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A parametric study on creep-fatigue endurance of welded joints

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This work is devoted to parametric study on creep-fatigue endurance of the steel AISI type 316N(L) weldments defined as type 3 according to R5 Vol. 2/3 procedure at 550°C. The study is implemented using a novel direct method known as the Linear Matching Method (LMM) and based upon the creep-fatigue evaluation procedure considering time fraction rule for creep-damage assessment. Seven geometrical configurations of the weldment, which are characterised by individual values of a geometrical parameter ρ, are proposed. Parameter ρ, which represents different grades of TIG dressing, is a ratio between the radius of the fillet of the remelted metal on a weld toe and the thickness of welded plates. For each configuration, the total number of cycles to failure $N^\star$ in creep-fatigue conditions is assessed numerically for different loading cases including normalised bending moment $\tilde{M}$ and dwell period Δt. The obtained set of $N^\star$ is extrapolated by the analytic function dependent on $\tilde{M}$, Δt and ρ. Proposed function for $N^\star$ shows good agreement with numerical results obtained by the LMM. It is used for the identification of Fatigue Strength Reduction Factors (FSRFs) effected by creep and dependent on Δt and ρ.

This paper presents a further extension of a recently developed approach [1], which is based upon a creep-fatigue evaluation procedure considering time fraction rule for creep-damage assessment and a recent revision of the Linear Matching Method (LMM) to perform a cyclic creep assessment [2]. The applicability of this approach was verified in [1] by the comparison of FEA/LMM predictions for an AISI type 316N(L) steel cruciform weldment at 550°C with experiments by Bretherton et al. [3, 4] with the overall objective of identifying fatigue strength reduction factors (FSRF) of austenitic weldments for further design applications. Apart from the influence of loading conditions (normalised bending moment $\tilde{M}$ and dwell period Δt) investigated in [1], the influence of a weld profile geometry on creep-fatigue strength has to be analysed within a parametric study. The introduction of geometrical parameters into the function $N^\star(\tilde{M}, \Delta t)$ allows the calculation of the FSRF as a continuous function able to cover a variety of weld profile geometries in dressed, as-welded and intermediate configurations.

In the present study, the geometry of the weld profile for type 3 weldments is specified in R5 Vol. 2/3 procedure [5] as shown in Fig. 1. The parametric model is developed based upon the regulations from British Standards [6,7] for the weldment, which contains a root gap between the parts to be joined. The type 3 weldment specimen contains 2 symmetric double-sided T-butt cruciform mitre-fillet welds. The parent material for all specimens are continuous plates of width $w = 200$ mm and thickness $thk = 26$ mm made of the steel type AISI 316N(L) at 550°C welded with $haz = 3$ mm according to experiments [3,4].

The fatigue performance of the as-welled type 3 weld profile is quite poor due to significant stress concentration in the weld toe caused by inconsistency of weld profile in 45°. Moreover, the gap between the welded parts decreases the effective cross-section limiting it to the only area of weld metal. For the purpose of the fatigue life improvement, different post weld treatment techniques are applied to the weld toe, as a potential location of failure. TIG dressing was found in [8] to be the best suited post weld treatment compared to burr grinding and ultrasonic impact treatment. In order to characterise different scales of TIG dressing and to reduce the computational costs, only 7 configurations of weld profile were chosen for parametric study. They are characterised by the ratio between the weld toe fillet radius and the plate thickness: $\rho = R_3 \,/\, thk$, having the values: 2.0, 1.5, 1.0, 0.5, 0.2, 0.1 and $\rho \to 0$ for the as-welled configuration. The 2D weldment FE-model is based upon the plane strain condition and uses ABAQUS element type CPE8R: 8-node biquadratic quadrilaterals with reduced integration.

The creep-fatigue strength of the 7 configurations with different ρ values are evaluated in a wide range of loading conditions. They are presented by different combinations of $\Delta\varepsilon_{\mathrm{tot}}$ in the parent plate outer fibre, as a characteristic of fatigue effects, and duration Δt of dwell period, as a characteristic of creep effects. For each configuration, 45 creep-fatigue evaluations must be performed with different values of $\Delta\varepsilon_{\mathrm{tot}}$ (5 values as in the experimental studies [3,4]) and Δt (9 values as in the previous simulation study [1]). Since the LMM requires lower computational effort compared to other methods, it appears to be an effective tool for express analysis of a large number of different loading cases. In order to perform 315 FE-simulations in CAE-system ABAQUS using the LMM method and retrieve corresponding values of $N^\star$, 3 analysis automation techniques have been applied to improve the efficiency in parametric studies of types 1 and 2 weldments [9].

For each of the configurations, the array of assessment results consisting of $N^\star$ values corresponding to particular values of $\tilde{M}$ and Δt is fitted using the least squares method by the following function proposed in the form of power-law in [1]:

$$\log\left(N^\star\right) = \frac{\tilde{M}^{-b(\Delta t)}}{a\left(\Delta t\right)}, \quad \text{with} \quad \left\{ \begin{array}{l} a\left(\Delta t\right) = a_3 \log\left(\Delta t + 1\right)^3 + a_2 \log\left(\Delta t + 1\right)^2 + a_1 \log\left(\Delta t + 1\right) + a_0 \\ b\left(\Delta t\right) = b_3 \log\left(\Delta t + 1\right)^3 + b_2 \log\left(\Delta t + 1\right)^2 + b_1 \log\left(\Delta t + 1\right) + b_0, \end{array} \right. \tag{1}$$

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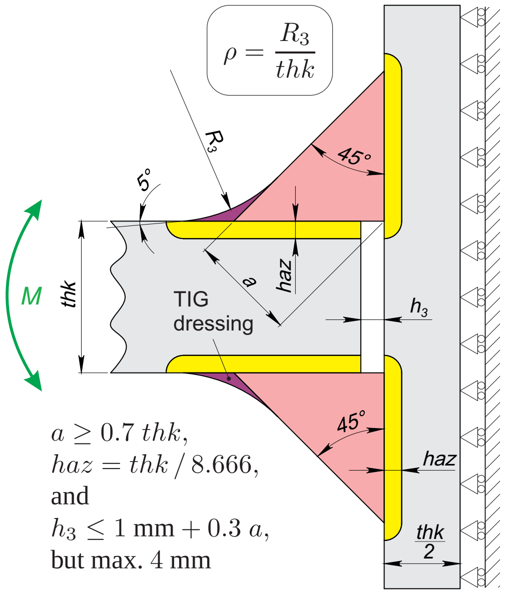

Fig. 1: Dimensions of type 3 weldment profile [6,7].

Conf.	1	2	3	4	5	6	7
FSRF	1.302	1.425	1.595	1.872	2.362	3.252	3.459

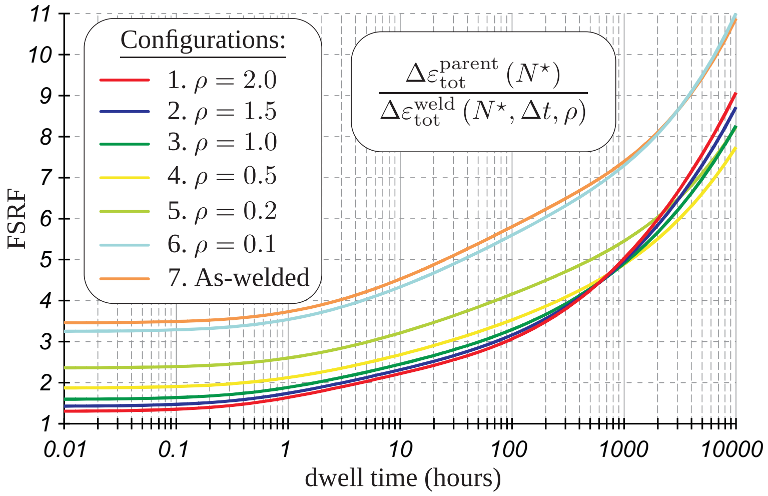

Fig. 2: FSRFs: constant for pure fatigue, and dependent on dwell period Δt for different configurations of type 3 weldments obtained with TIG dressing.

where the fitting parameters (a_0 - a_3, b_0 - b_3) have individual values for each configuration. In order to capture all configurations with an unified set of fitting parameters, they are defined as dependent on ρ using the least squares method:

$$\begin{aligned} a_0^{\rm T3}(\rho) &= -4.506\cdot 10^{-2}\ \ln(\rho+1) + 0.285, & b_0^{\rm T3}(\rho) &= 0.118\ \ln(\rho+1) + 0.57,\\ a_1^{\rm T3}(\rho) &= 4.1\cdot 10^{-2}\ \ln(\rho+1) + 4.701\cdot 10^{-2}, & b_1^{\rm T3}(\rho) &= 8.742\cdot 10^{-2}\ \ln(\rho+1) + 0.195,\\ a_2^{\rm T3}(\rho) &= -3.202\cdot 10^{-2}\ \ln(\rho+1) - 7.575\cdot 10^{-3}, & b_2^{\rm T3}(\rho) &= -7.197\cdot 10^{-2}\ \ln(\rho+1) - 0.152,\\ a_3^{\rm T3}(\rho) &= 8.74\cdot 10^{-3}\ \ln(\rho+1) + 2.10773\cdot 10^{-3}, & b_3^{\rm T3}(\rho) &= 1.397\cdot 10^{-2}\ \ln(\rho+1) + 4.034\cdot 10^{-2}. \end{aligned} \tag{2}$$

The current approach in R5 Volume 2/3 Procedure [5] operates with the fixed values of FSRF for 3 different types of weldments accounting for dressed and as-welded variants, which consider only the reduction of fatigue strength of weldments compared to the parent material. Therefore, the approach [1], which additionally accounts for the influence of creep, is applied to obtain Δt-dependent FSRFs for a variety of configurations defined by ρ. For this purpose Eq. (1) is converted analytically to the relation $\tilde{M}(N^\star, \Delta t)$ and inserted into the group of relations $\Delta\varepsilon_{\rm tot}(\tilde{M})$ as explained in [9], resulting in the relation $\Delta\varepsilon_{\rm tot}(N^\star, \Delta t, \rho)$ for weldments S–N diagrams, which is used for the estimation of FSRFs:

$$\text{FSRF} = \Delta\varepsilon_{\rm tot}^{\rm par}(N^\star)\,/\,\Delta\varepsilon_{\rm tot}(N^\star, \Delta t, \rho) \quad \text{with} \quad \log\left(\Delta\varepsilon_{\rm tot}^{\rm par}\right) = p_0 + p_1\ \log\left(N^*\right) + p_2\ \log\left(N^*\right)^2, \tag{3}$$

where the coefficients of the parent material S–N diagram [10] are: $p_0 = 2.2274$, $p_1 = -0.94691$ and $p_2 = 0.085943$.

The FSRF for type 3 dressed weldments shown in Fig. 2 is within the range 1.302–1.425, for welded joints with moderate TIG dressing it is within the range 1.425–2.362 depending on the amount of TIG dressing, while R5 also doesn't give any value for these cases. The FSRF for as-welded joints without any additional treatment may reach up to 3.252–3.459, while R5 gives the value 3.2, which corresponds to lower bound for the range. It should be noted that the value of FSRF for type 3 recommended by R5 procedure may be significantly conservative, if some kind of TIG dressing is applied.

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References

[1] Y. Gorash and H. Chen, Int. J. of Pressure Vessels & Piping **104**, 1–13 (2013).
[2] H. F. Chen, W. Chen, and J. Ure, in: Proc. ASME PVP Conf., , No. PVP2012-78065 (ASME, Toronto, Canada, 2012), July 15-19.
[3] I. Bretherton and P. Budden, in: Trans. 15th Int. Conf. SMiRT, , No. SMiRT15–F05/2 (IASMiRT, Seoul, Korea, 1999), pp. 185–192.
[4] I. Bretherton et al., Report for British Energy no. RJCB/RD01186/R01, Serco Assurance, Warrington, UK, 2004.
[5] R5: An Assessment Procedure for the High Temperature Response of Structures, Issue 3 (British Energy, Gloucester, UK, 2003).
[6] British Standard, No. EN 1708-1:2010 (The British Standards Institution, London, UK, 2010).
[7] British Standard, No. EN ISO 5817:2007 (The British Standards Institution, London, UK, 2007).
[8] M. M. Pedersen et al., Welding in the World **54**(7-8), R208–R217 (2010).
[9] Y. Gorash and H. Chen, Int. J. of Fatigue **55**, 112–125 (2013).
[10] S. K. Bate et al., Report for British Energy no. SA/EIG/11890/R002, Serco Assurance, Warrington, UK, 2005.