Fracture Mechanics Assessment of a Bi-Metallic Welded Joint

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ABSTRACT: *Analysis methods for the fracture mechanics assessment of a surface defect in a bi-metallic weld have been investigated and verified during a three-year European research programme BIMET. Two large-scale 4-point bend tests on a piping assembly containing a ferritic to stainless steel weld with a notch at the interface between the ferritic steel and the buttering layer were carried out. The paper reports on an engineering assement and results of finite element analyses performed at GKSS accounting for the material gradients in the weldment. A CTOD criterion is applied to predict crack initiation and growth. It appears to be better suited for welded structures than J as CTOD is a near-field quantity which does not suffer from problems like path dependence, material gradients etc. CTOD based resistance curves can be easily determined experimentally even for welded structures.*

INTRODUCTION

Ferritic-austenitic welds occur in PWR and BWR design where heavy section low alloy steel components are connected to stainless steel primary piping systems. Analysis methods for the fracture mechanics assessment of a surface defect in a bi-metallic weld have been investigated and verified during a three-year European research programme "Structural Integrity of Bi-Metallic Components" (BIMET). The project was formed around two large-scale 4-point bend tests on a piping assembly containing a ferritic to stainless steel weld. The weld has been notched at the interface between the ferritic steel and the buttering layer. The particular problem with this kind of structure is its material inhomogeneity. The mechanical properties, strength and toughness, vary in a wide range between the various alloys and no verified fracture mechanics asssessment methods exist for such structures. Hence, a range of analysis methodologies, including engineering flaw assessment methods (EAM) and finite element analyses (FEA), have been applied within the project to predict the critical load for crack growth initiation, extent of crack growth and crack path up to maximum load [1].

TABLE 1: Structural Integrity of Bi-Metallic Components
(European Commission, DG XII, Euratome Programme 1994-1998),
overview over subjects and participants

Task Group	Subject	Institute	Country
TG.1	weld procurement	JRC Petten	NL
TG.2	material characterization	VTT	FIN
TG.3	residual stresses	JRC Petten	NL
TG.4	benchmark experiments	EdF	F
TG.5	analysis	GKSS	D
		AEAT	UK
		CEA	F
		TWI	UK
		Framatome	F
TG.6	project evaluation	AEAT	UK
TG.7	project coordination	EdF	F

The present contribution restricts to the contributions of GKSS [2, 3], namely the application of the "Engineering Treatment Model (ETM)" [4, 5] and 3D FEA accounting for the material gradients in the weldment.

TEST SET-UP AND MATERIAL CHARACTERIZATION

Figure 1 shows the complete test assembly. Two segments of thickwalled tubes made of SA 508 and AISI 304 L, respectively, are welded together forming the actual test component. They are provided with two bending arms of St 52 on either side, and the whole structure is subject to 4-point-bending. Due to the different yield strengths of SA 508 and AISI 304 L, the loading had do be applied non-symmetrically in order to approximately realize a constant bending moment in the centre segment under plastic deformation. The appropriate position of the loading traverse was determined by finite element calculations prior to the test.

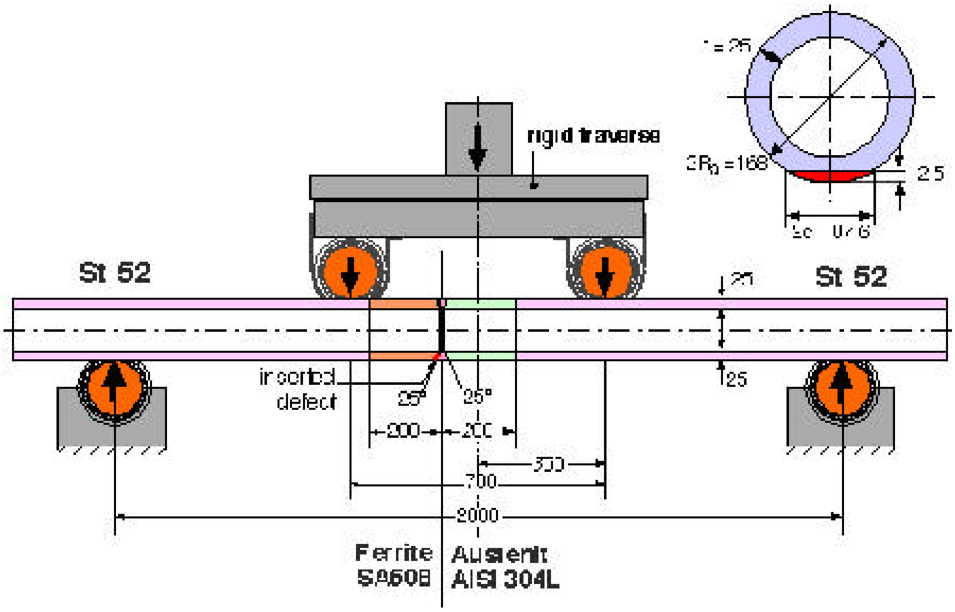

Figure 1: Geometry and dimensions of the total test assembly and pipe cross section with *t*/2 defect

A sharp crack-like notch of 0.2 mm width was inserted by spark erosion close and parallel to the ferritic heat affected zone. Two tests were performed at Electricité de France with two different crack sizes, namely a *t*/2 and a *t*/3 defect, but only the results for the *t*/2 defect will be reported in the present paper. A schematic of the weldment with the varying material properties and the location of the defect is given in Figure 2a.

As the stress-strain curves of the various materials have an important influence on the global deformation behaviour and the local stress and strain fields at the defect, a detailed material characterization was performed within Task Group 2 by VTT [6]. Tensile tests on small round and flat bars in axial (T) and circumferential (L) orientations were used to determine true stress-strain curves, see Figure 2b. The variations in the tensile properties are huge, and any analysis which does not account for these material gradients will not be able to describe the deformation and crack growth behaviour correctly.

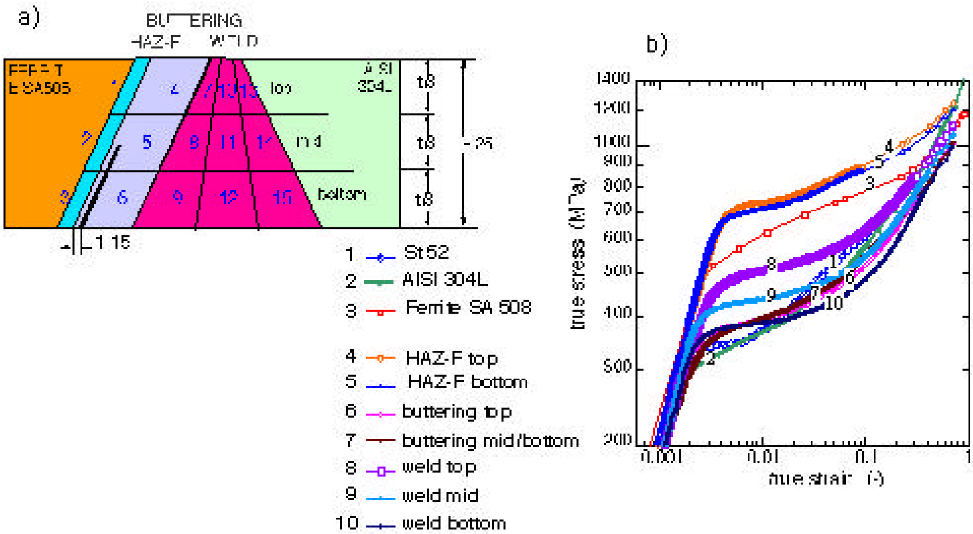

Figure 2: Geometry of the weldment with material gradients (a) and tensile properties (b)

Crack growth resistance curves in terms of *J* integral have also been determined for the various materials [6]. Specimens from the fusion line failed by brittle fracture, but a rather unique R-curve resulted from the buttering layer in L orientation, which is the crack plane. An alternative concept for determing the crack growth resistance bases on the application of crack tip opening displacement (CTOD) as fracture parameter. It can be used for non-homogeneous structures whereas *J* is restricted to homogeneous specimens. A δ_5 R-curve was determined by multiple specimen technique from 4-point bend specimens of 10 × 20 mm cross section which had been machined from the welded pipe [2, 3]. It has been used for a prediction of crack initiation and growth in the pipe.

FRACTURE MECHANICS ANALYSIS

EAM like the ETM [4] base on idealizations of the structure and the material behaviour and provide analytical formula for some fracture parameter like *J* or δ. As the plastic limit load is usually taken as a characteristic quantity in elastic-plastic fracture mechanics (EPFM), the respective concept has to include equations for limit loads. Extensions to strength mis-matched structures have been established [5] but can of course not account for the complexity of material behaviour as shown in Figure 2 so that additional assumptions have to be made. Figure 3 demonstrates that an astonishingly good prediction of the CMOD in dependence on the applied bending moment can be made with a modified ETM accounting for the real stress-strain curve (ETM/σε) instead of an appoximate power law and that the experimentally determined initiation moment of 154 kNm is predicted well (161 kNm) using a d_{5i} value obtained from the 4-point bend specimens. Details of the assessment can be found in [3] and would exceed the available space.

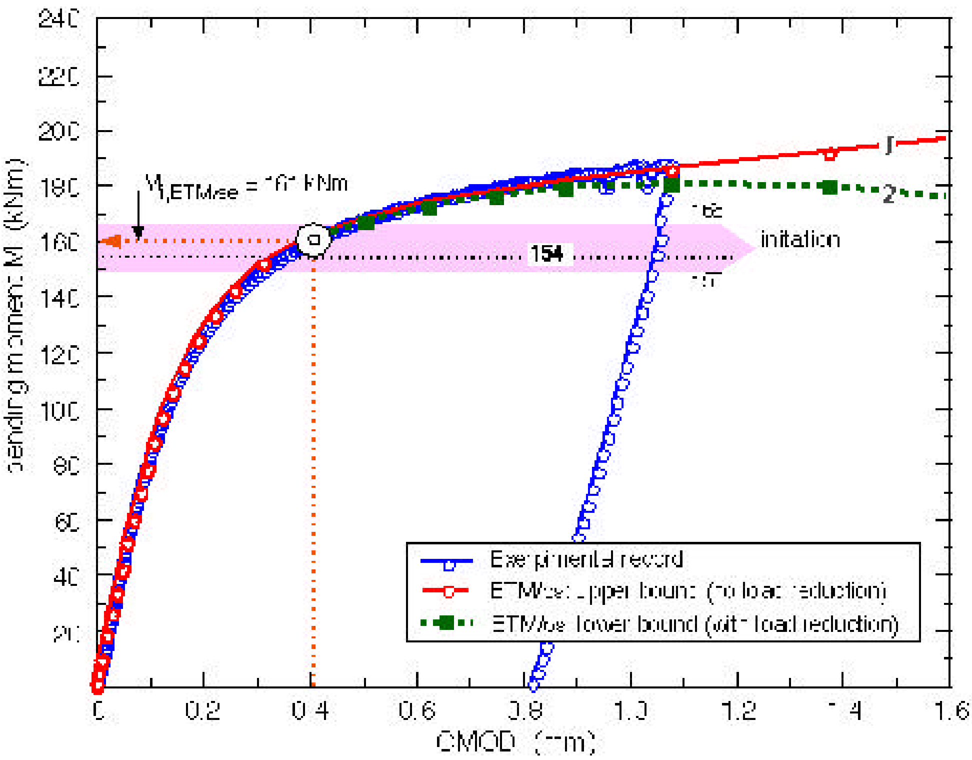

Figure 3: Prediction of the bending moment vs CMOD curve with GKSS ETM/σε, compared with test results; #1: stationary crack (without crack growth), #2: load reduction due to crack growth.

Three-dimensional FEA are much more time consuming and expensive than the application of EAM but give much more detailed informations on the deformations and stresses in the vicinity of the defect. And as soon as a FE model is established, it allows for arbitrary parameter studies which help in understanding the mechanical behaviour of a structure with material gradients. Figure 4 illustrates that the deformation mechanism in the bi-material weld is quite different from that in a homogeneous pipe. As full three-dimensional fields of mechanical quantities are calculated, even the local variation of crack extension along the crack front can be predicted, see Fig 5, based on the d_5 R-curve.

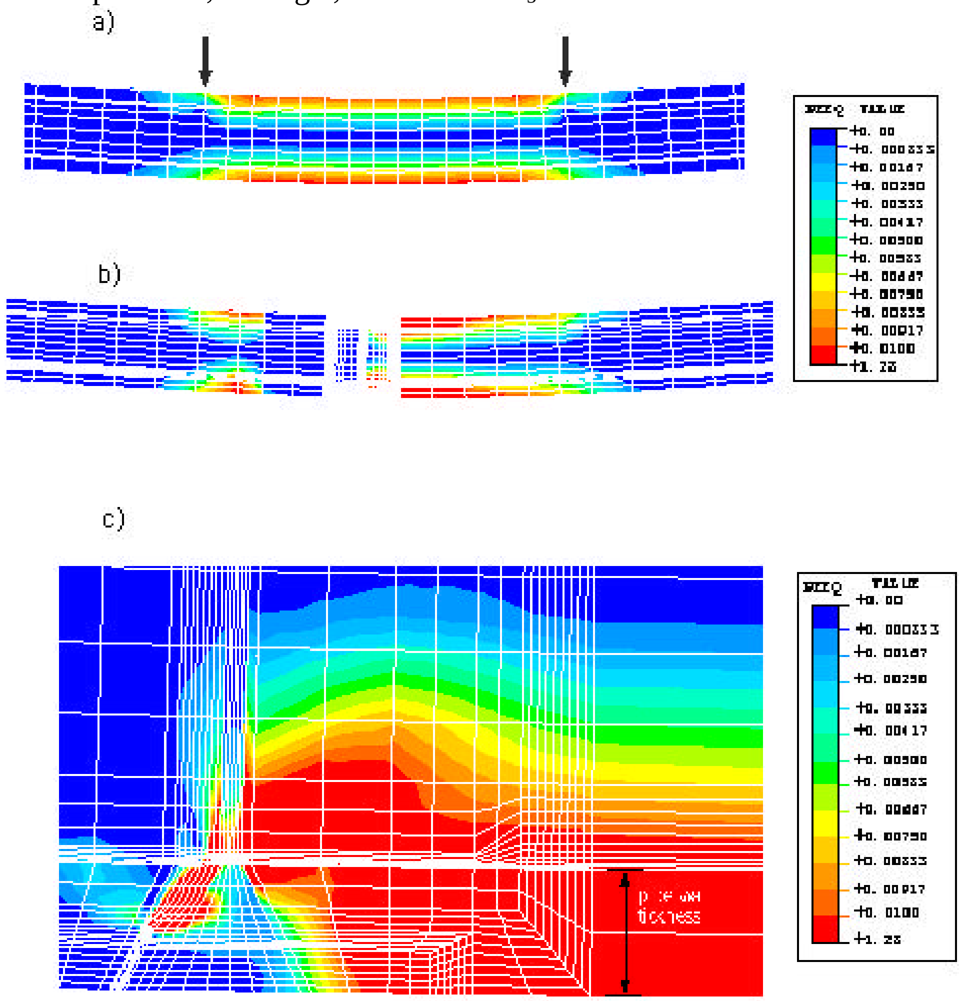

Figure 4: Distribution of equivalent plastic strain from FE analysis, (a) homogeneous pipe (AISI 304 L-L), (b) pipe with bi-material weld, accounting for all material gradients, (c) detail of the weldment for case (b).

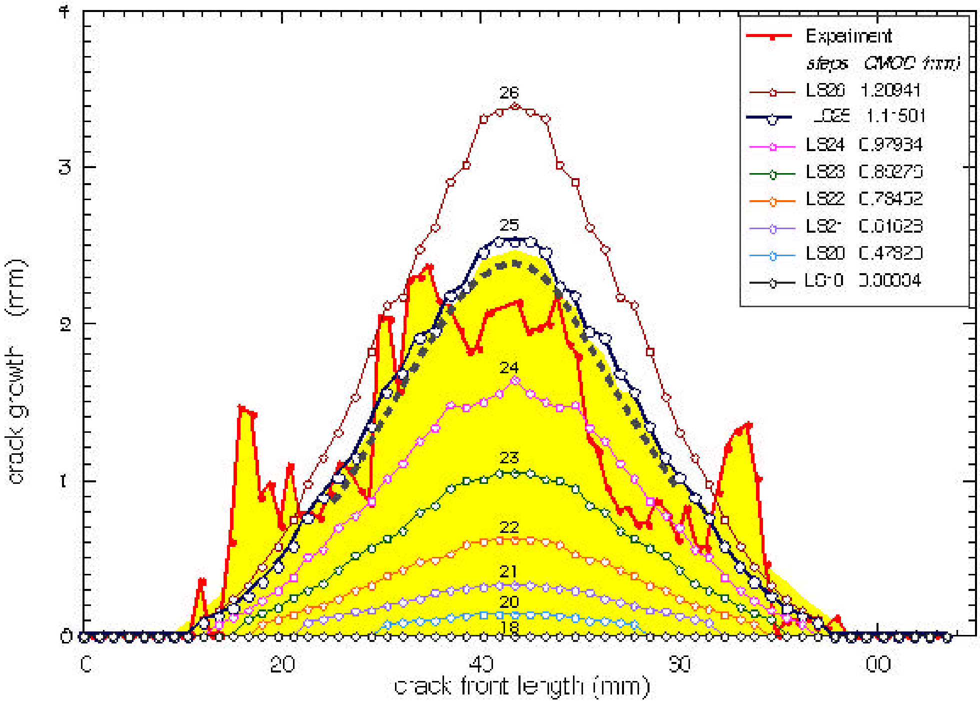

Figure 5: Prediction of crack growth based on FE analysis and d_5 resistance curve compared to test result at final load

SUMMARY AND CONCLUSIONS

- A realistic FE model and reliable predictions of the deformation behaviour require sufficiently exact information and data for geometry and dimensions, material properties and boundary conditions. True stress-strain curves are needed for analyses in the elastic-plastic regime which go beyond the range of uniform elongation in a tensile test. In particular, heterogeneous structures require a detailed material characterization.
- A CTOD criterion has been applied to predict crack initiation and growth. It appears to be better suited for welded structures than *J*, as it is a near-field quantity which does not suffer from problems like path dependence, material gradients etc., and CTOD resistance curves can be easily determined experimentally even for welded structures.
- The analyses have contributed to improving and extending the application of FE simulations as part of integrity assessment of complex structures by

pointing out crucial factors and most sensitive parameters and by showing strategies of systematically handling the meshing.

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