APPLICATION OF ENGINEERING METHODS ON REACTOR PRESSURE VESSEL INTEGRITY ASSESSMENT

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An easy–to–use integrated program system for fast engineering integrity assessment is presented. It has been specially tailored for analyses of pressurised thermal shock loading of reactor pressure vessels.

The applicability of the program system is demonstrated with an integrity evaluation of a cladded VVER–440 type reactor pressure vessel under strip–like cooling. The results agree well with those of detailed finite element analyses at the deepest point of the crack.

INTRODUCTION

Emergency cooling causes very severe loading on a reactor pressure vessel of a nuclear power plant. The high thermal stresses, combined with stresses due to internal pressure, may cause initiation and propagation of a possible crack in the material, which has been degraded by irradiation embrittlement.

To estimate the reactor pressure vessel structural safety in case of detected or postulated flaws, accurate finite element analysis methods are necessary. However, because in spite of powerful computers, they may be rather time-consuming to use, various engineering assessment methods are important as well. The latter are especially valuable in sensitivity analyses: for example, to study the criticality of several load cases combined with cracks in various locations of the structure.

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PROGRAM SYSTEM MASI

At VTT a program system has been developed for fast integrity assessment, especially for reactor pressure vessel (RPV) safety analysis under pressurised thermal shock (PTS) loading. This program system, called MASI, comprises effective routines for calculation of stresses, stress intensity factor values and plastic limit loads for the most common geometries in nuclear applications (Talja (1)).

The program system is completed with a Windows based user interface, which integrates the separate computing programs into an easy-to-use assessment tool (Figure 1). The event-driven graphical user interface helps the user in modelling the problem, judging the structural integrity and reporting and visualising the results. It takes care of the data exchange between computing programs and controls their execution.

PTS assessment with MASI

A PTS assessment is performed using MASI according to the following steps:

1) Geometrical, material and thermal loading parameters are defined in the Geometry, Material and Loading modules.
2) A DIFF input file is generated and the DIFF program is started in the Computing module to perform the thermal and stress analysis.
3) VTTSIF input files are generated by internally reading the output results of DIFF. VTTSIF is run to obtain the stress intensity factor values.
4) The results are presented as a stress intensity factor vs. crack tip temperature diagram.

Description of computing programs for PTS assessment

The DIFF program for thermal transient analysis in axisymmetric geometry (Raiko et al (2)) can handle temperature dependent material properties, two-layer cladded walls, time dependent boundary conditions, inside and outside temperatures and heat transfer coefficients on the surface. The thermal transient analysis is based on the method of finite differences. The program can consider simultaneously two sets of thermal boundary conditions, allowing an approximation of the effects of circumferentially varying cooling zones. Besides thermal analysis, the program calculates the stress state of the cylinder due to thermal and pressure loads. The stresses are calculated according to the analytical solution for a thick cylindrical shell. Linear material behaviour is assumed and the stress–free temperature of the bimetallic structure is used as an input parameter.

The VTTSIF program (Mikkola (3)) is applied to calculate stress intensity factor values. It applies either direct superposition of reference solutions for different load cases, the weight function method, or a combination of these. A weight function approximation method and in some cases also direct weight functions can be used.

At present the solutions available in the VTTSIF program are limited to crack opening mode I. They cover ten two–dimensional geometry cases, such as an edge crack in a finite width strip and crack cases in cylindrical geometry. The six three–dimensional geometry cases cover an embedded elliptical crack in an infinite solid, semi–elliptical surface crack in a plate and in a cylinder. In cylinder geometry, inner and outer surface axial crack cases and inner surface circumferential crack cases are available. Another real geometry case is a semi–elliptical surface crack on the inner surface of a pressure vessel nozzle connecting weld.

ASSESSMENT OF A VVER–440 REACTOR PRESSURE VESSEL

As an example, a cladded VVER–440 reactor pressure vessel with a hypothetical circumferential surface crack in a core region weld was analysed under pressurised thermal shock loading. Extensive comparative three–dimensional thermoplastic finite element analyses for the case have been presented by Sievers et al. (4).

The inner radius of the pressure vessel was 1771 mm, the cladding thickness 9 mm and the wall thickness including the cladding 149 mm (Figure 2). The loading was a thermo–mechanical transient due to a medium size loss of coolant with high pressure injection. The chosen transient consisted of an axisymmetric cooling phase followed by a strip–like cooling period. The time–dependent coolant temperatures in the strip and mixed areas are shown in Figure 2 and the corresponding heat transfer coefficient values in Table 1 (Kokkonen and Tuomisto (5)).

In the engineering assessments with MASI semi–elliptical circumferential inner surface through–cladding cracks with depths of 12 and 15 mm and a half crack length of 25 mm was assumed. The material parameters in Table 2 were used. The thermal boundary conditions were treated in a somewhat conservative way so that the temperature at the height of the nozzle, T_1, was applied along the whole strip length. A heat transfer coefficient value of 8 W/m^2K was used at the outer surface. In accordance with the proposals by Rajamäki (6) the stress–free temperature of the bimetallic pressure vessel wall was taken as 230°C. It was conservatively assumed that the internal pressure remains at a constant level of 13.7 MPa throughout the transient. The residual stresses in the circumferential weld were neglected.

TABLE 1 – Heat transfer coefficient values at the inner surface

Mixed area	Strip area, t < 1550 seconds	Strip area, t ≥ 1550 seconds
2000 W/m^2K	2000 W/m^2K	5000 W/m^2K

TABLE 2 – Material parameter values used in the engineering assessment.

	Base & weld metals		Cladding	
	20°C	300°C	20°C	300°C
Thermal conductivity [N/sK]	40.2	37.9	15.1	18.8
Specific heat per unit volume [N/m^2K]	$3.92*10^6$	$3.92*10^6$	$3.6*10^6$	$4.18*10^6$
Thermal expansion coefficient [1/°C]	$11.3*10^{-6}$	$13.1*10^{-6}$	$16.3*10^{-6}$	$17.4*10^{-6}$
Young's modulus [GPa]	210	195	205	180

For a cladded pressure vessel wall the present methodology can be applied accurately only at the deepest point of the crack. The stress intensity factor values are based on linear stress analysis only. In a thermal shock loading, the different thermal expansion properties of base and cladding materials cause a steep stress gradient at the cladding base material interface: high tensile stresses in the cladding and low compressive stresses in the base material. Thus the weight function method applied can yield only approximate stress intensity factor values in the cladding and cladding base material interface areas. For complex crack configurations no weight functions have been determined.

The stress intensity factor results are compared as a function of crack tip temperature at the deepest point of the crack in Figure 3 with the finite element results. The differences among the finite element results can be attributed to differences in modelling, like crack depth and shape (Fig. 3), description of the asymmetry of the cooling strip, and consideration of welding residual stresses (4). Interestingly, the stress intensity factor values for the 12 mm deep crack are somewhat higher than for the 15 mm deep crack. This is due to the special type of stress distribution. As a whole, the MASI results seem to correlate very well with those of finite element analyses. This is interesting, especially considering the small modelling and computing effort involved.

SUMMARY AND CONCLUSIONS

The MASI computing system for fast integrity assessments of cracked structures was presented. The applicability and accuracy of the system were demonstrated by analysing a strip–like pressurised thermal shock load case of a cladded VVER–440 reactor pressure vessel. The results at the deepest point of the crack showed that effective engineering assessment tools may yield results which agree well with those obtained using extensive elastic–plastic three–dimensional finite element analyses. Thus they offer a very useful way to extend the coverage of safety assessments, as detailed finite element analyses can still only be performed with a limited number of the most critical parameter value sets.

ACKNOWLEDGEMENT

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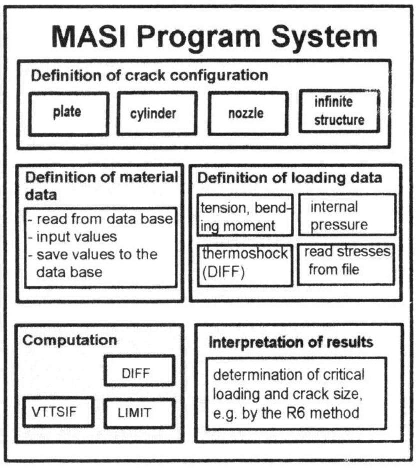

Figure 1 Structure of the MASI program system

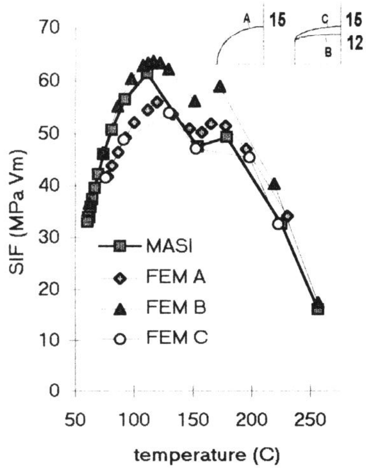

Figure 3 Results of the VVER RPV assessment

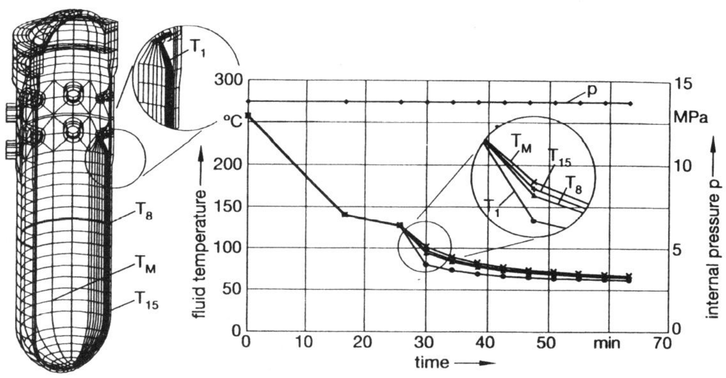

Figure 2 Geometry and loading assumptions in the PTS assessment for a VVER reactor pressure vessel (4)