Assessment of Sub-Clad Flaw based on Finite Element Analyses

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Abstract. The main goal of this research was to study the crack front position of sub-clad flaws how influences the J-integral value. 3D FE models were applied for the analysis with elastic-plastic material properties. The residual stress was considered. Straight crack fronts were discretized with average crack lengths. Different crack front position was analyzed.

Introduction

The purpose of this work was to study the effect of the crack size of sub-clad flaws in 4PB specimens in case of WWER-440 reactor pressure vessel steel. The research was performed within the framework of NESC-6 project “WWER Cladded Reactor Pressure Vessel Integrity Evaluation (with Respect to PTS Events)”. Three specimens were analyzed with different crack lengths (two specimens with short crack and one specimen with long crack), and 3D finite element models were generated for them, which were presented in a previous work [1]. J-integral was calculated for each sharp crack tips. Cracks were modeled with straight crack fronts to simplify the analysis, and average crack lengths were considered. Residual stresses were taken into account in the calculation.

Material

The analyzed material was a WWER reactor pressure vessel steel and its properties and fracture data were provided by the Nuclear Research Institute, Rez. Elastic-plastic material properties were used in the FE model. The material properties can be seen in the Table1. Poisson’s ratio ν=0.3 was used in all cases. The residual stress was also considered during the analyses.

Table 1.: Material properties of the specimens

Material properties	Aged base metal	Aged cladding
Young modulus, [GPa]	211	162
Yield stress, [MPa]	887.8	337.9
Ultimate tensile stress, [MPa]	984.1	593.9
Thermal expansion coefficient, [1/K]	$12.55*10^{-6}$	$17.1*10^{-6}$

Specimen geometry

4PB specimen geometry was discretized and used in the finite element analyses. Two different crack front positions were analyzed, and three specimens were modelled by FEM (two short cracks and one longer crack). The specimen geometry and one of the meshed models can be seen in the Fig. 1. The specimens’ data are summarized in Table 2. MSC.MARC 2007r1 finite element code was used for the analysis. 20 nodes hexahedron elements were applied for generating 3D FE models of specimens. Symmetry conditions were applied in the model.

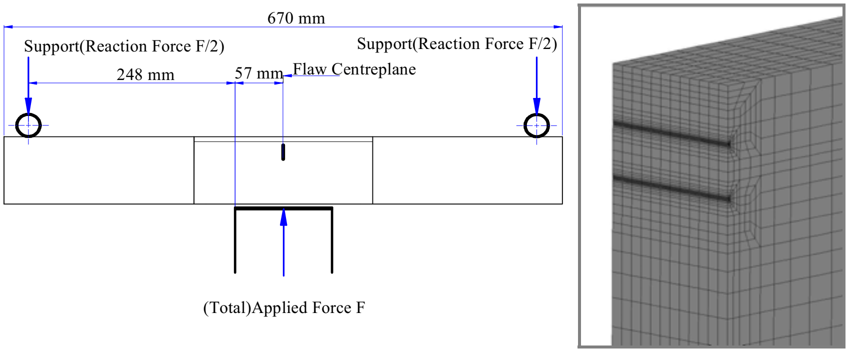


Figure 1. Specimen geometry and the meshed 3D finite element model

Table 2.: Crack geometry data

	1E2 specimen	1E4 specimen	1E7 specimen
Cladding thickness, [mm]	10.8	11.35	11.25
Distance of upper crack front from the bottom side of the specimen, [mm]	69.81	70.76	70.63
Distance of lower crack front from the bottom side of the specimen, [mm]	55.88	55.87	30.78
Crack length, [mm]	13.93	14.89	39.85
Maximum applied force at fracture, [kN]	259.7	339.4	205.5

Residual Stress

Residual stress was considered in the analyses based on the stress free temperature method. This means that residuals stress arises from difference of the thermal expansion coefficients. Stress free temperature: T=350°C. Thermal expansion coefficient for base metal was 12.55*106 and and for the cladding was 17.1*106. The longitudinal and transversal component of residual stress can be seen in the Fig. 2.

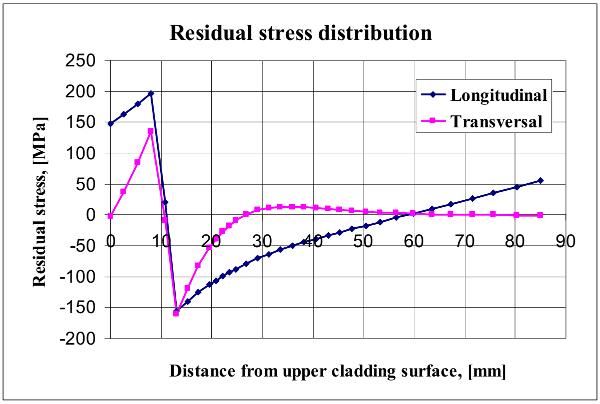


Figure 2. Residual stress distribution calculated by BZF

Validation of FE model based on the measurement of NRI

The LLD curves of specimens were post-processed, compared with the data of NRI, and the results are in good agreement with each other (Fig. 3.).

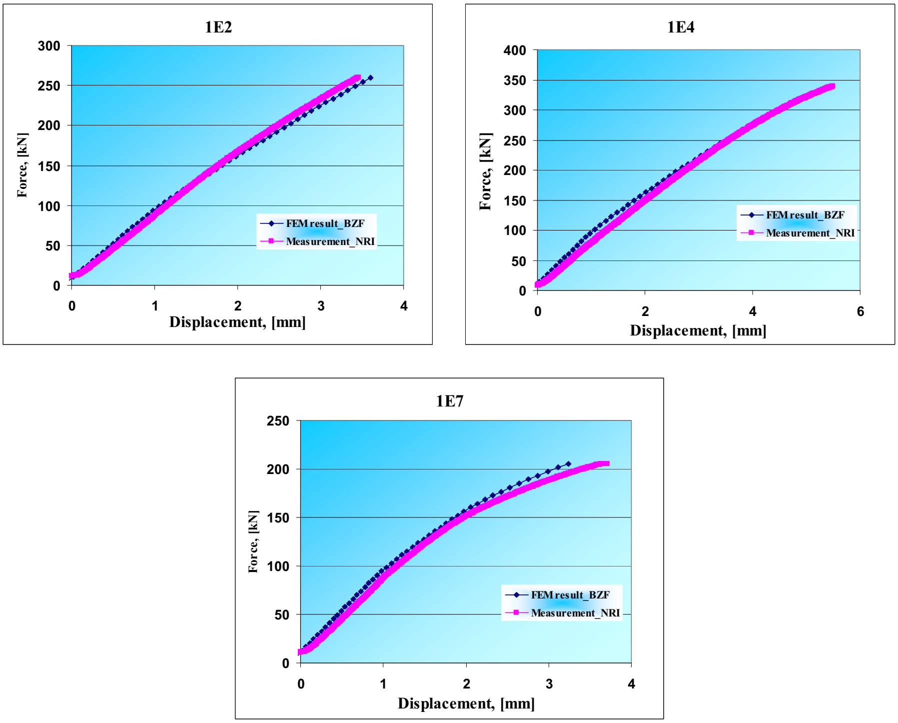


Figure 3. Validation of LLD curves of certain specimens

J-integral calculation

The effect of crack front position was studied in this work for all specimens. 1E2 and 1E4 specimens have a crack with two sharp crack tips, but the lower crack tip was drilled out in the case of 1E7 specimen. In the J-integral calculation the significant effect of the cladding interface had to be taken into account at the upper crack tips. As the upper crack tips are very close to the fusion line of the cladding in all cases, it is not so easy to study the crack size effect.

So it was decided, that the crack size will decrease first in two steps, then it will be increased in one step. It means, that shorter initial crack lengths were supposed, and these cracks then were grown.

Three different cases were separately examined in the case of 1E2 and 1E4 specimens:

- Upper crack front moving
- Lower crack front moving
- Both crack fronts moving at the same time.

When only one crack front was moved, the value of moving steps was 0.5 mm. It means, that first the original crack length was decreased with 0.5 mm, then again with 0.5 mm, so the initial crack length was shorter with 1mm, than the original. After that, the original crack length was increased with 0.5 mm.

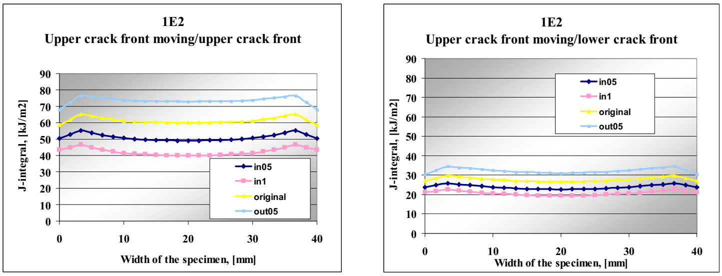
However, moving both crack fronts, the moving step was also 0.5 mm, but in one step the crack length was shorter with 1 mm. So the initial crack length was shorter with 2 mm, and the final crack was longer with 1 mm, than the original crack.

In the case of 1E7 specimen, only the upper crack front was moved, because the lower one was drilled out. The procedure was similar, than in the previous cases, so the moving step was 0.5 mm, the initial crack was shorter with 1 mm, and the final was longer with 0.5 mm, than the original crack of the given specimen.

J-integral values were calculated for each crack fronts of the specimens for different integration path. At a certain crack tip several integration radius were defined, and results were post-processed, where the J-integral values reached a constant value. The post-processed J-integral path plot can be seen in the Fig. 4-6. and the meaning of the colours are in the Table 3. Only the curves of 1E2 specimen presented here, because of the text limitation.

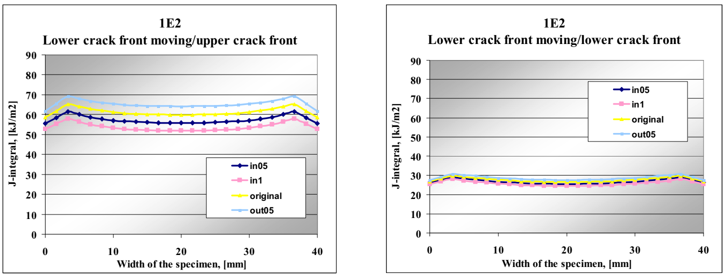
Table 3.: Identification of colours in the diagrams

	The crack tip was **moved into** the crack by **0.5 mm**
	The crack tip was **moved into** the crack by **1 mm**
	The crack has the **original crack length**
	The crack tip was **moved out from** the crack by **0.5 mm**



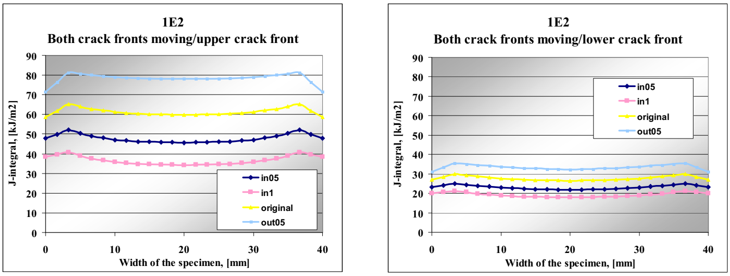
J-integral at upper crack front J-integral at lower crack front

Figure 4. J-integral path plot along the crack fronts of 1E2 specimen, upper crack front moved



J-integral at upper crack front J-integral at lower crack front

Figure 5. J-integral path plot along the crack fronts of 1E2 specimen, lower crack front moved



J-integral at upper crack front J-integral at lower crack front

Figure 6. J-integral path plot along the crack fronts of 1E2 specimen, both crack fronts moved

The larger changes in the J-integral values are occurred, when the upper crack front was moved. It has significant effect on result in case upper and lower crack front, as well. When only the lower crack front was moved, this effect was much lesser. The two main reasons are maybe the following: The upper crack front is very close to the fusion line of the cladding so the residual stress has effect on the J integral values, and the tensional stress is higher above the upper crack front, than below the lower crack front due to the bending.

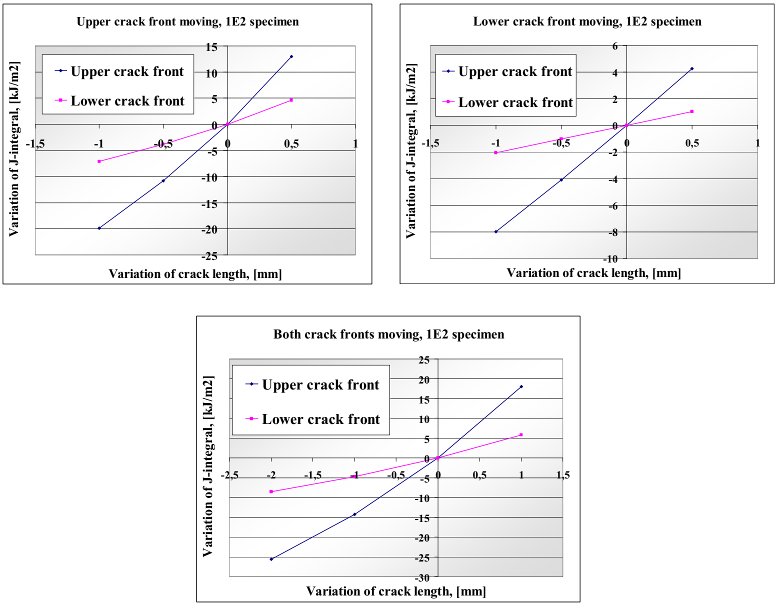


Figure 7. dJ/da diagram for 1E2 specimen

dJ/da calculation

After the J-integral calculation, dJ/da diagrams were plotted to show how the crack front position variation effects on the J-integral values at upper and lower crack fronts in case of each specimens ('a' is the crack length). In the Fig. 7. dJ/da diagrams can be seen only for the 1E2 specimen.

Based on the Fig. 3., the relationship between the J-integral and the crack length is almost linear. This linear relation can be applied, if the J-integral value is unknown at a given crack length. It should be noted, that reliability of this relationship and its validity range are not discussed here. It would be worth doing a study to determine the applicability range of this linear relationship.

Relative effect of crack size on the J-integral values

The effect of the crack length variation on the J-integral values is expressed in term of percentage in the Table 4. $\frac{\Delta J}{\Delta a} \cdot \frac{a}{J}$ is the crack sensitivity index in non-dimensional form, it means, this value show how changes the J-integral relatively, if the crack length is modified by 1 per cent.

Table 4.: Relative effect in case of 1E2 specimen

1E2 specimen	J-integral at the upper crack front	J-integral at the lower crack front	Variation of the crack length	$\frac{\Delta J}{\Delta a} \cdot \frac{a}{J}$ at the upper crack front	$\frac{\Delta J}{\Delta a} \cdot \frac{a}{J}$ at the lower crack front
Upper crack front moving	82.37 %	60.25 %	11.60 %	7,10	5,19
Lower crack front moving	23.57 %	12.58 %	11.60 %	2,03	1,08
Both crack fronts moving	127.33 %	80.24 %	25.15 %	5,06	3,19

Conclusions

J-integral calculation was performed to study the effect of crack size in case of sub-clad flaws. Straight crack front was modeled by 3D finite element method. The effect of moving the crack fronts were analyzed separately: only one crack front was moved in two cases (lower and upper crack front was moved separately), and both crack fronts were moved at the same time. Elastic-plastic material properties were applied, and the residual stresses were considered during the analysis. J-integral values were plotted along the crack fronts for all cases. dJ/da diagram were also generated to show the effect of crack size on the J-integral values. A summary about the relative variation of J-integral are also given.

References

[1] Large scale cladded beam specimen tests, *Description of the project for NESC*, Nuclear Research Institute Rez plc, Divison of Integrity and Technical Engineering, Rez, September 2006.

[2] Material properties & Residual stresses measurement, *Information for NESC*, Nuclear Research Institute Rez plc, Divison of Integrity and Technical Engineering, Rez, September 2006.