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# Numerical determination of J-integral value in case Sub-Clad Flaw

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## 1 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. Since J-integral values have shown high sensitivity to the distance from the cladding interface, J integral have been determined at the fusion line as well. The determination of J integral based on the virtual crack extension method (VCEM) take into consideration the secondary discontinuity at the interface of the based material and cladding. The method has been verified and the J-integral values for the situation when the crack tip is "on" the interface have been determined with the proposed new method. The calculation results show that the J-integral has a significant discontinuity at the interface that has to be taken into consideration at the fracture mechanical evaluation.

## 2 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. 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.

## 3 MATERIAL

The analyzed material was a WWER reactor pressure vessel steel and its properties and fracture data were provided by the Nuclear Research Institute. Elastic-plastic material properties were used in the FE model. The material properties can be seen in the Table1. Poisson's ratio $\nu=0.3$ 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] | $12.55 \cdot 10^{-6}$ | $17.1 \cdot 10^{-6}$ |

# 4 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 a longer one). The specimen geometry and one of the meshed models can be seen in the Fig. 1. 20 nodes hexahedron elements were applied for generating 3D FE models of specimens. Symmetry conditions were applied in the model.

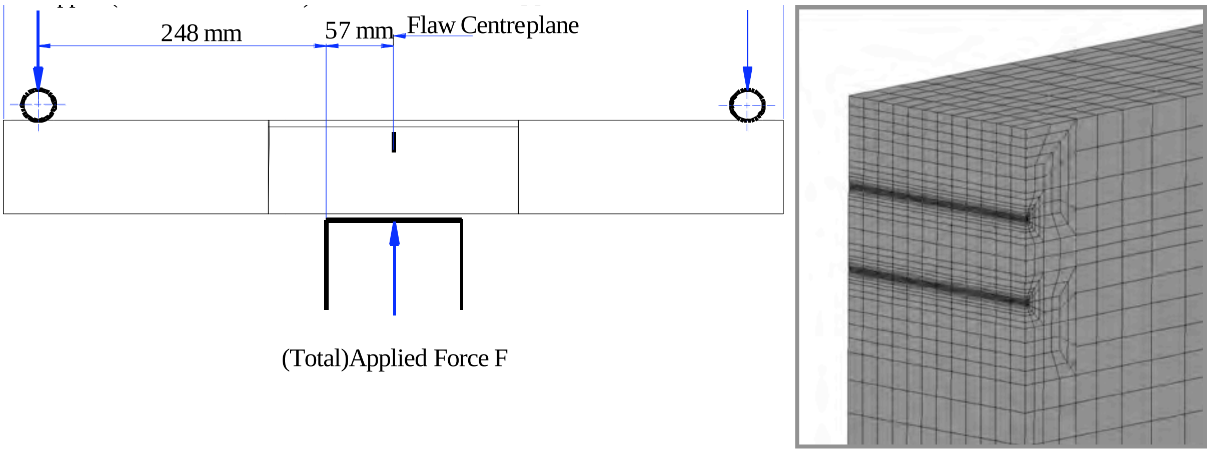



**Figure 1.** Specimen geometry and the meshed 3D finite element model

# 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 $12.55*10^{-6}$ and for the cladding was $17.1*10^{-6}$. The longitudinal and transversal component of residual stress can be seen in the Fig. 2.

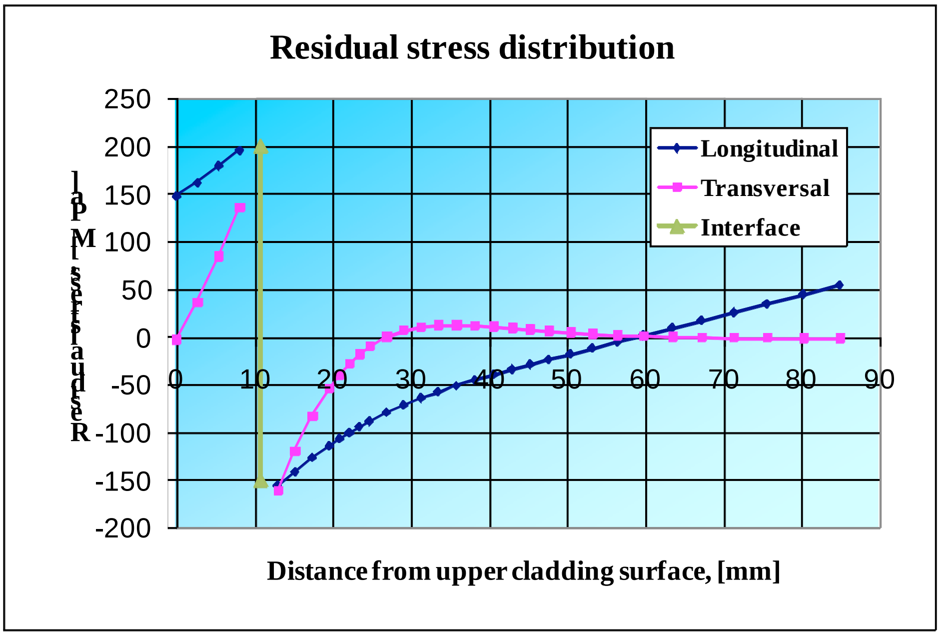



**Figure 2.** Residual stress distribution calculated by BZF

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.).

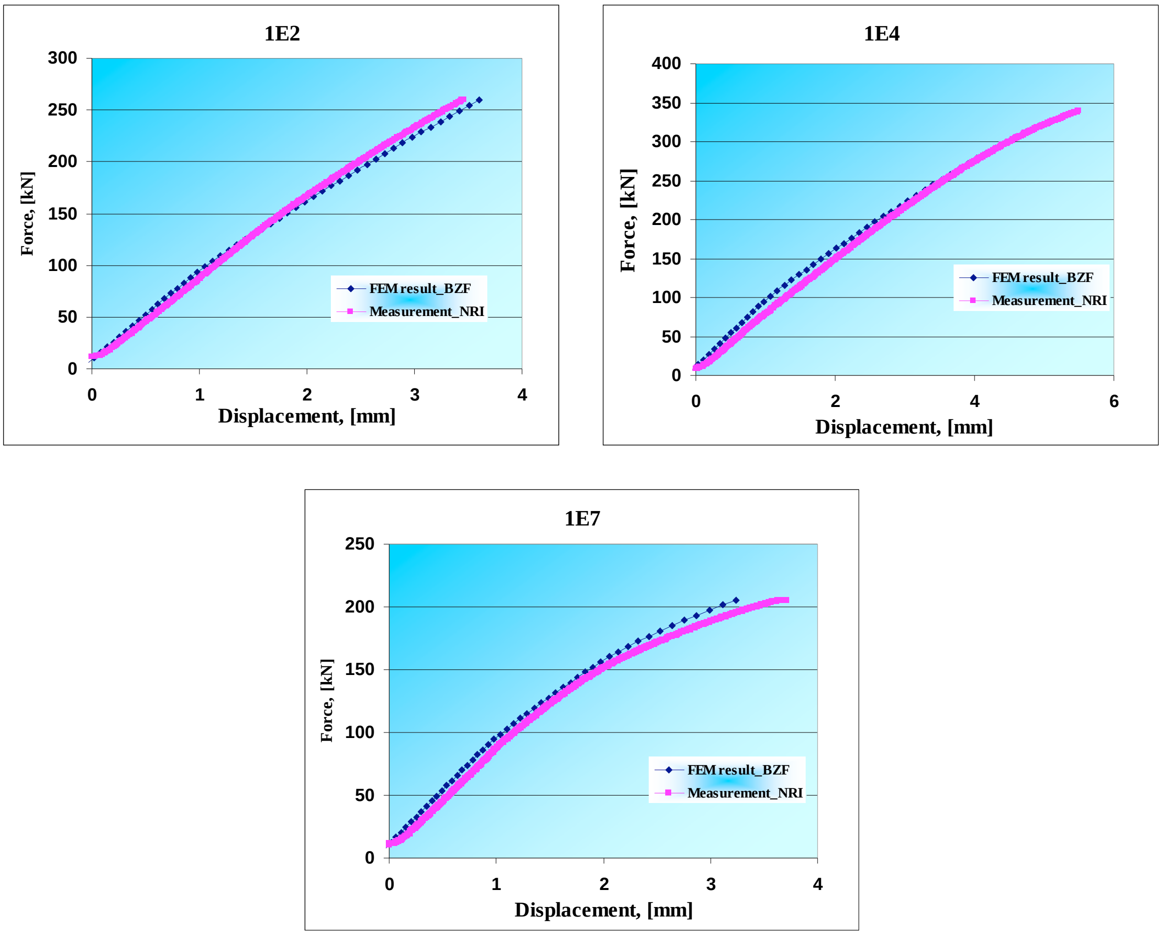



**Figure 3.** Validation of LLD curves of certain specimens

## 6 J-INTEGRAL CALCULATION

The effect of crack front position was studied in this work for all specimens. 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 upper crack front has been moved down first in two steps, then moved up in one step.

J-integral values were calculated for each crack fronts of the specimens for different integration path. Having the relationship between the J-integral and the crack length is possible to extrapolate the J values to the interface but the applicability range of the extrapolation has to be checked. Based on the J-variation at the upper crack front linear, quadratic and cubic extrapolation can be done as it is shown on the Fig. 4. As the figures show, the extrapolation based on the available J-values in not reliable, so further calculations are needed close to the interface.

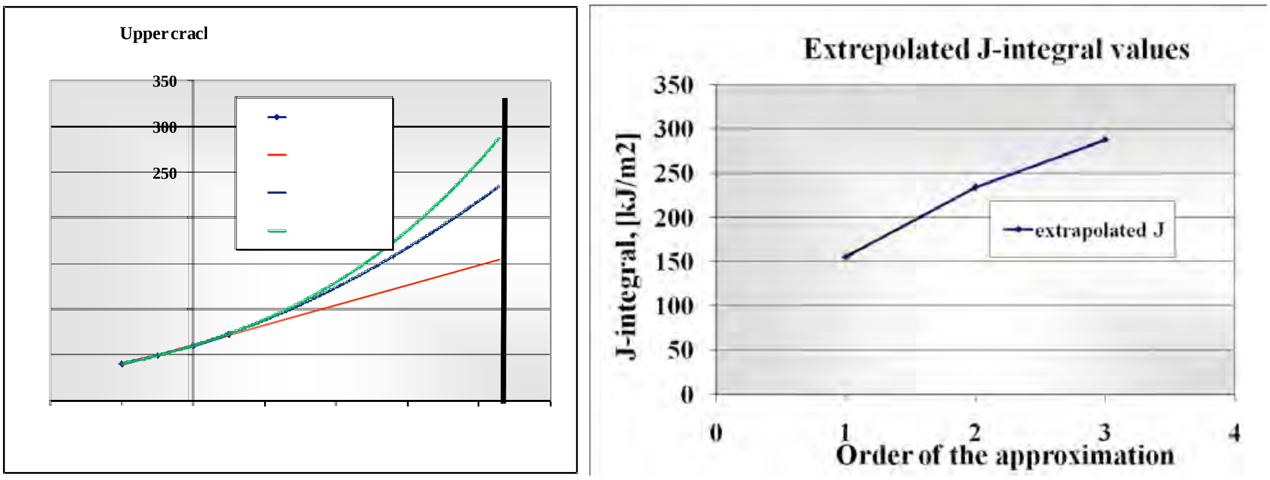



**Figure 4.** Extrapolation to the interface

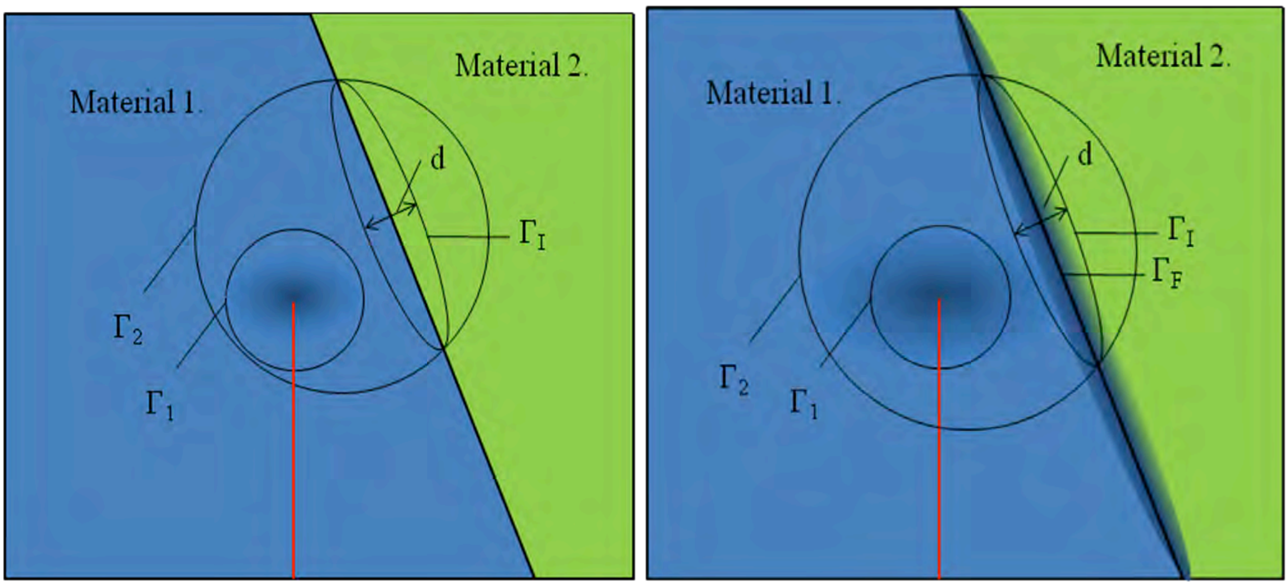
**6.1** J-integral calculation close to the interface

The J-integral is path independent if the integration path is out of the plastic zone that occurs around the crack tip and the path does not cross any other discontinuity such as the bimetallic interface. If the crack tip is close to the interface, it can be a problem to find a proper path that does not cross the interface. In this case the total integral has to be separated into two parts, one caused by the crack as a primary discontinuity and the other one caused by the bimetallic interface as a secondary discontinuity:

$$J^* = J_{\Gamma_1} = J_{\Gamma_2} - C_F \qquad (1)$$

where $C_{\Gamma I}$ is J like integral around the section of the interface that had been cut out as by $\Gamma_2$ it shows the Fig. 5a. $C_{\Gamma I}$ is independent from the „d" thickness of the $\Gamma_I$ if the deformation around the fusion line are linear elastic. If plastic deformation occurs around the interface $C_{\Gamma I}$ is strongly dependent from the „d" thickness and can be calculate as the follows:

$$C_{\Gamma_F} = C_{\Gamma_F^{M1}} + C_{\Gamma_F^{M2}} = \lim_{d \to 0} C_{\Gamma_I} \qquad (2)$$




Small plastic zone at the crack tip Plastic zone at the interface as well

**Figure 5.** J-integral path in case of bimetallic structures

For calculation of CΓF based on FEM results there are two ways:

„Exact” $C_{\Gamma F}$ calculation by path integral:

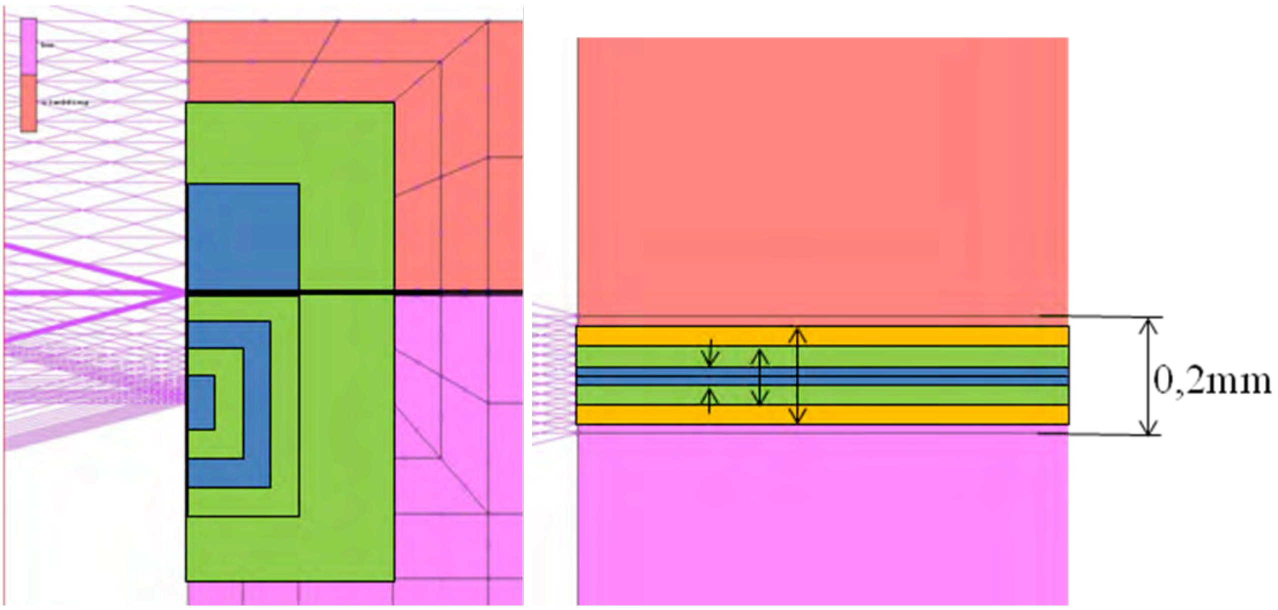
- This way gives the most reliable result, but
- Not supported directly by FEM software (usually)
- Stress and strain data should be post-processed
- Additional external calculation program needed

$C_{\Gamma F}$ calculation by virtual crack extension method:

- It is based on domain integration
- „d” cannot be equal 0
- Smooth mesh is needed perpendicular to the fusion line
- At least 3 domain integral is needed for convergent result
- crack tip must be out of the $\Gamma_I$
- It can be done by commercial FEM codes without external programs (Excel is useful)

Since in our case only a few calculations were needed the second way has been applied. In FEM representation of the J-integral calculation the path integral is transformed to domain integral and calculated by virtual crack extension method.

At first, for validation, the method has been applied for the original upper crack tip. The domains that have been defined can be seen on Fig. 6.




Domains for total J-integral calculation around the upper crack

Domains for $C_{\Gamma I}$ calcualation

**Figure 6.** Integration domains for J and $C_{\Gamma F}$ calculation by virtual crack extension method

The results of the calculation can be seen on the Fig. 7 and it can be concluded that the J-integral values calculated on the domains including the interface are really path independent when $C_{\Gamma F}$ has been taken off from the “total” J so the method applicable.

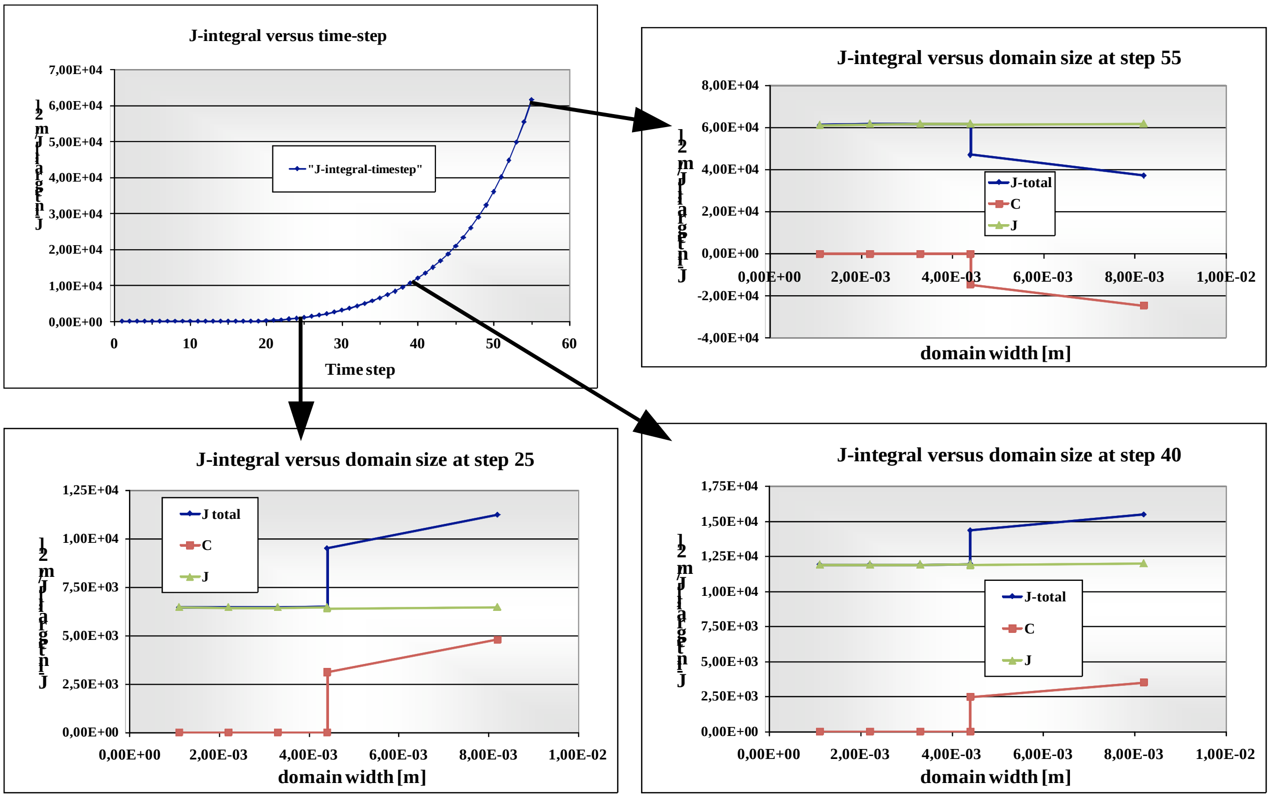



**Figure 7.** Path independent J after taking off $C_{\Gamma F}$

## 6.2 J calculation when crack tip is on the interface

Since the method applicable only when crack tip out of the $\Gamma_I$, J-integral has to be calculated both side of the fusion line. On the other hand determination of J-integral on the interface is still a theoretical question since it has discontinuity there as well. For the calculation two crack tips have been defined only 0,137 mm far from interface at both sides. It is pretty close to be able to make conclusion to the interface. As before J and $C_{\Gamma F}$ calculation have been done by virtual crack extension method. For the interface $C_{\Gamma F}$ has been calculated by interpolation.

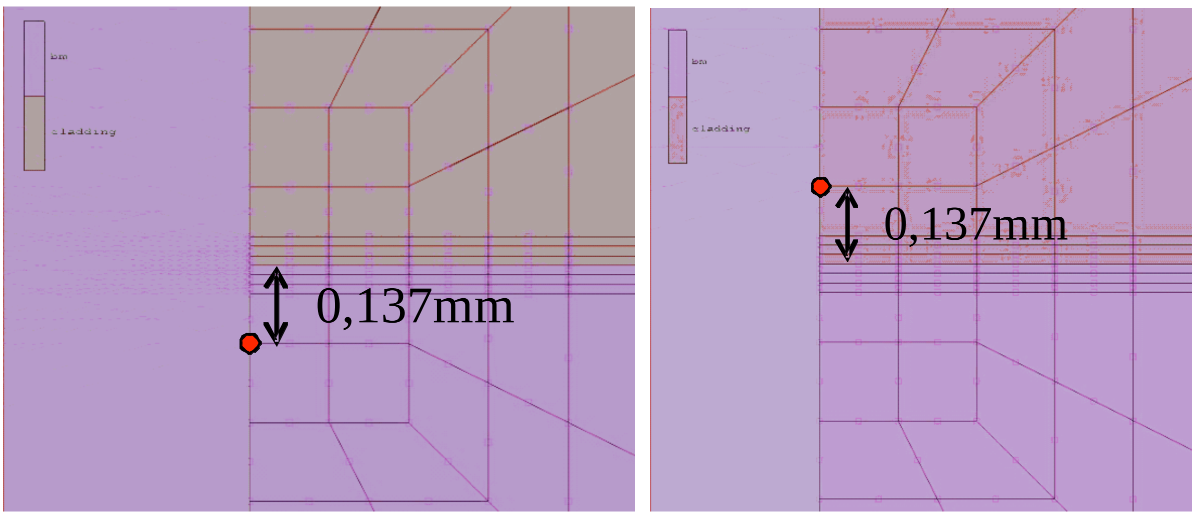



**Figure 8.** Crack tip and mesh at both side

The results can be seen on the Fig. 9. The total J-integral values are almost the same when the crack tip is under or above the interface but the $C_{\Gamma F}$ is strongly different. So the J is different because of the $C_{\Gamma F}$. J-integral values are also path independent when $C_{\Gamma F}$ has been taken off from the "total" J so the method applicable for this case as well.

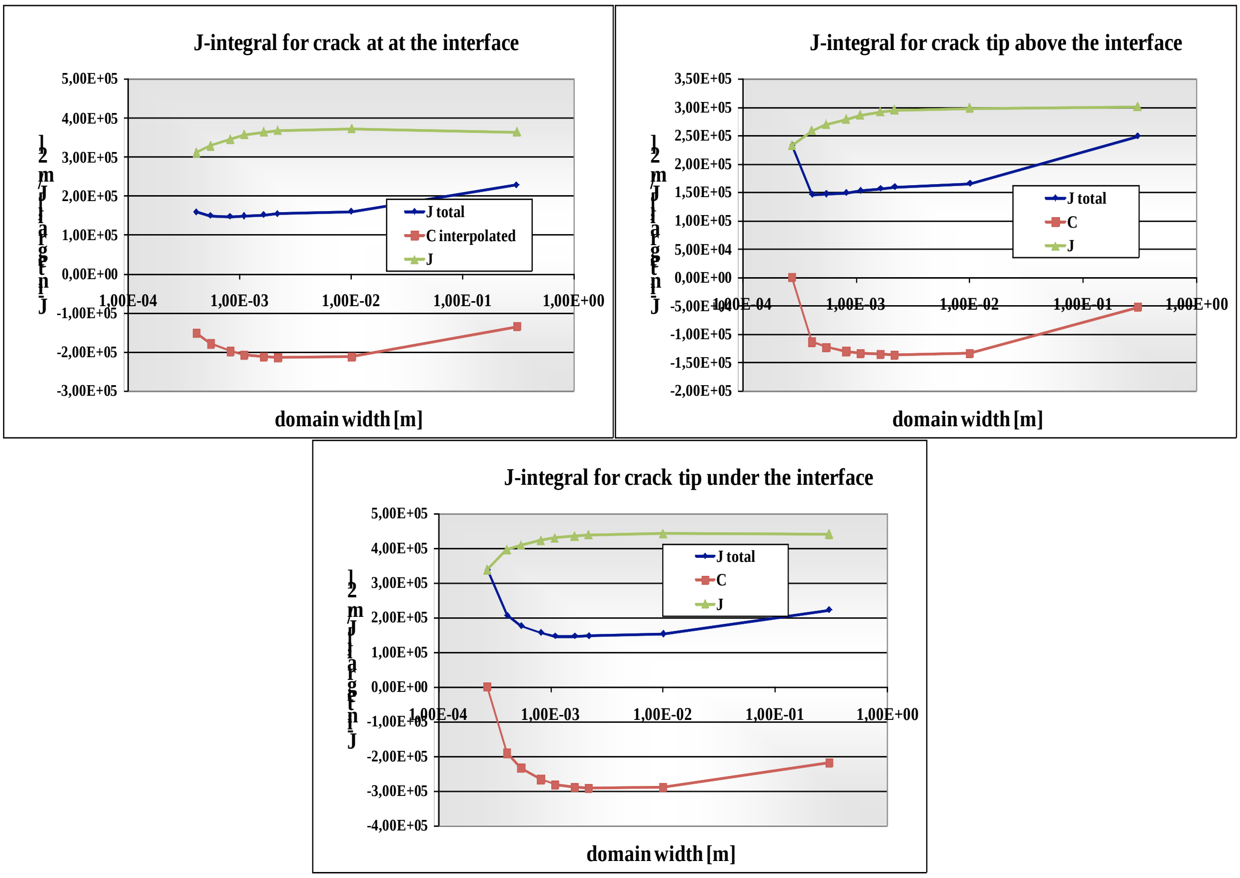



**Figure 9.** Integral values versus domain with close to the interface

The results can be plot together with the previously calculated J-integral values for under clad crack (Fig. 10.). It can be see that the extrapolation based on 3rd order approximation gives much lower values than the value determined by the applied method. At the interface there is a significant drop in J due to the different $C_{\Gamma F}$. However the J-integral value have been plotted as well it is no more than an average value since $C_{\Gamma F}$ has discontinuity at the interface.

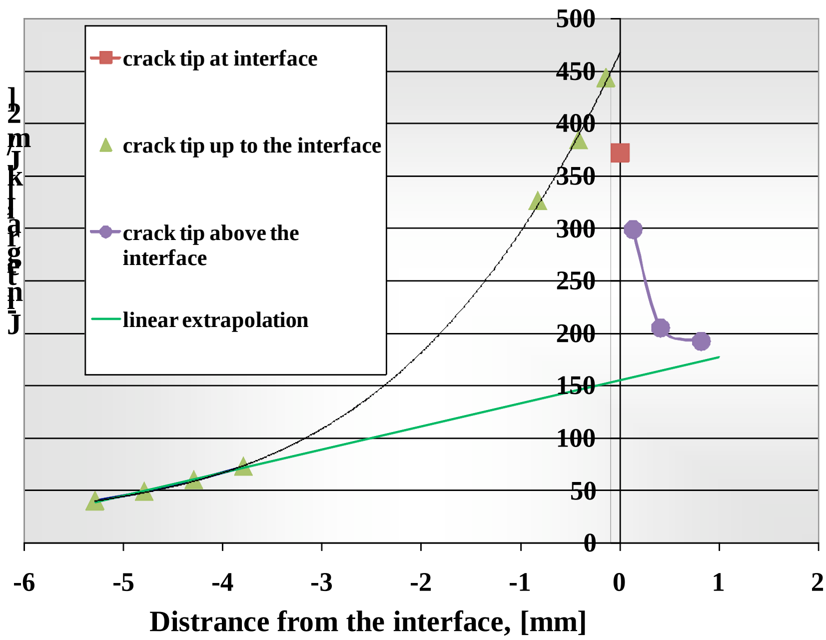



**Figure 10.** J-integral versus distance from the cladding interface

# 7 CONCLUSIONS

J-integral calculation was performed to study the effect of crack size in case of sub-clad flaws. Elastic-plastic material properties were applied, and the residual stresses were considered during the analysis. The effect of modified crack fronts was analyzed. $\Delta J/\Delta a$ have shown that the J-integral at upper crack front is sensitive for the crack tip position and conclusion cannot be drown to the interface, so virtual crack extension method has been extend to the cases when the integration domain contains secondary discontinuity. The proposed new method has been verified and the J-integral values for the situation when the crack tip is "on" the interface have been determined with the proposed new method. The calculation results show that the J-integral has a significant discontinuity at the interface that has to be taken into consideration at the fracture mechanical evaluation.

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