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Application of a constraint correction failure assessment procedure for cracks located at the fusion line of weldments

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ABSTRACT

The application of the JQM Approach is demonstrated with reference to an offshore project. The platform is designed in high strength steel, yield stress between 500 and 580 MPa, and the influence of even- or undermatch of the weld metal yield strength for cracks located at the fusion line of welds has been quantified with respect to brittle fracture.

The results have been compared with standardised FAD calculations, and the application of toughness constraint correction is demonstrated.

Key words: constraint correction, brittle fracture, fracture mechanics, failure assessment, weldments, mismatch, high strength steel

Introduction

The Failure Assessment Diagrams (FAD) used in BS 7910:1999 [1], represent high structural constraint applications. The standard give literature references for constraint correction methods, but none of these are included in the standard.

The purpose of the present paper is to demonstrate the use of the JQM approach for geometry and mismatch constraint correction of the fracture toughness, Zhang, Thaulow et al [2-5].

First we present the Grane offshore project, and the geometrical detail to be investigated. A standard FAD analysis is performed and a critical defect size with respect to brittle fracture calculated. A JQM analysis is then applied on the Grane case, and the results are compared with the FAD calculations.

Grane is an integrated production-, drilling- and living quarter's platform on a steel jacket. The first oil production is expected in October 2003.

Because of weight reduction the yield strength shall be min. 500 MPa for the whole range of thickness, and the max yield strength is set to 580 MPa. The min tensile strength is 600 MPa and the design is based on a tensile to yield strength ratio of min. 1.2.

The reason for selecting high strength steel is the cost savings. A weight reduction of approximately 8% is obtained compared with 420 MPa steel. The main contribution to the cost saving is the possibility for single lift and less hook up, but also reduced steel- and welding volume will add. The steel price will, however, increase.

The risk for brittle weld metal properties increases with increasing weld metal strength. Acceptable weld metal properties have been documented from previous projects on 420 MPa steels, and use of existing consumables from this class of steel is therefore assumed. As a result, the minimum yield strength of the welding consumable is set to 560 MPa. In practice, a slight undermatch or evenmatch, must be expected.

The risk of brittle fracture due to the high strength and the mismatch conditions must be quantified.

Failure Assessment Diagram (BS 7910:1999)

Designers from the Grane project selected an I-beam welded to a plate, Figure 1, as the case to be investigated. The I-beam is loaded in a combination of bending and tension. The most conservative assumption is a surface crack located at the top flange. Locally at this position the tension stress will dominate. In the analyses the geometry is therefor simplified to a plate 500x30 mm, e.g. the top flange of the I-beam, loaded in tension with a surface crack in the middle.

The failure assessments is performed according to Level 2A in BS 7910 with the initial residual stresses equal the yield strength and a CTOD equal 0.25 mm. The residual stresses are reduced in accordance with BS 7910 when the structure is loaded.

The most critical assessment was for the lowest chosen yield strength, 500 MPa in base material, and membranes stress equal 500 MPa. For this combination the critical crack height is 3.64 mm for a 30 mm long surface crack on the top flange of the I-beam.

In the calculation procedure only the lowest yield strength in the area around the crack tip enters into the assessments. The tensile strength has influence only when plastic

collapse is predicted which was not the case for the present assessments. This means that the only strength information that will influence on the assessments for fusion line cracks is the lowest yield strength of base material and weld metal that is used in the assessments. The effect of the mismatch in itself is not included in the analysis. To investigate the effect of mismatch it is necessary with failure assessments based on the J-Q-M approach.

JQM CONSTRAINT CORRECTION

A 2D plane strain FE model, Figure 1, represents the selected detail. ABAQUS version 5.8 is used for the FE analyses. The crack tip is modelled with an initial radius of 10 μm, which is also a characteristic dimension for the smallest element size. In the analysis, 4 node plain strain quadrilateral elements (ABAQUS element CPE4) are used.

The crack sizes evaluated are 5 mm, e.g. somewhat larger than the critical crack size according to the FAD analysis, and a larger crack of 9 mm.

The plasticity is modelled according to the J2 flow theory (incremental plasticity), and a small strain formulation is used.

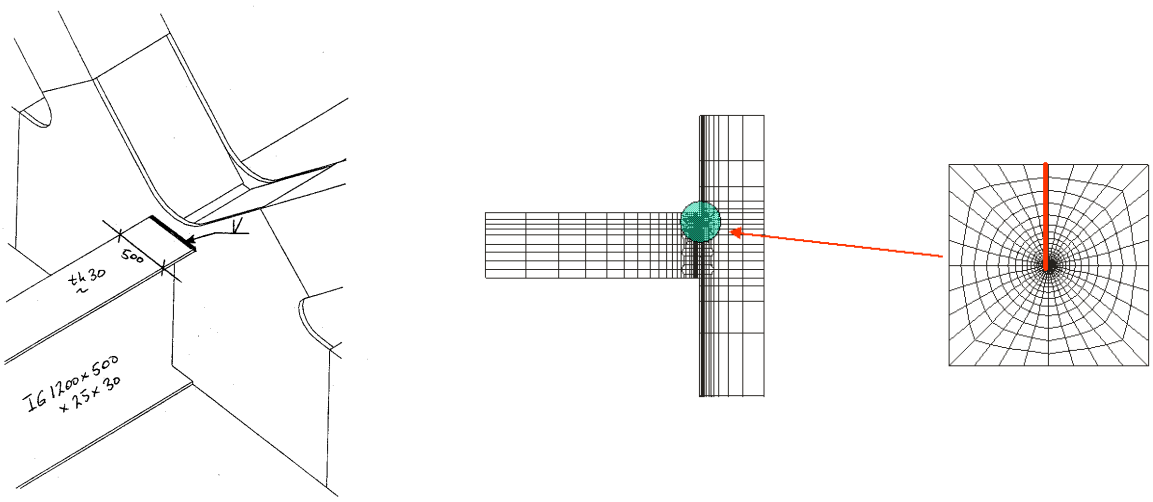

Figure 1: Detail from the Grane platform, I-beam welded to a plate (left), FE model of the detail (right).

The CTOD relationships between the reference MBL solution and the Grane geometry are shown in Figure 2. Overmatching the weld metal increases the constraint at initial loading, but after net-section yielding the effect levels out. Undermatcing, however, reduces the constraint for all loads.

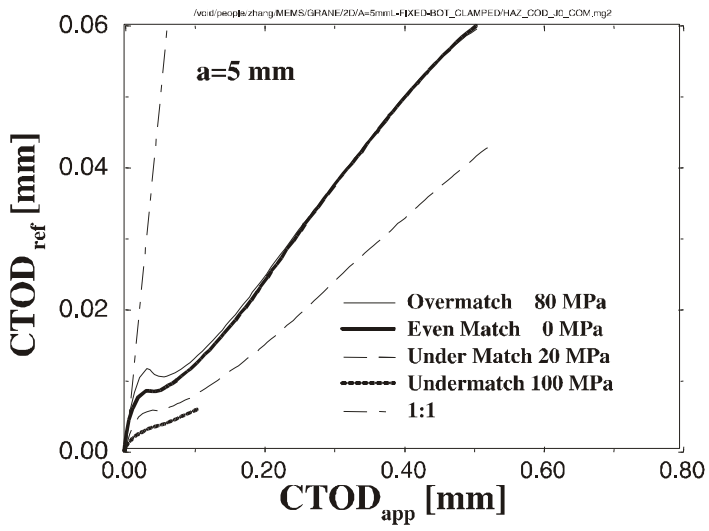

Figure 2: CTOD Relationships between the MBL reference solution and the Grane geometry. Effect of mismatch for a=5mm.

In Figure 3 the relationship with the gross stress (or remote loading) is plotted. Very low reference toughness levels are calculated.

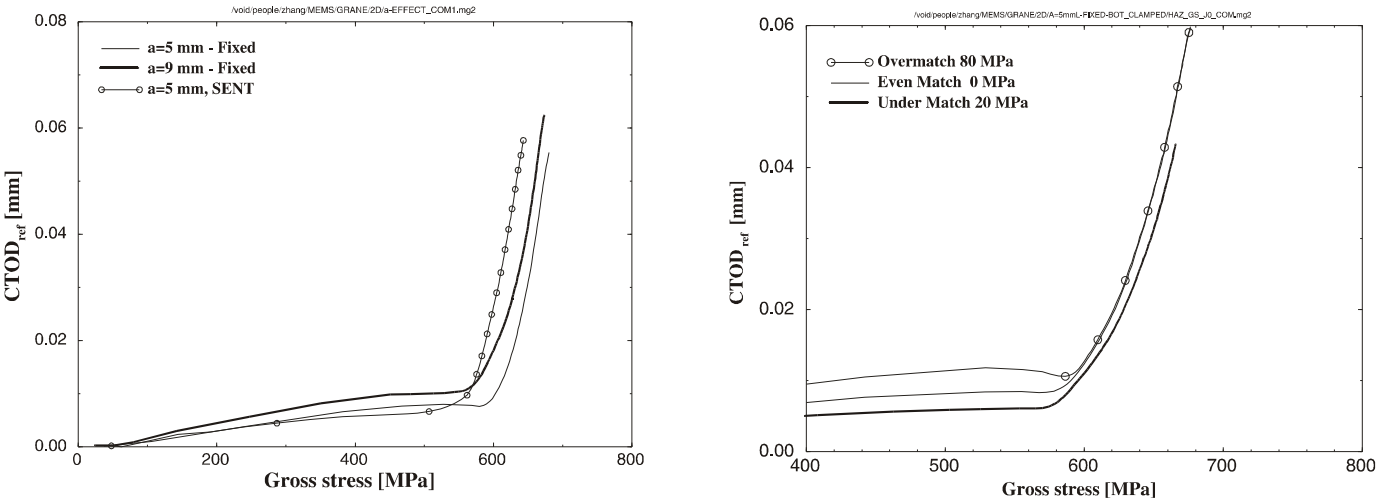

Figure 3: Relationships between the MBL reference solution and the remote loading of the Grane geometry. a) Effect of geometry and b) effect of mismatch for a=5mm.

Weld thermal simulation testing of similar steel qualities as the Grane steel, have lower bound values in the range of CTOD=0.06-0.07 mm. This is far beyond the critical values calculated in Figure 3, and should imply that there is no risk of brittle fracture. The effect of residual stresses has not been considered. But since this effect will be most pronounced at low load levels, and figure 3 shows only minor influence of the load before general yielding, the above conclusion is also valid in the case of residual stresses.

Effect of absolute size of specimens

There is always a competition between increase of constraint due to crack size and the simultaneous decrease due to reduced ligament size and through thickness yielding.

A limited study on SENT specimens, with a constant a=10 mm and increasing thickness from 20 to 70 mm, was performed. When the horizontal lines in Figure 4 (left) are attained brittle fracture is no longer assumed. The cut-off lines refers to that

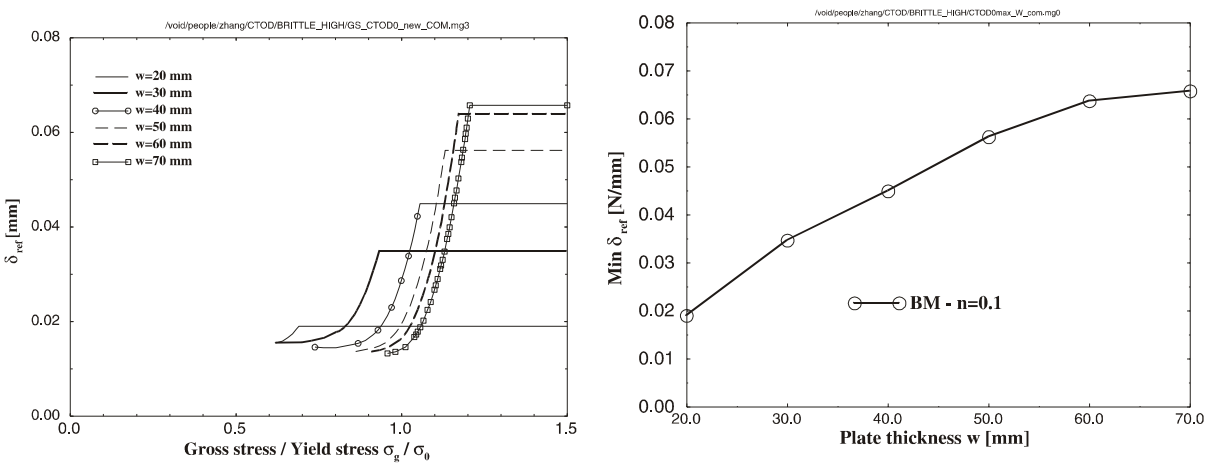

Figure 4: The MBL reference vs. the remote load of SENT specimens (left) and minimum toughness of the MBL reference value to avoid brittle fracture vs. thickness of the SENT specimens for a constant a=10mm (right).

the stress level at the distance $r = 2J/\sigma_0$ ahead of the crack tip falls below $2.5\sigma_0$. σ_0 refers to the yield strength. Hence, if the reference CTOD value is above a critical minimum value there will be no risk of brittle fracture, Figure 4 (right).

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Conclusions

-The JQM Approach effectively quantifies the constraint with respect to brittle fracture caused by geometry and material mismatch for cracks located at the fusion line of welds.

-The JQM Approach is demonstrated on a case from an offshore platform. The standardised FAD calculations predicted a critical crack size of about 3.5 mm for a 30

mm thick plate loaded in tension, while the JQM Approach concluded that brittle fracture will not take place for two cases with crack size of 5 and 9 mm, respectively.

-The critical fracture toughness of the reference material, is either determined by weld thermal simulation testing or alternatively by correcting the toughness results from standardised fracture mechanics testing.

- The critical defect size can either be determined directly by comparing the reference solution with the remote load of the component/structure, or by using the constraint corrected fracture toughness as input in FAD calculations.

-The competition between increase of constraint due to crack size and the simultaneous decrease due to reduced ligament size and through-thickness yielding has been investigated, and the critical minimum value of the reference material to avoid brittle fracture determined

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