EXPERIENCES WITH SOME EUROPEAN FLAW ASSESSMENT PROCEDURES

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ABSTRACT

In 1999 the European flaw assessment procedure SINTAP (**S**tructural **Int**egrity **A**ssessment **P**rocedure for European Industry) [1] was published as the outcome of a European project. Aspects of the procedure have been discussed in a special issue of Engineering Fracture Mechanics (Vol. 67, 2000, pp. 479-668) and elsewhere, e.g. [2]. At about the same time, there were developments in a number of major flaw assessment procedures worldwide as described in a special issue of International Journal of Pressure Vessels & Piping (Vol. 77, 2000, pp.853-963). Some of these developments were related to the SINTAP project, including the revisions to BS7910 [3] and R6 [4]. In this paper the results of several validation studies of these European procedures are summarised, concentrating on SINTAP and R6 in which the authors have been involved. These studies give an insight into the potential of the procedures in assessing flawed structures and provide some guide to their accuracy and conservatism.

1 THE SINTAP AND R6 PROCEDURES

The SINTAP [1] and R6 [4] procedures are not described in detail here as they have discussed elsewhere [2, 5]. Instead, brief overviews are given, introducing specific issues investigated in the case studies summarised below.

SINTAP follows a hierarchical structure, based on the quality of the available input parameters, in particular the stress-strain data. Higher levels are more complex than lower ones and need improved input information; however, the user is "rewarded" by less conservative results. The most important analysis levels are:

- The **Default Level** requires the yield strength of the material only and allows the fracture resistance to be estimated from Charpy data. A Default Level analysis will usually be highly conservative but enables a fracture mechanics analysis with a minimum of input information.
- The **Basic Level** requires the fracture toughness, the yield strength and the ultimate tensile strength. It offers different sets of equations for materials with and without Lüders plateau.
- The **Mismatch Level** is a modification of the Basic Level for inhomogeneous configurations such as strength-mismatched weldments, but requires data for more than one material.
- The **Standard Level** requires fracture toughness data and the complete stress-strain curve. The results of a Standard Level analysis are conservative, i.e. the critical load and crack size are underestimated. The degree of conservatism should, however, be lower than that of the other analysis levels.

R6 has a similar hierarchy in terms of failure assessment diagrams: Option 1 (needs only yield strength data), Option 2 (needs the complete stress-strain curve) and Option 3 (needs the complete stress-strain curve and results of an inelastic analysis). It also allows the treatment of weld strength mismatch and a range of input toughness data.

Both SINTAP and R6 allow results to be represented in terms of a failure assessment diagram (**FAD)** or a crack driving force (**CDF**). In R6, the FAD route is the main approach. The FAD and CDF routes, however, yield numerically identical results. In the FAD route, a roughly geometry independent failure line is constructed by normalising the crack tip loading by the material's fracture resistance and the load by the limit load. The component assessment is then based on the location of a geometry dependent assessment point relative to a failure line. In the simplest application the component is regarded as safe if the assessment point lies within the area below the failure line. In the CDF philosophy, the determination of the crack driving force in the component and its comparison with the fracture resistance of the material are separate steps. Like the failure line of the FAD, the crack driving force curve can, by suitable normalisation, be made approximately geometry independent, but it is dependent on the material deformation behaviour. Both the FAD and CDF representations are used in the validation cases presented in this paper.

Both R6 and SINTAP contain detailed guidance on determination of the input parameters. For example, methods are given for obtaining a conservative measure of fracture toughness, guidance is given on treating secondary stresses such as welding residual stresses, compendia of stress intensity factors, limit loads and welding residual stress profiles are included.

2 CASE STUDIES

The aspects which have been investigated in the validation exercises discussed below cover: the hierarchical structure of the procedure, strength mismatch, constraint effects, local approach methods, leak-before-break applications, application to thin walled structures, and an -example of a failure analysis exercise.

2.1 The hierarchical structure of the procedures

The hierarchical structure of assessment procedures has been investigated by applying various levels of the SINTAP procedure to 97 full-scale pipe tests with through-wall and surface cracks subjected to internal pressure and four-point bending [6]. All experimental data sets were taken from the literature. Example results are shown in Fig. 1. Each analysis yielded conservative results in that the experimentally observed maximum load was underestimated. The higher analysis levels yielded less conservative results than the lower levels, as expected. Thus, an unacceptable result from an assessment at a lower level does not necessarily mean failure of a component. Instead, it provides motivation for repeating the analysis at the next higher level. On the other hand, if a lower level analysis indicates safety the user does not need improved input information to perform a more complex analysis.

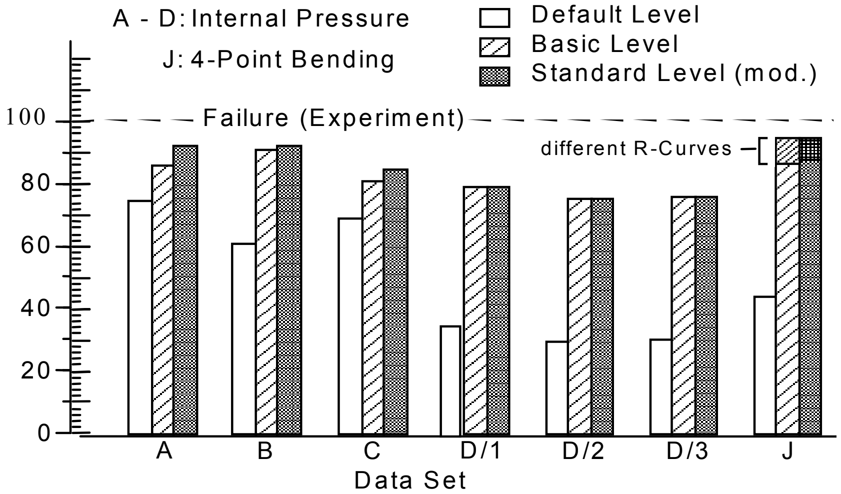

Fig 1: Ratios of predicted and experimentally determined failure loads (x100) of hollow cylinders subject to internal pressure or bending (various SINTAP assessment levels) [6].

A source of uncertainty in the pipe tests was the fracture toughness data. The influence of two different R-curves reported in the literature is shown for case J in Fig. 1. This indicates that even within one analysis level, it may be possible to refine an assessment by obtaining more accurate input data. The conservatism in terms of the maximum load of the default level analysis based on Charpy impact data was found to range from 20 to 70%, mainly dependent on the material.

Another case study based on the SINTAP default level in combination with Charpy data was carried out for a data set of 7 welded bend specimens treated as "components" [7]. From the Charpy data the Master Curve T_0 transition temperature was estimated by the rules given in SINTAP. Based on this, a probability density function of the fracture toughness in the ductile-to-brittle transition was obtained and used to predict the component failure load. In comparison to the "component" tests, the predictions yielded conservative results in the lower tail of the curve (Fig. 2). The inherent safety margin was found to be in the order of 15% for a failure probability of 20% and increased to about 35% for a failure probability of 5%. At failure probabilities larger than 50% the procedure was accurate, with no excessive conservatism.

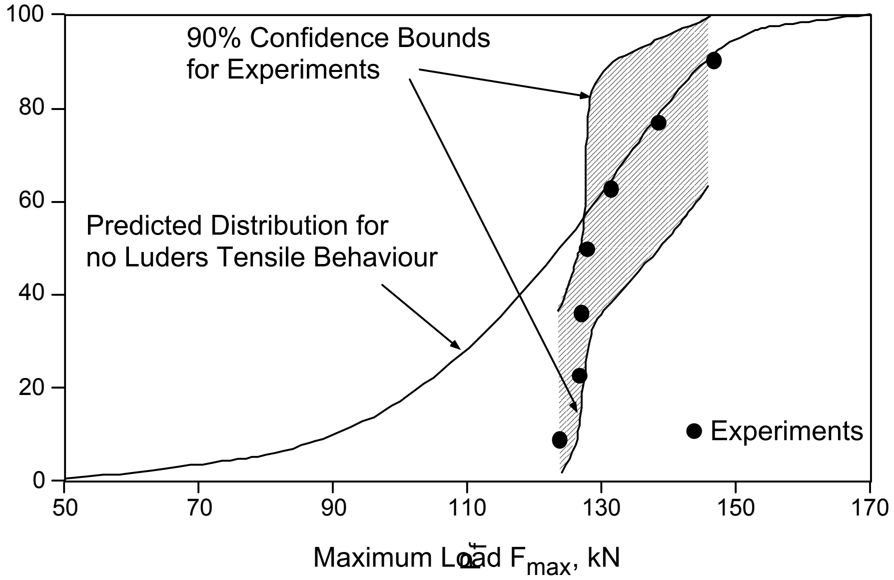

Fig 2: Predicted and experimentally determined probability distribution in welded bend specimens (SINTAP Default Level) [7].

2.2 Strength mismatch

Several studies have been undertaken for validating the procedures for treating strength mismatch in the R6 and SINTAP procedures. In [8], 12 tests on undermatched and overmatched bending plates were used as case studies for evaluating the SINTAP procedure. The mismatch ratio was about 50% for both, under- and overmatching and two different crack lengths were introduced into the plates. The results are summarised in Fig. 3. It could be demonstrated that the analyses yielded moderately conservative results in all cases. Again the higher analysis level did show less conservatism than the lower level.

A Basic Level analysis of three laser welded plates, the base metal of which showed different strength was reported in [9]. Three positions of the pre-crack were chosen: base metal, heat affected zone and fusion zone. In all cases, the SINTAP procedure yielded satisfactory predictions of the load versus J-integral curves.

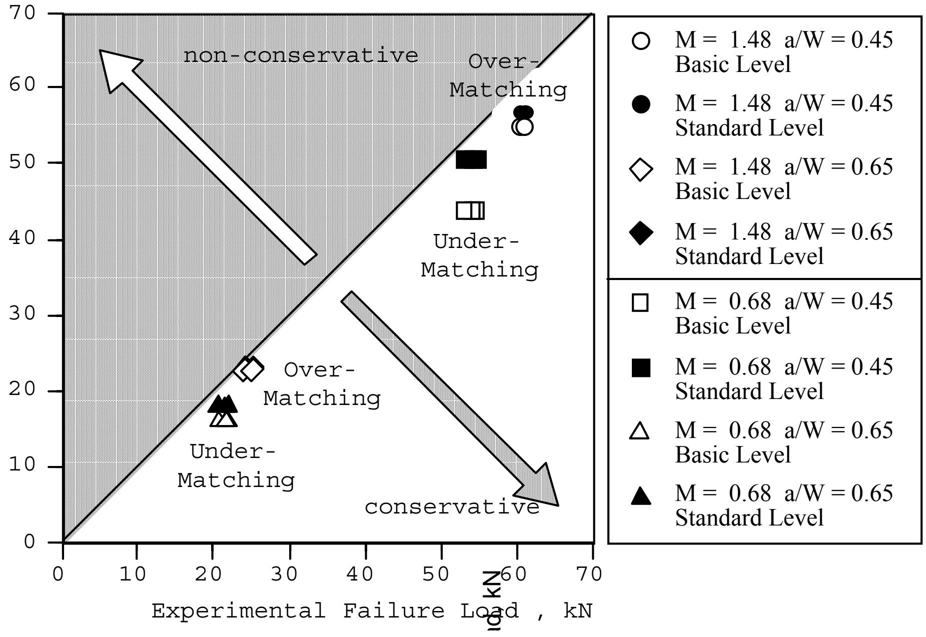

Fig 3: Predicted and experimentally determined failure loads of mismatched bend specimens (SINTAP Basic and Standard Levels) [8].

2.3 Constraint effects

In R6, there are procedures that allow benefit to be taken for the effects of low crack tip constraint increasing the effective fracture toughness [10]. Validation of these procedures has been addressed for both cleavage and ductile fracture on a range of materials. For example, cleavage fracture in two low constraint biaxial bend specimens on A533B steel plates in the lower transition region has been assessed using the R6 constraint approach. This reduced the conservatism of the basic Option 1 and option 2 failure assessment curves leading to a 30-40% benefit in terms of load margin for the lower constraint geometry, whilst maintaining conservatism. However, when the same approach was applied to ductile failure of a large single-edge notched A533B plate at 20˚C, the constraint method gave the same load margin as the basic approach because the constraint level was not particularly low. This latter result also demonstrated that for high constraint cases, procedures such as R6 and SINTAP are often not unduly conservative

2.4 Local approach methods

With the development of more reliable micro-mechanistic or local approach models of both ductile and cleavage fracture, R6 has included advice on their application. Validation of this advice has also been addressed. For example, the Beremin cleavage model has been used to assess the influence of in-plane constraint on fracture in mild steel single edge cracked bend specimens. The Beremin model was tuned to fit data on specimens with relative crack depths, a/w, in the range 0.22-0.73 and then used to predict fracture in specimens with a/w between 0.01 and 0.025. The predictions were conservative when compared to measured data as shown in Fig. 4.

For ductile fracture, the Rousselier damage model was applied to an extended axial defect in a spinning cylinder test on an A508 steel [11]. The experimentally measured ductile crack extension as a function of rotational speed was closely, but conservatively, predicted by the model, Fig. 5.

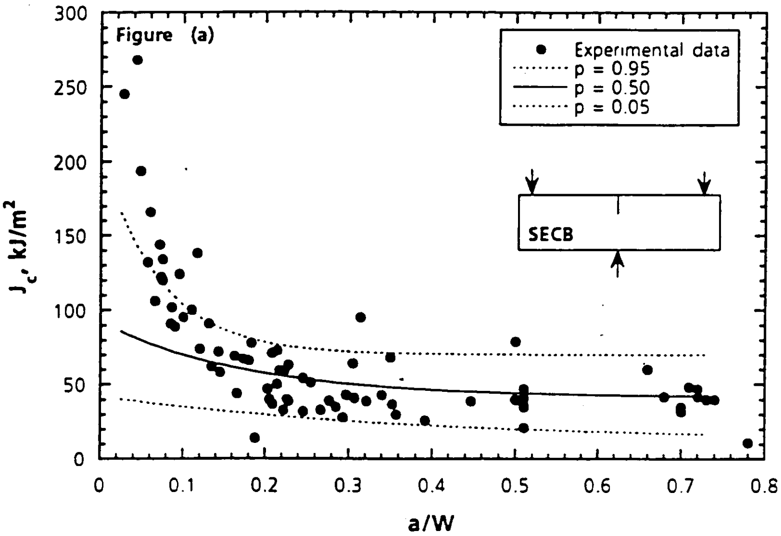

Fig. 4 Comparison of local approach predictions of the fracture behaviour of BS 4360 43A mild steel plate at -50°C with experimental data

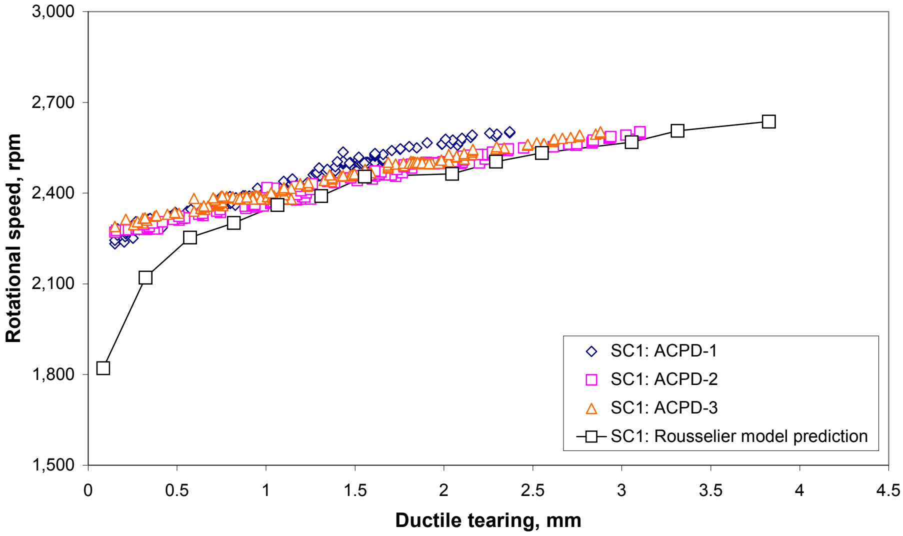

Fig. 5 Predicted and experimental rotational speed vs. ductile tearing for Spinning Cylinder Test 1

2.5 Leak-before-break applications

There are a number of different calculations in a leak-before-break assessment, including calculation of the limiting length of a through wall defect and calculation of crack opening area. Validation of methods for calculation of the limiting length of a through wall defect is covered by validation of the flaw assessment procedures, as described above. Calculation of crack opening area has been performed by comparing calculated crack opening displacements with experimental pipe test data. Both elastic and simplified elastic-plastic reference stress methods have been shown to underpredict crack opening displacement and therefore to give a conservative prediction of leak-before-break. It is to be noted, however, that alternative methods overpredicting the crack opening area would be needed to provide a conservative estimate of the consequences of leakage.

2.6 Application to thin walled structures

When dealing with thin walled structures, some special features which have to be accounted for, are pronounced stable crack extension before failure and the absence of accepted test standards for low constraint geometries. A draft testing standard has, however, been proposed recently [12] for obtaining low constraint data and an assessment approach for thin-walled structures was published in [13]. A detailed description of this is not given here but Fig. 6 shows a sample of results [14]. In each case the fracture toughness in terms of a CTOD-δ_5-R curve was obtained from CT specimens. The analyses were then carried out on biaxial tension loaded plates with biaxial ratios of –0.5, 0, +0.5 and +1 with and without mixed mode. The investigations used different data sets generated at GKSS and DLR and recommendations for mixed mode from the R6 procedure [4]. As can be seen from Fig. 6 and further data in [13] the predictions of the maximum loads were acceptable

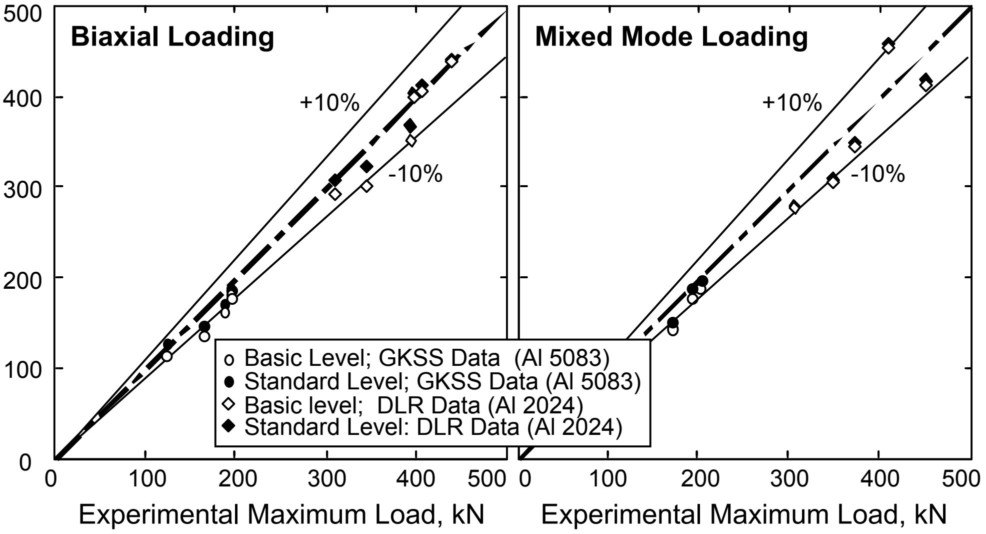

Fig 6: Predicted and experimentally determined failure loads of biaxial tension loaded and mixed mode loaded plates (SINTAP Basic and Standard Levels R6 Mixed Mode, slightly modified)[14].

2.7 Example of a failure analysis exercise

The application of an assessment approach to a failure analysis was reported in [15]. A fork of a forklift broke at a hole. At the design load the SINTAP Standard Level analysis revealed a critical

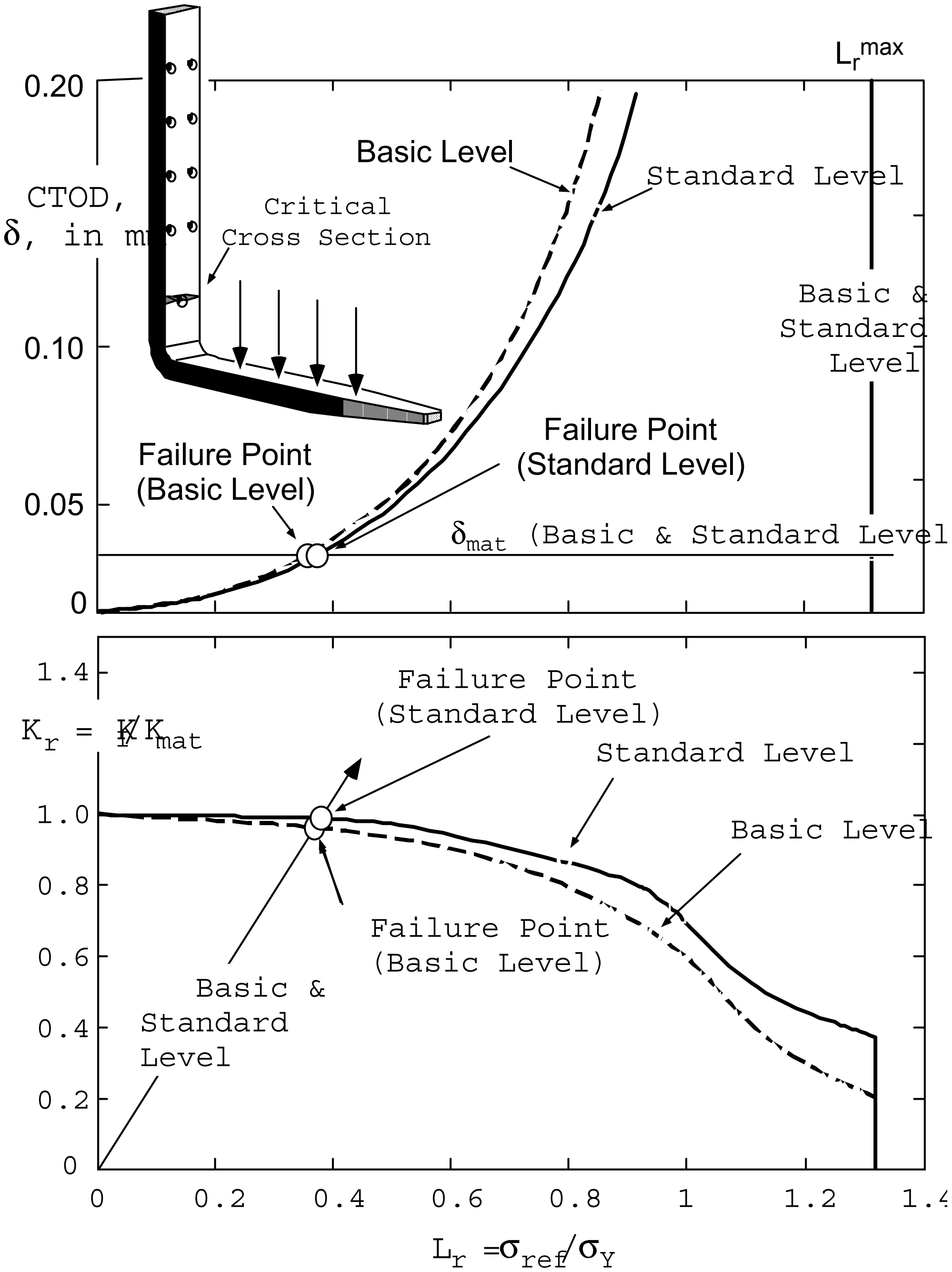

Fig 7: Application of the SINTAP procedure to failure analysis of a broken fork of a forklift [15].

crack size about 22% smaller than the real crack size at failure. This application pointed to an inadequate design rather than to misuse of the component. In Fig. 7 the analysis is illustrated for the Default, Basic and Standard Levels for both FAD and CDF philosophies.

3. CONCLUSIONS

The R6 and SINTAP flaw assessment methods have been subjected to wide ranging validation covering a number of different aspects of the procedures. These have been illustrated in this paper and give confidence in the practical use of these methods. The applications also illustrate the conservatism in the procedures and how this can be reduced by following higher levels of analysis.

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