volume that has a characteristic length that has to be regarded as a material property but that is different from that used for assessing the fracture in static condition. In particular, dealing with the fatigue assessment of steel welded joints in the as-welded conditions realized through conventional welding technique, the control volume characteristic length is equal to 0.28 mm while the fatigue assessment is based on the fatigue design curve, reported in Figure 3, determined from different sets of experimental fatigue data with different loading conditions and geometry (Berto and Lazzarin, 2009).

In order to establish the fatigue strength through the SED method, under the hypothesis of linear elastic behaviour, the mean-SED value, $\Delta\overline{W}_i$, determined at the weld toe or root for a remote tensile stress, $\Delta\sigma_i$, through a static FE simulation is used together with the mean-SED based fatigue strength of the component, $\Delta\overline{W}_L$ (0.058 Nmm/mm3 with a probability of survival of PS= 97.7%), to determine the remote tensile stress $\Delta\sigma_L$ that represents the fatigue limit of the component:

$$\Delta\sigma_L = \Delta\sigma_i \left(\frac{\Delta\overline{W}_L}{\Delta\overline{W}_i} \right)^{\frac{1}{2}} \tag{3}$$

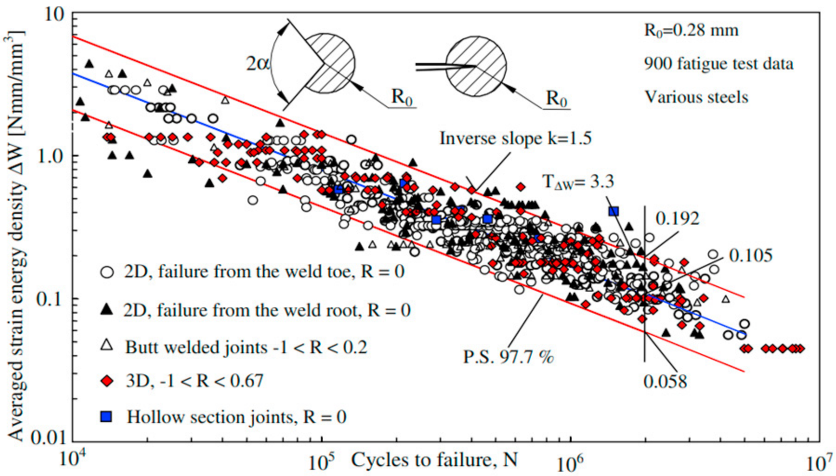


Figure 3: SED based fatigue scatter band for steel welded joints in as welded conditions.(Berto and Lazzarin, 2009)

3. Finite Element Analysis

The application of the SED method requires a finite element (FE) model that has been created through the software Ansys APDL in order to perform parametric analysis for the purpose of the present work. The model, shown in Figure 4, involves some simplifications in determining the welding bead shape that are however consistent with measurements performed on real weldments realized through conventional welding techniques. The welding bead is indeed modelled as a sharp V-notch-considering that real toe radii range from 0.2 mm to 0.8 mm-with an opening angle of 2α= 135° -typical for a welding bead.

The symmetry of the component analysed allowed to model only a quarter of the geometry of the detail analysed optimizing the computational time required for the simulation. A PLANE183 element has been used under plane strain condition.

The SED approach also requires the presence in the FE model of the control volume that, in the case the weld root and toe, has the shape of a sector-shaped cylinder with a radius of 0.28 mm [ref] dealing with weldments realized by conventional techniques. According to the SED method the model of the welding has been created as a homogeneous material having the mechanical properties of the base material (E= 206 GPa, ν= 0.3).

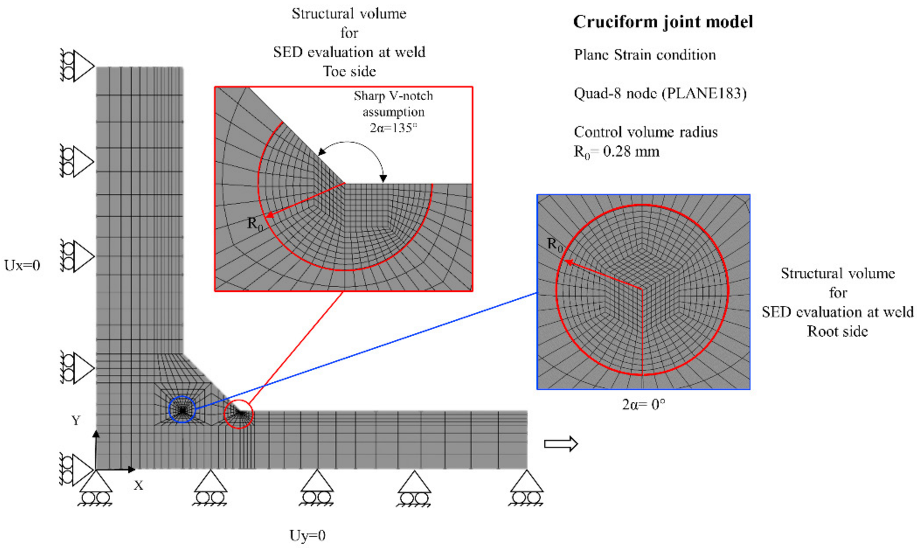
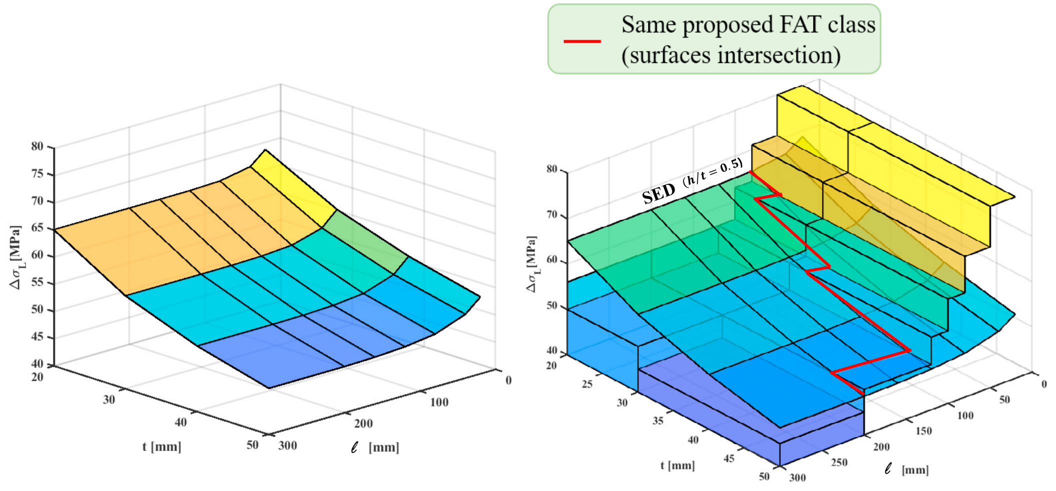


Figure 4: Finite Element Model of the cruciform joint. Symmetry conditions and control volumes at root and toe side were modelled.

4. Results

Through the parametric FE model, it was possible to investigate the effect of the main geometrical parameters of the joint according to the Eurocode 3, l and t in Figure 1a, on its fatigue strength employing as failure criterion the one established by the SED method ($\Delta\overline{W}_L$ = 0.058 Nmm/mm^3 with a probability of survival of PS= 97.7%) and obtaining the results expressed in terms of nominal stress through Eq. (3). The outcomes of this investigation, reported in Figure 5 for the full penetration condition, highlights the lower effect of the intermediate plate thickness, l, on the fatigue strength of the component in comparison with the effect expected by the standard. The attached plate thickness, on the other hand, shows a great influence on the FAT class of the component. An overall comparison between the FAT classes established by the Eurocode 3 and the ones predicted through the SED method shows huge discrepancies with the standard overestimating the fatigue strength of the component at low values of the intermediate plate thickness and underestimating it with increasing this last parameter. Similar conclusions can be achieved studying the joint in its incomplete penetration and partial penetration conditions ($0 < 2a/t \leq 1$).

As already explained in section 2.1, the lack of penetration results for the standard in a double assessment both at the weld toe and the weld root through different FAT classes with changing the point considered. The SED method,



a) b)

Figure 5: a) FAT classes by SED method; b) Comparison between FAT classes, SED vs. Eurocode 3

on the other hand, assess the fatigue strength of both weld root and toe through a unique fatigue curve (see Figure 3), allowing for a direct comparison between them to establish which is the most critical point in the component. This feature of the SED method together with the low computational resources required allowed to perform a numerical investigation in order to find those geometrical conditions that lead to an equiprobability of failure from the weld root and weld toe. As it is possible to see from the schematization provided in Figure 6a, low values of the lack of penetration, i.e. the parameter $2a/t$, result in more critical value at the weld toe, a condition to be preferred for inspection purposes. The outcomes of this investigation are reported in Figure 6b-c. Geometrical conditions that fall above the surface will have failure from the weld toe.

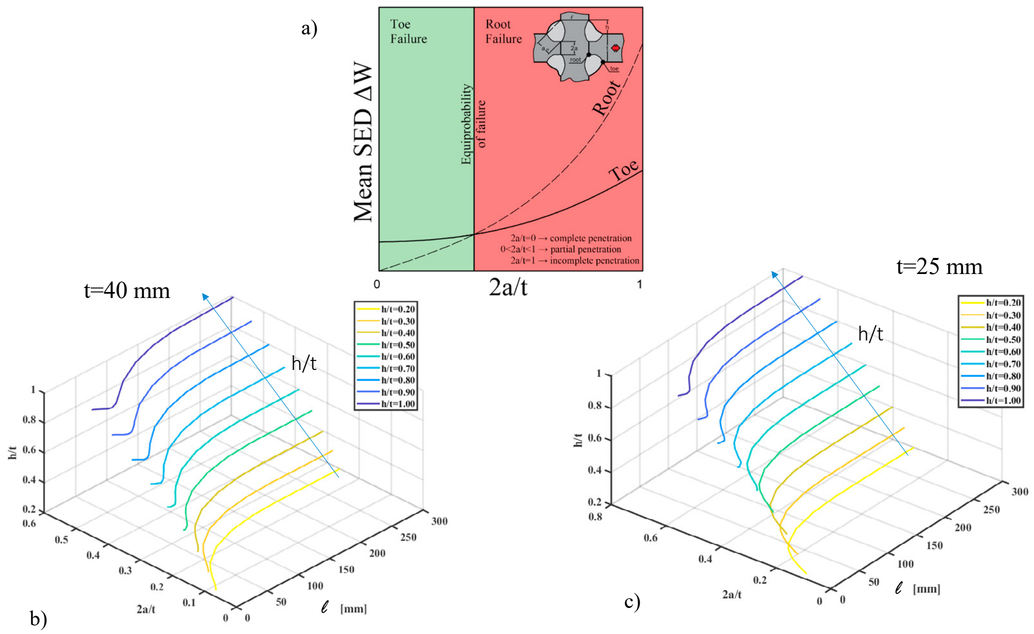


Figure 6: a) Equiprobability of failure toe vs. root; b) Effect of lack of penetration for t= 40mm; c) Effect of lack of penetration for t= 25mm.

5. Conclusions

The present work provides a comparison between the fatigue assessment of a common welded detail through both a global approach, recommended by the Eurocode 3, and a local approach, the SED method. The main geometrical parameters describing the joint according to the standard and the lack of penetration condition have been considered in deriving the outcomes of the present work. A parametric FE model allowed the application of the SED method making also possible to assess the effect of the different geometrical parameters on the fatigue strength of the component. The main conclusions are as follow:

- The establishment of the FAT classes for ranges of geometrical parameters, as considered by the Eurocode 3, is not suitable to describe the fatigue strength of a welded detail resulting in a fatigue assessment quite approximative.
- The investigation of the effect of the cruciform joint main geometrical parameters on fatigue life performed through the SED method shows how the intermediate plate thickness has a lower effect than the one expected by the standard.
- Parametric investigations requiring low computational efforts are possible through the SED method. In the case considered in the present work, i.e., the lack of penetration in the joint, the outcome of this kind of study resulted in the establishment of surfaces that differentiate geometrical conditions that lead to failure from the weld toe from geometrical conditions that leads to failure from the weld root.

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