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Fatigue assessment of steel rollers using an energy based criterion

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Abstract

Weldments geometry with failures occurring at the weld toe or at the weld root cannot, by its nature, be precisely defined. Parameters such as bead shape and toe or root radius vary from joint to joint even in well-controlled manufacturing operations. The worst case configuration can be achieved by modelling as a sharp, zero radius, notch both the toe and the weld root. The intensity of asymptotic stress distributions obeying Williams' solution are quantified by means of the Notch Stress Intensity Factors (NSIFs). For steel welded joints with failures originated from the weld roots, where the lack of penetration zone is treated as a crack-like notch, units for NSIFs are the same as conventional SIF used in LEFM. The different dimensionality of NSIFs for different notch opening angles does not allow a direct comparison of failures occurring at the weld toe or at the weld root. In order to overcome the problem related to the variability of the V-notch opening angle, a simple scalar quantity, i.e. the value of the strain energy density averaged in the structural volume surrounding the notch tip, has been introduced. This energy is given in closed form on the basis of the relevant NSIFs for modes I, II and III. The radius R_C of the averaging zone is carefully identified with reference to conventional arc welding processes being equal to 0.28 mm for welded joints made of steel.

The local-energy based criterion is applied here to steel welded rollers produced by Rulmeca subjected to prevailing mode I (with failures at the weld root). The aim of the paper is firstly to describe the employed methodology for the fatigue assessment and secondly to show the first synthesis of fatigue data by means of local SED for a specific geometry.

Keywords: Welded Joints; Fatigue Strength; Notch Stress Intensity factor; Strain Energy Density; Elasticity.

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1. Introduction

Weld bead geometry cannot be precisely defined mainly because parameters such as bead shape, toe or root radius and length of lack of penetration vary from joint to joint even in well-controlled manufacturing operations (Radaj 1990, Taylor et al. 2002). It is, in fact well known that, the weld toe radius decreases with the local heat concentration of the welding process, i.e. it is extremely small for automated high-power processes, especially for laser beam welding. Since also conventional arc welding techniques result in small values of toe radius (Yakubovskii and Valteris 1989), in the Notch Stress Intensity Factor (NSIF) approach the weld toe region is modelled as a sharp notch and local stresses are given on the basis of the relevant mode I and mode II NSIFs (Yakubovskii and Valteris 1989, Dunn et al. 1997). When the opening angle at the weld toe is large enough to result in a non-singular contribution for stress components due to the mode II, the fatigue behaviour can be correlated only to mode I NSIF (Dunn et al. 1997). A comparison among different steel welded joints can be performed on the basis of the relevant theoretical stress concentration factors, after having imposed a fictitious notch radius ρ_f=1.0 mm. This value is valid only if the real radius at the weld toes and roots is thought of as zero (Lazzarin and Tovo 1998). Fatigue failure is generally characterized by the nucleation and growth of cracks (Ayatollahi et al. 2014a; Ayatollahi et al. 2014b; Ayatollahi et al. 2015; Ayatollahi et al. 2017; Razavi et al. 2017). As widely discussed in the previous literature, the differentiation of two stages is "qualitatively distinguishable but quantitatively ambiguous" (Jiang and Feng 2004). In this context NSIFs were found capable of predicting not only the part of life spent in crack nucleation but also the total fatigue life (Berto and Lazzarin 2014, Ferro 2014, Radaj 2014, Radaj 2015). This happens when a large amount of life is consumed at short crack depth, within the zone governed by the notch singularity at the weld toe or root. Different set of experimental data proved this behaviour. Dealing with transverse non-load-carrying fillet welded joints Lassen (1990) demonstrated that for various welding procedures, up to 40 percent of fatigue life was spent to nucleate a crack having a length of just 0.1 mm. Singh et al. (2003a, 2003b) showed by testing load-carrying fillet joints in AISI 304L that the number of cycles required for the crack to grow by 0.5 mm in excess of the original lack of penetration reached 70 percent of the total life.

From a theoretical point of view the NSIF-based approach cannot be applied to joints characterized by weld flank angles very different from 135 degrees or for comparing failures at the weld root (2α =0°) or weld toe (2α =135°). That is simply because units for mode I NSIF are MPa(m)$^{\beta}$, where the exponent β depends on the V-notch angle, according to the expression β = 1- λ_1, λ_1 being Williams' eigenvalue (Williams 1952). This problem has been overcome in some recent papers by using the mean value of the strain energy density range (SER) present in a control volume of radius R_C surrounding the weld toe or the weld root. SER was given in closed form as a function of the relevant NSIFs, whereas R_C was thought of as dependent on welded material properties. The approach, reminiscent of Neuber "elementary volume" concept, was later applied to welded joints under multiaxial load conditions (Lazzarin et al. 2004). The simple volume is not so different from that already drawn by Sheppard (1991) while proposing a volume criterion based on local stresses to predict fatigue limits of notched components. Some analogies exist also with the highly stressed volume (the region where 90% of the maximum notch stress is exceeded) proposed by Sonsino dealing with high cycle strength of welded joints (Sonsino 1995).

The same based on energy approach has been employed here for the fatigue assessment of steel rollers made by Rulmeca with failure occurring at the weld root. The rollers considered in the present investigation belong to the category PSV which is particularly suited to conveyors that operate in very difficult conditions, where working loads are high, and large lump size material is conveyed; and yet, despite these characteristics, they require minimal maintenance. The bearing housings of the PSV series are welded to the tube body using autocentralising automatic welding machines utilizing a continuous wire feed.

From the point of view of the fatigue behavior under load, the weakest point of the entire structure is the lack of penetration of the weld root. Therefore, if the roller is loaded well above its declared nominal admitted load (Rulmeca Bulk Catalogue 2014) it would experience fatigue failure starting at the level of the weld root.

The aims of the present work are:

- to describe the procedure for modelling the roller by using the finite element method combined with three-dimensional analyses (the procedure is described in more detail in (Berto et al. 2016));
- to describe the sensitivity of the model to the length of the lack of penetration;
- to show the procedure for evaluating the SED in a control volume surrounding the crack tip in a real