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STUDY OF THE NUCLEAR POWER PLANT CONTAINMENT DAMAGE CAUSED BY IMPACT OF A PLANE

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Abstract: *The article is a contribution to the discussion concerning nuclear safety which has intensified after the Fukushima Daiichi nuclear disaster. The parametric study presented here is focused on the containment damage evaluation for various materials, containment wall thicknesses and different aircraft speeds before impact. A detailed analysis of plane impact is also included. The solution was obtained by the explicit finite element method utilizing the RFEM program. The knowledge gained from this study might also be applied to the detailed impact analysis of a plane on other particular nuclear power plant containment structures as needed. The purpose of this study was also to foster experiential suggestions for improving the explicit method in the RFEM program in order to release it for RFEM users.*

Keywords: ***Damage extent, explicit method, finite element method, impact, nuclear safety.***

1. Introduction

Every After the Fukushima Daiichi nuclear disaster on March 11, 2011 great interest in nuclear safety has arisen among the public, professionals and authorities, exemplified in a paper by Králik. Following the accident, every country generating nuclear energy launched assessing of the response of the nuclear power plant to severe external events in order to verify safety. The presented article is a contribution to this discussion. The paper investigates the effects of the impact of an airliner on the containment structure of a nuclear power plant. A parametric study was performed and some its results are presented in the sections below.

The shape and dimensions of the containment structure correspond with the Bushehr nuclear power plant containment. The choice of dimensions of the structure model was based on data found in technical literature. A Boeing 737 was chosen as the impacting body. Parameters of the model (such as dimensions, weight etc.) were chosen in accordance with Boeing 737 specifications. A parametric study was performed for various materials, wall thicknesses and different plane speeds before impact. Wall thicknesses of the steel containments were within the range of 0.05 m to 0.14 m. Wall thicknesses of the reinforced concrete containments were within the range of 0.5 m to 1.8 m. As for the speed of the aircraft before the impact, two different values were considered. The speed of 500 km/h was chosen to represent the accidental impact of a plane into the structure. The speed of 876 km/h, which is the maximum speed of a Boeing 737, was considered in representing an intentional plane crash.

2. The calculation method used

Solution of the problem was obtained by the explicit finite element method, which has been successfully applied to various nonlinear transient dynamics problems in past decades. This method is currently in development and is used either in manufacturing processes or research activities. It is suitable for the analysis of (highly) nonlinear fast processes such as impact (crashworthiness analysis), explosion, bullet penetration, metal cutting etc.

Explicit FEM is basically an incremental method. The time domain is divided into a finite number of time instants and the distance between two instants is called time step size Δt . The first and second

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time derivatives of displacement (position) $\boldsymbol{u}_i$ are approximated by the finite difference method. The central difference method ranks among the most popular explicit methods in computational mechanics. Velocity $\dot{\boldsymbol{u}}_i$ and acceleration $\ddot{\boldsymbol{u}}_i$ are then approximated by means of the central difference method as:

$$\dot{\boldsymbol{u}}_i = \frac{\boldsymbol{u}_{i+1} - \boldsymbol{u}_{i-1}}{2\Delta t} \tag{1}$$

$$\ddot{\boldsymbol{u}}_i = \frac{\boldsymbol{u}_{i+1} - 2\boldsymbol{u}_i + \boldsymbol{u}_{i-1}}{\Delta t^2} \tag{2}$$

The system of equations of motion can be written using (1) and (2) in the form:

$$\left(\frac{1}{\Delta t^2}\boldsymbol{M} + \frac{1}{2\Delta t}\boldsymbol{C}\right)\boldsymbol{u}_{i+1} = \boldsymbol{F}_i - \left(\boldsymbol{K} - \frac{2}{\Delta t^2}M\right)\boldsymbol{u}_i - \left(\frac{1}{\Delta t^2}\boldsymbol{M} - \frac{1}{2\Delta t}\boldsymbol{C}\right)\boldsymbol{u}_{i-1} \tag{3}$$

As the method was seen to have all the advantages of the explicit scheme as long as the damping matrix $\boldsymbol{C} = \boldsymbol{0}$ or $\mathbf{C} = \alpha\mathbf{M}$, Raileigh damping (4) with coefficient $\beta = 0$ was applied to the model. The coefficient α was reflected with a magnitude of 3.0 for the reinforced concrete and 0.1 for the structural steel.

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K} \tag{4}$$

The explicit method is conditionally stable. It means that a stability condition (5) has to be satisfied.

$$\Delta t < \Delta t_{crit} \tag{5}$$

$$\Delta t_{crit} = \frac{2}{\omega} \quad \text{or} \quad \Delta t_{crit} = \frac{l}{c} \tag{6}$$

where ω is the lowest element natural frequency, *l* is the characteristic length of the smallest element and *c* is the wave speed. For the reinforced concrete containment a time step of 5e-5 sec was applied and for the steel containment a time step of 1e-5 sec was applied. Calculations were terminated when the vibrations of the containment structure became negligible. The analyses were performed by the RFEM program.

3. Containment damage

The study focused on two types of containments: steel and reinforced concrete containment structures. In the case of the steel containments common structural steel was used and the von Mises yield criterion was applied. As regards reinforced concrete containments, a degree of reinforcement was assumed that would guarantee that no yielding would occur when loading the containment by a constant value of overpressure. This value was 0,43 MPa, as recommended in technical papers.

A series of calculations of varying thicknesses of the steel and reinforced concrete containments were performed. The resulting containment damage was for purposes of this study assessed by means of the value of permanent deformation and extent of plastic strain. Graphical representational examples of the studied maximal values displayed on the deformed containment structures are presented below. Comparing the reinforced concrete and steel containments, qualitatively different deformation shapes could be observed. The permanent displacement shapes of reinforced concrete containments are approximately circular and the permanent displacement shapes of steel containments are rather irregular. This qualitative difference in deformation and plastic yielding patterns is caused by the fact that these two materials (reinforced concrete and steel) have different ratios between bending and membrane stiffnesses. Membrane stiffness increases linearly with thickness whereas bending stiffness increases with the third power of thickness.

Fig. 1 displays the course of the plane impact into the containment structure in real time of 0.05 s, 0.13 s, 0.25 s a 0.6 s.

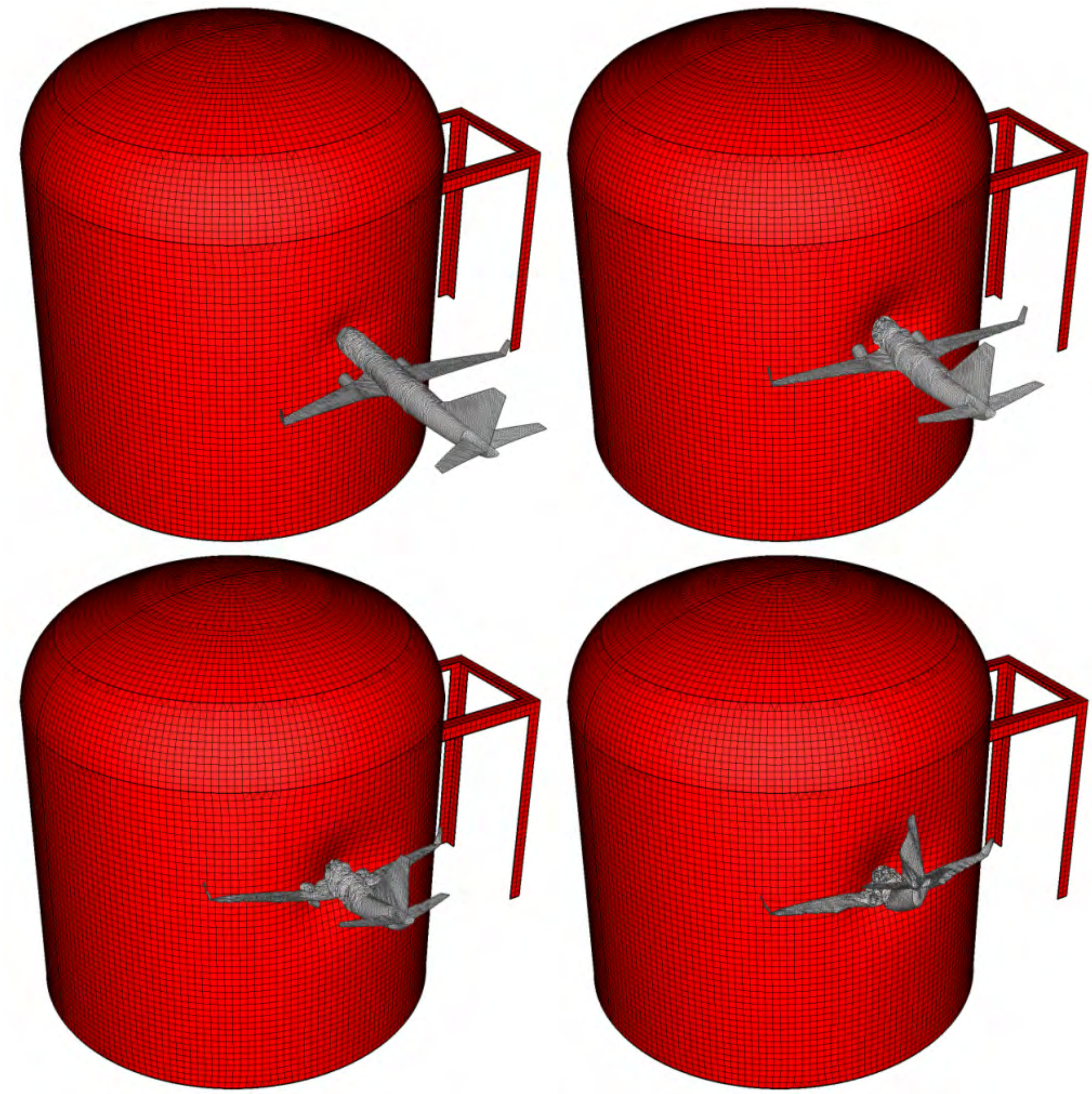

Fig. 1 *Impact of a plane*

3.1 The steel containments

Fig. 2 and 3 represent a series of calculations concerning plane impact at maximum speed and the speed of 500 km/h into steel containment structures. The deformed structure and the extent of plastic strain for the steel containment with a wall thickness of 0.05 m are displayed in these figures. The results summary is given in the Tab. 1.

Tab. 1 Steel containments damage

	Wall thickness [m]	0,05	0,08	0,10	0,12	0,14
500km/h	Max displacement [m]	2,80+0	1,03E+0	8,71E-1	2,35E-1	1,73E-1
	Plastic yielding	2,58E-2	1,80E-2	1,30E-2	7,20E-3	5,10E-3
876km/h	Max displacement [m]	1,03E+1	5,84E+0	4,03E+0	3,27E+0	2,66E+0
	Plastic yielding	9,18E-2	5,31E-2	4,36E-2	3,55E-2	3,23E-2

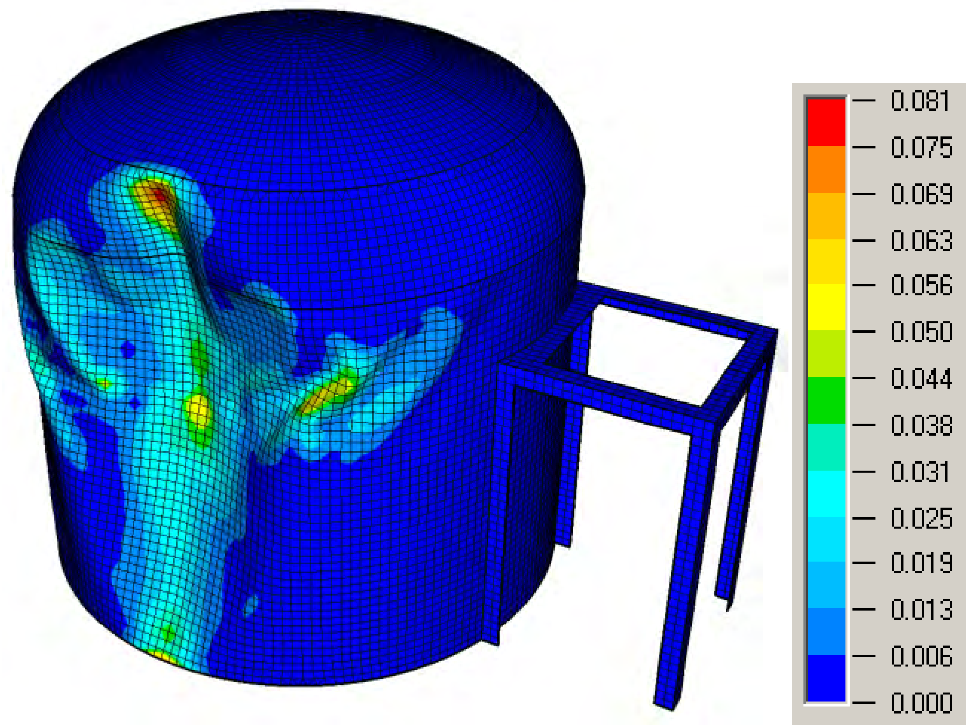

Fig. 2 *Steel containments – maximum speed*

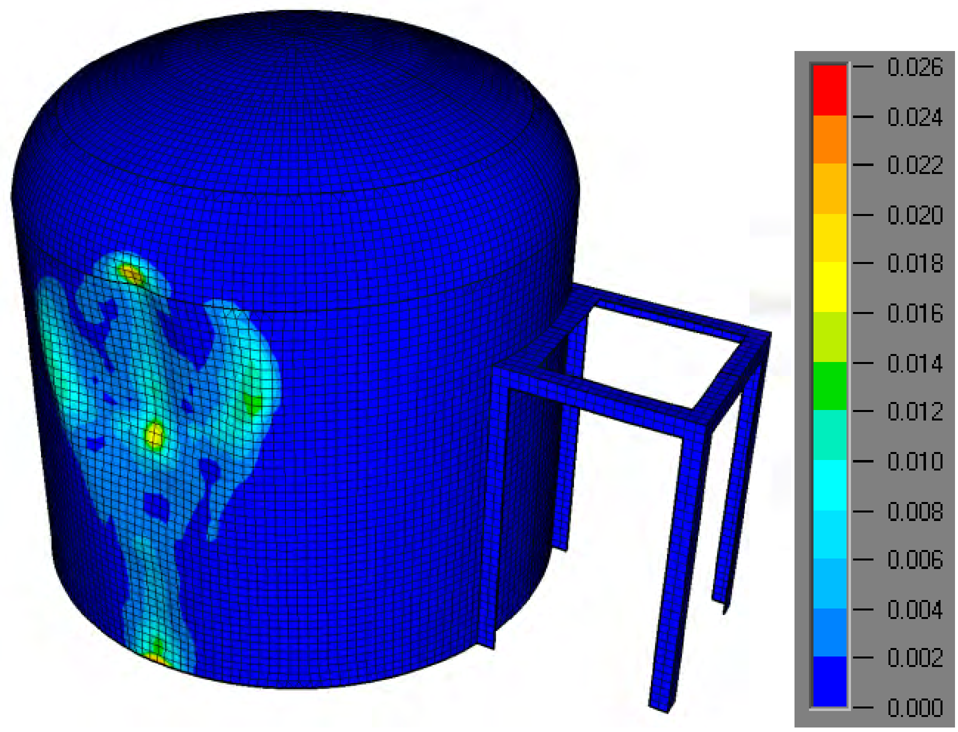

Fig. 3 *Steel containments – 500 km/h*

3.2 The reinforced concrete containments

The deformed structure and the extent of plastic strain for a reinforced concrete containment with a wall thickness of 0.6 m are displayed in the Fig. 4 and 5 for both investigated speeds of the plane before the impact. The results summary is given in the Tab. 2.

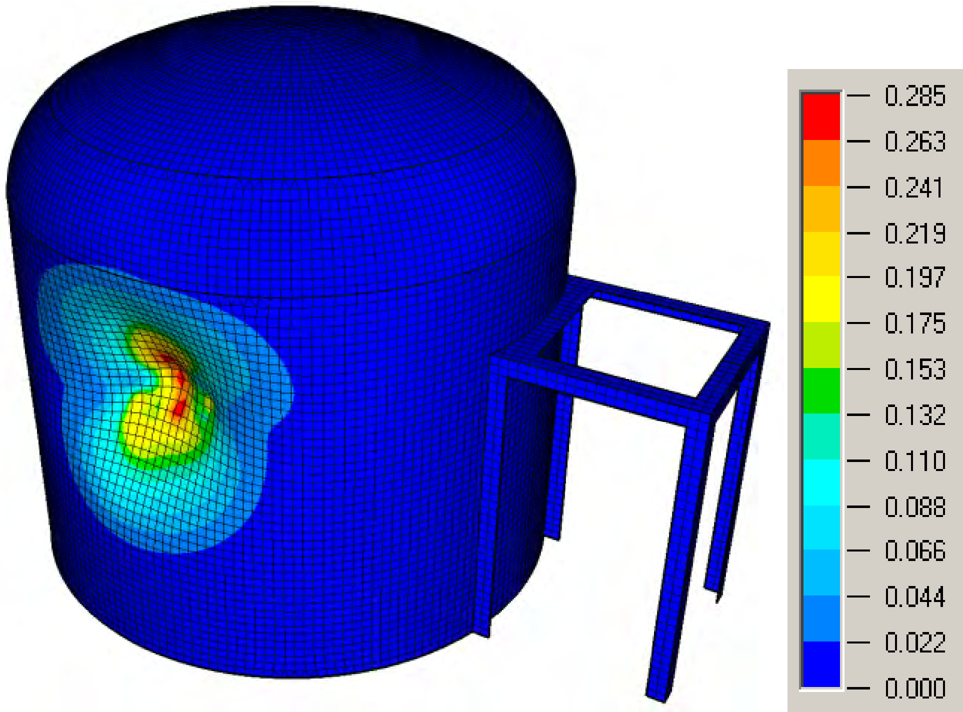

Fig. 4 *Reinforced concrete containments – maximum speed (876 km/h)*

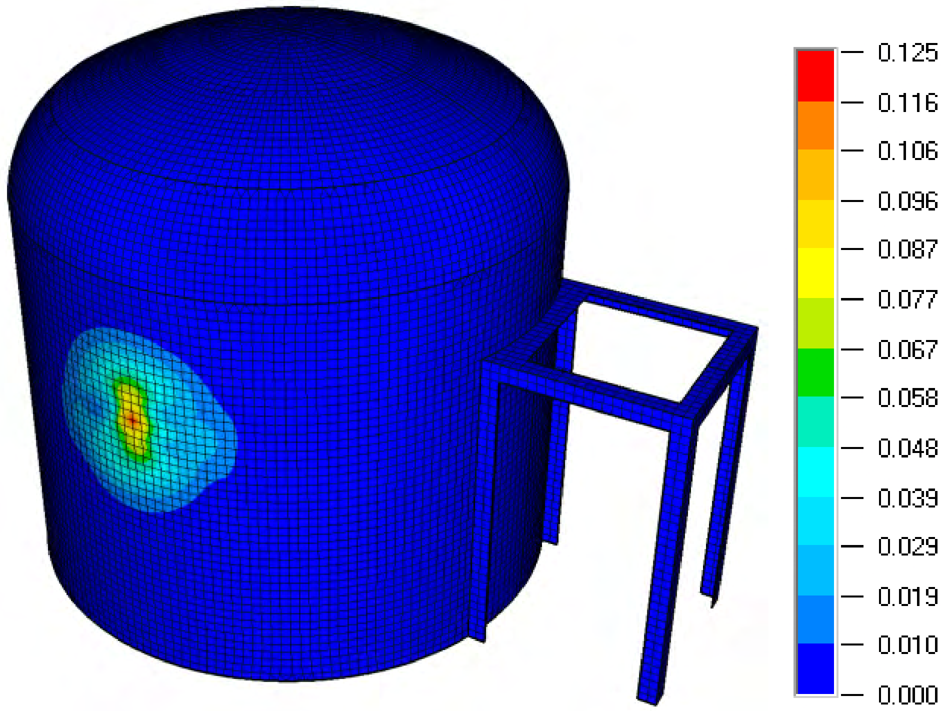

Fig. 5 *Reinforced concrete containments – 500 km/h*

Tab. 2 Reinforced concrete containments damage

	Wall thickness [m]	0,60	0,80	1,00	1,20	1,40	1,60	1,80
500km/h	Max displacement [m]	2,43E+0	9,90E-1	1,37E-1	1,61E-2	4,01E-3	1,01E-3	2,16E-4
	Plastic yielding	1,25E-1	8,00E-2	1,70E-2	2,70E-3	9,40E-4	4,26E-4	1,90E-4
876km/h	Max displacement [m]	8,26E+0	6,06E+0	4,52E+0	3,25E+0	2,07E+0	1,06E+0	4,19E-1
	Plastic yielding	2,85E-1	2,65E-1	2,54E-1	2,40E-1	1,88E-1	1,27E-1	6,40E-2

4. Conclusions

The paper has introduced a parametric study of the damage caused by impact of an airliner on a nuclear power plant containment structure. The parametric study was a serial analysis of reinforced concrete and steel containment structures of different thicknesses. A conventional containment structure (large dry PWR) was chosen as the target and an aircraft the size of a Boeing 737 was chosen as the impacting body for the study.

The study proves the capability of the RFEM program to analyze nonlinear transient dynamic effects. The results of the study can also serve in estimating the damage caused by the impact of a plane into any similar nuclear power plant containment. The study also indicates that there is low probability of radioactive material leakage from the analyzed containments during such an event despite extensive damage to the structures.

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