DEFECT ASSESSMENT PROCEDURE FOR STRENGTH MISMATCHED STRUCTURES - SINTAP

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One of the main objectives of the Brite-Euram project SINTAP (Structural Integrity Assessment Procedures for European Industry) is to provide the most appropriate defect assessment method specific to defective welded structures with significant strength mismatch. A key step to the SINTAP procedure for mismatch is to investigate whether existing assessment procedures can produce similar results regardless of how they are interpreted. Such compatibility is the main issue of this paper.

A worked example shows that not only do two existing procedures, the ETM-MM and the modified R6 methods, produce very close results but also both estimation schemes are in excellent agreement with the FE results. Finally the evolving SINTAP procedure for mismatch is briefly discussed.

INTRODUCTION

Within the Brite-Euram project SINTAP (Structural Integrity Assessment Procedures for European Industry), Task 1 deals with strength mismatch effects on the defect assessment procedure, aiming for two objectives; firstly, to quantify the strength mismatch effect on mechanical and fracture behaviour of welded joints, and secondly and more importantly, to provide the most appropriate defect assessment method of quantifying the behaviour of such joints. Currently defect assessment procedures specific to strength mismatched structures are limited (see for instance [1-4]). Among these, two most complete procedures have been considered within the SINTAP project; the Engineering Treatment Model for Mis-Match (ETM-MM) [1] and the modified R6 method [2]. The SINTAP procedure is to contain the advantages of both methods. Thus it requires compatibility between both methods in the sense that both methods should provide close results. This demonstration is the objective of this paper.

Firstly the ETM-MM and the R6 methods are briefly reviewed. Then compatibility is discussed and illustrated by means of a worked example. Finally, the evolving SINTAP procedure is briefly given.

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ENGINEERING TREATMENT MODEL FOR MISMATCH (ETM-MM)

The ETM method [5] using the crack driving force (CDF) diagram has been extended to incorporate the strength mismatch effect in ETM-MM. Although the currently available ETM-MM method [1] only provides a CTOD route in terms of δ_5, a J route has also been recently developed, which will be shown in the following.

To use the ETM-MM method, the plastic portion of the stress-strain curves for each constituent should be represented by a power law, such that

$$\begin{cases} \sigma/\sigma_{YW} = (\varepsilon/\Delta\varepsilon_W)^{N_W} & \text{for the weld material} \\ \sigma/\sigma_{YB} = (\varepsilon/\Delta\varepsilon_B)^{N_B} & \text{for the base material,} \end{cases} \quad \textbf{(1)}$$

where N is a constant (the hardening coefficient), σ_Y is either the 0.2% proof stress or the lower yield stress. In eqn. (1), $\Delta\varepsilon$ is set equal to $R_{p0.2}/E+0.002$ for continuous hardening materials, and to the extent of the Lüders strain for materials exhibiting a Lüders plateau. The subscripts B and W refer to the base and weld metal respectively. The ETM-MM equations take different forms, depending on the type of the stress strain curves of the base and weld metals. For the sake of space, the equations are given below only for the case where both base and weld metals do not exhibit Lüders plateau. For contained yielding (load $F<F_{YM}$, the *mismatch yield load* of the cracked structure of interest),

$$J = J_e \cdot \frac{\left[1 + 1/2\left(F/F_{YM}\right)^2\right]}{\left[0.3 + 0.7\exp\left\{-2N_M\left(F/F_{YM}\right)^6\right\}\right]} \quad \textbf{(2)}$$

where the elastically calculated value of J is $J_e=K^2/E'$ where K is the elastic stress intensity factor and E' is the elastic modulus. The hardening coefficient of the mismatched structures, N_M, is calculated from

$$N_M = \frac{(M-1)}{\left(F_{YM}/F_{YB}-1\right)/N_W + \left(M - F_{YM}/F_{YB}\right)/N_B} \quad \textbf{(3)}$$

where $M=\sigma_{YW}/\sigma_{YB}$. For the fully plastic region ($F \geq F_{YM}$),

$$J = J_Y \cdot \left[\frac{F}{F_{YM}}\right]^{(1+N_M)/N_M} \quad \textbf{(4)}$$

where J_Y denotes the value of J at $F=F_{YM}$ from eqn. (2).

Although not shown here, for other cases such as when both base and weld metals do exhibit Lüders plateau, equations are similar with minor differences to incorporate the effect of the Lüders strain on J.

MODIFIED R6 PROCEDURE

Within Nuclear Electric, the R6 method using a failure assessment diagram (FAD) has been extended to incorporate the strength mismatch effect [2], with two major modifications: the mismatch yield load and the equivalent material concept. For instance, the R6 option 2 curve modified for mismatched structures becomes

$$K_r = \left(\frac{E\varepsilon_e}{L_r\sigma_{Ye}} + \frac{L_r^3\sigma_{Ye}}{2E\varepsilon_e} \right)^{-1/2} \; ; \; K_r = K/K_{mat} \; ; \; L_r = F/F_{YM} \qquad \textbf{(5)}$$

where K_{mat} is the fracture toughness of the material. In eqn. (5), ε_e is the true strain obtained from the uniaxial stress-strain curve for the *equivalent* material at a true stress $L_r\sigma_{Ye}$. The stress-strain curve for the equivalent material is given by

$$\sigma_{ref}^{(e)}(\varepsilon^p) = \frac{(F_{YM}/F_{YB}-1)\cdot\sigma_W(\varepsilon^p) + (M - F_{YM}/F_{YB})\cdot\sigma_B(\varepsilon^p)}{(M-1)} \qquad \textbf{(6)}$$

Note that (F_{YM}/F_{YB}) in eqn. (6) is defined for $M=M(\varepsilon^p)=\sigma_W(\varepsilon^p)/\sigma_B(\varepsilon^p)$ at a number of plastic strain values ε^p. The equivalent yield stress σ_{Ye}, the flow stress $\overline{\sigma}_e$, and the cut-off L_r^{max} are defined as

$$\sigma_{Ye} = [F_{YM}/F_{YB}]\cdot\sigma_{YB} \; ; \; \overline{\sigma}_e = \left[F_{YM}(\overline{\varepsilon}^p)/F_{YB}\right]\cdot\sigma_B(\overline{\varepsilon}^p) \; ; \; L_r^{\max} = \overline{\sigma}_e/\sigma_{Ye} \qquad \textbf{(7)}$$

MISMATCH YIELD LOAD AND COMPATIBILITY

As shown in the previous sections, both the ETM-MM and the R6 equations share one common input, the mismatch yield load F_{YM}. It has been shown that F_{YM} is the most crucial parameter for the defect assessment of welded joints. Within the SINTAP project, an extensive series of mismatch yield load solutions have been generated for plates as well as for specific cylindrical geometries [1,2]. Those solutions together with extensive stress intensity factor solutions have been collated to form a common library. An example of the mismatch yield load solutions is shown in Fig. 1 for plane strain centre cracked tensile (CCT) plates, Fig. 2.

Since both the ETM-MM and R6 methods share common inputs, K and F_{YM}, a consistency can be achieved when the FAD and the CDF expressions are related by

$$K_r = \sqrt{J_e/J} \qquad \textbf{(8)}$$

Eqn. (8) thus provides compatibility between CDF and FAD approximations. See [7] for more details of such compatibility.

WORKED EXAMPLES

In this section, the ETM-MM curve, eqns. (2)-(4), and the R6 option 2 curve, eqn. (5), are compared for a number of cases covering a wide range of mismatch ratios. Detailed analyses based on the elastic plastic finite element (FE) method were carried out using a general purpose FE programme, ABAQUS [6]. For the sake of space, the results are presented here only for plane strain centre-cracked tensile (CCT) plates (Fig. 2) with a/W=0.5 and (W-a)/H=3. The particular value of (W-a)/H=3 shows a strong mismatch effect on yield loads, as shown in Fig. 1. In the FE analysis, instead of using generic stress strain data, "real" stress strain data were used for both the base and weld metal to produce "simulated" welds covering a wide range of mismatch ratios. These FE analyses led to the J value as a function of load. The J values are estimated according to the ETM-MM and the R6 methods.

The R6 option 2 curves are compared with the ETM-MM curves for the case where both base and weld metals do not exhibit Lüders plateau in Figs. 3a-3c. Resulting curves are also compared with the detailed FE results which are plotted with the finite element values of J inserted in eqn. (8). The figures include stress strain curves of base and weld materials, together with the mismatch ratio M. Although explicit equations are not given in this paper, worked examples for the case where both base and weld metals do exhibit Lüders plateau are also shown in Figs. 3d-3f. These show that firstly both curves are very close, and moreover show excellent agreement between both curves and the FE results.

SINTAP PROCEDURE FOR MISMATCH

The examples shown in the previous section provide confidence in existing defect assessment procedures for mismatched structures, such as the ETM-MM and the R6 methods. Moreover, compatibility provides a full consistency; results can be interpreted either in terms of a FAD or a CDF. Based on those two methods, the SINTAP procedure for mismatch will be produced with only minor adjustments; different levels of the procedure will be set out by blending the essence of those two methods, to cope with the quality of input information.

Acknowledgements

This paper is a part of an European Brite Euram project SINTAP and hence the authors wish to thank the CEC for their financial support. Contributions from the project partners (AEA Technology, UK; British Steel, UK; The Welding Institute, UK), Prof. K.-H. Schwalbe and Dr. U Zerbst at GKSS are greatly appreciated.

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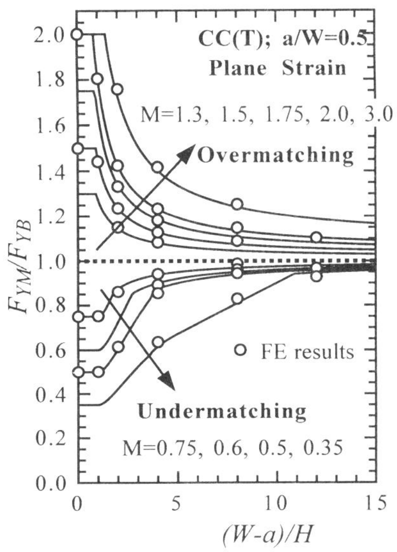

Fig. 1 Mismatch yield load solutions for plane strain CCT plates, Fig. 2.

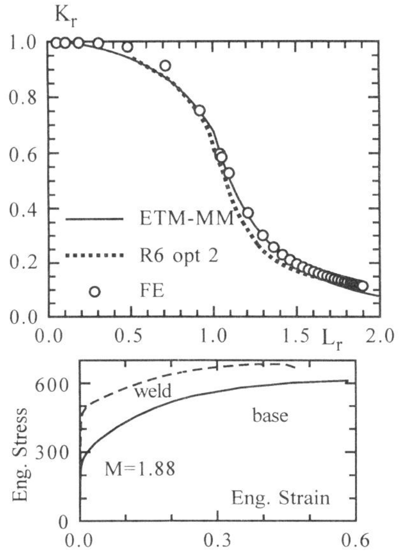

Fig. 3 FE results compared with the R6 and ETM-MM based FAD.

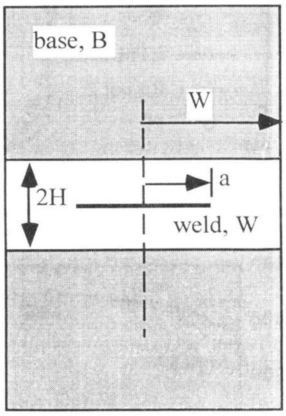

Fig. 2 Definition of geometrical variables in mismatched CCT plates.

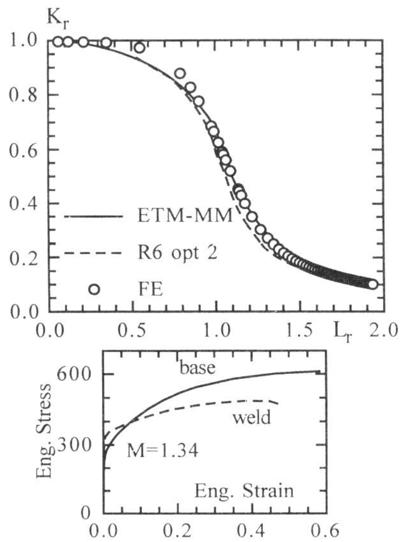

Fig. 3b

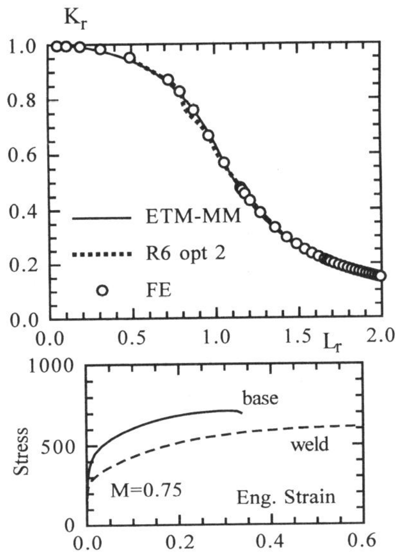

Fig. 3c

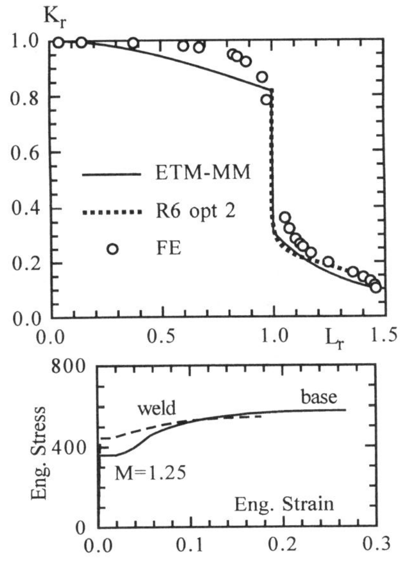

Fig. 3e

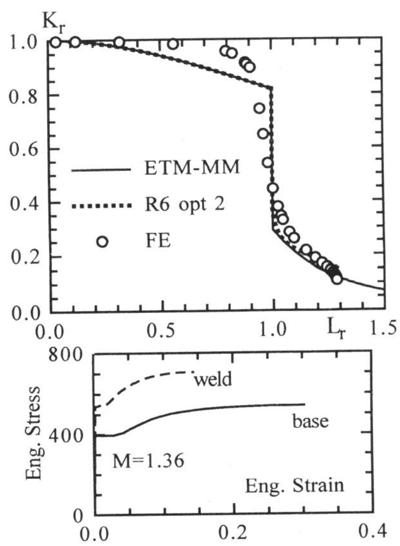

Fig. 3d

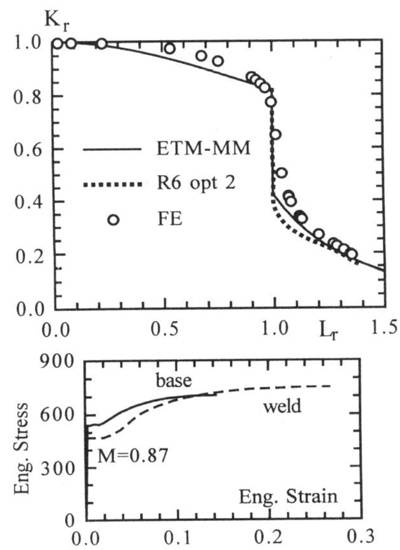

Fig. 3f