Fracture Assessment of Reactor Circuit (FAR)

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Introduction / background

The objective of the FAR project was to develop and to validate numerical and experimental methods for reactor circuit structural integrity assessment. Numerical fracture mechanical assessment methods, Leak-Before-Break (LBB) approach, irregular and shallow-shaped cracks with low constraint stress state and dissimilar metal welds (DMW) characterization methods were studied in the project.

XFEM

The extended finite element method is an extension of the finite element method. It uses discontinuous element shape functions and additional degrees of freedom to add the effects of cracks as shown in Figure 1a. In the project the applicability of the XFEM implementation in Abaqus was studied. It was found that modelling of static and growing cracks is relatively straightforward but the result accuracy is limited at this time due to the oscillation of the crack driving forces. The most promising targets of application are cases with multiple or irregular cracks that require sensitivity analyses. An example of a pipe break simulation with XFEM is shown in Figure 1b.

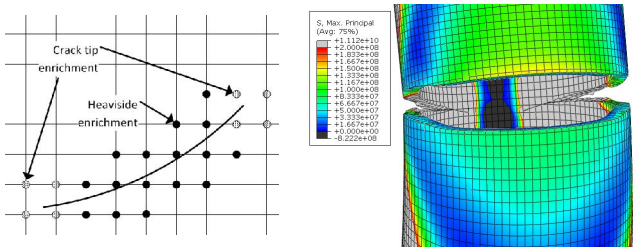

Figure 1. Left: Internal degrees of freedom that define the crack in XFEM analyses. Right: Crack growth path example from a pipe break analysis.

LBB

The Leak-Before-Break approach was studied in the project. Based on the state of the art knowledge of ductile tearing assessment and LBB, a new procedure with new safety factor definitions is proposed. The state-of-the-art procedure follows European consensus and the FITNET assessment procedure. The safety factor rules are based on the latest US NRC research. With the new procedure the resulting safety is at least comparable to the safety of the original ASME safety factors but the application is specific for LBB and over-conservatism is avoided. The new procedure is in line with the YVL guidelines.

The LBB approach was utilized for a steam generator collector dissimilar metal weld simulation case (Figure 2). The collector is subjected to thermal and mechanical loads. Sensitivity of crack driving force and leak rates were computed with respect to different loading and material conditions. It was found that LBB principle is not applicable if material fracture toughness is less than 20 kJ/m^2.

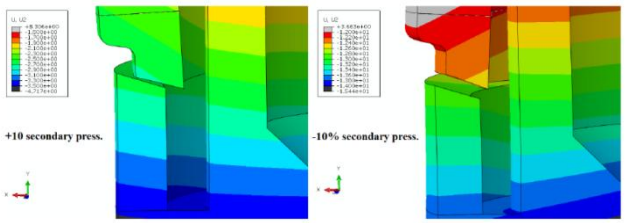

Figure 2. Crack opening displacements from steam generator collector case study.

In connection to LBB behavior the instability of long cracks was experimentally studied. Fracture resistance specimens with different slenderness were tested to study whether the slenderness affects the tearing resistance. It was found that the fracture resistance seems not to decrease as a function of slenderness or crack growth. Limit load decrease was observed with high strength steels but this is not relevant for the typical thicknesses and strengths of nuclear materials.

CLEAVAGE FRACTURE

The Master Curve and the Unified Curve are two different cleavage fracture toughness assessment methods. They differ especially in the assumed fracture toughness temperature dependence. In the project a fully objective comparison using the maximum likelihood have been made for 50 large data sets. The MC shows overall a trend of higher likelihood than the UC. It is also shown theoretically that the Unified Curve cannot be universally applicable.

DMW

The fracture toughness and crack driving force onset value important to LBB assessment of a Ni base DMW mock-up was experimentally studied using small-scale SE(B) specimens (Figure 3). It was found that all specimens demonstrated ductile tearing and the crack onset of ductile fracture for the DMW specimen is above 80-100 kJ/m^2. Relatively straight crack paths without deviations into neighboring near-interface zones were observed.

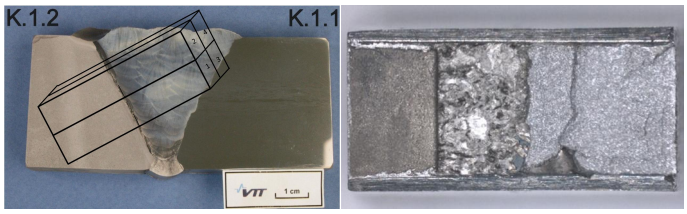

Figure 3. DMW mock-up, SE(B) specimens and resulting fracture surface.

Conclusions

The FAR project focused on numerical and experimental methods for reactor circuit fracture assessment. The XFEM approach was studied. LBB procedure was developed and utilized. Comparisons of cleavage fracture methods were made. DMW fracture characterization experiments were performed within the project.

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