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Study of a Nuclear Power Plant Containment Damage Caused by Impact of a Plane

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ABSTRACT: *This article is a contribution to the discussion about nuclear safety which has arisen after the Fukushima Daiichi nuclear disaster. The paper does not deal with the containment of a particular nuclear power plant, but analyses the impact of an airliner on a containment structure. The following parametric study involving different materials and thicknesses could be used to estimate the extent of damage caused by the impact of a plane on any specific planned or existing nuclear power plant containment structure. 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.*

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

I. INTRODUCTION

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 [1]. 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 its results are presented in the sections below.

The paper is organized as follows:

Section 2 introduces the shape and parameters of the containment and the plane. Section 3 describes the applied calculation method and the parameters of calculation. In section 4 the calculation results are presented and finally in section 5 conclusions are stated.

II. THE CONTAINMENT AND THE PLANE

The shape and size of the containment building was derived from the Bushehr nuclear power plant containment. The choice of dimensions of the structure model (see Fig. 2.1) was based on data found in [2] - [4]. 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 papers [2] and [4].

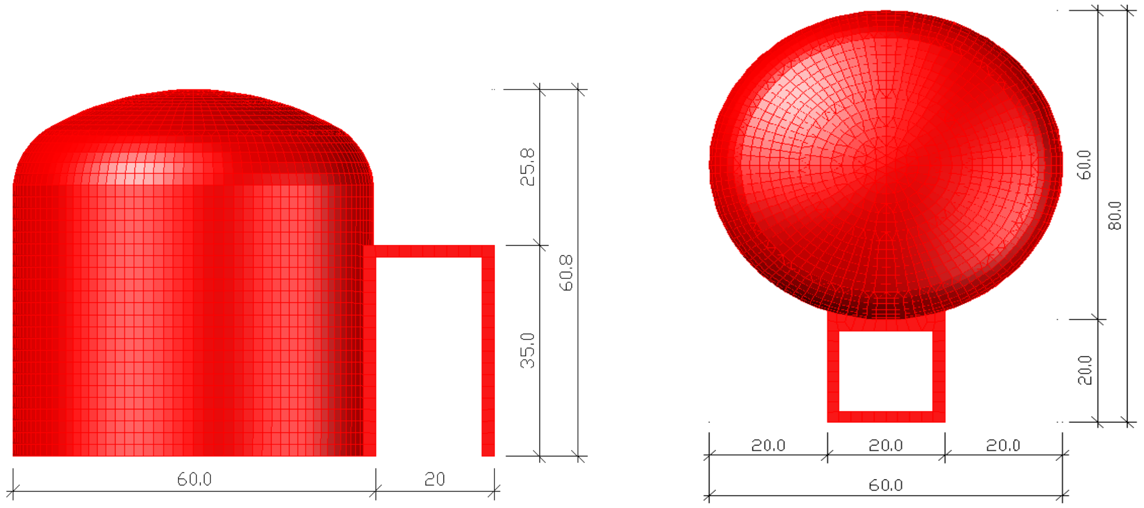

Fig. 2.1 Shape and dimensions of the containment structure model

The airliner model dimensions correspond to a Boeing 737 (see Fig. 2.2.). Parameters of the model (such as dimensions, weight etc.) were chosen in accordance with Boeing 737 Specifications stated in [5]. For calculation of the plane's impact on the containment, a speed of 500 km/h at the moment of impact was chosen.

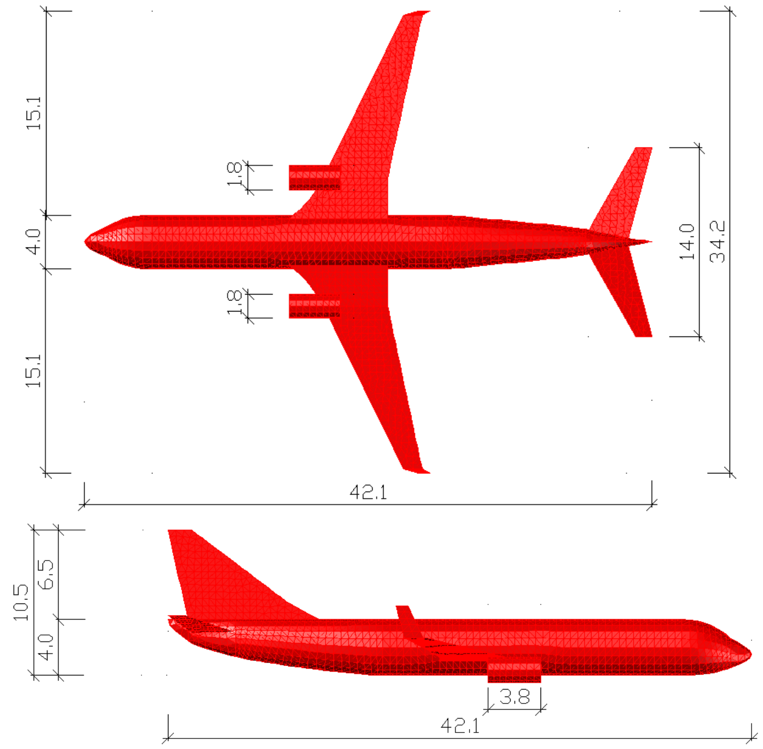

Fig. 2.2 Dimensions of the airliner model

III. 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 [6]. 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 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 [7]. Velocity $\dot{\boldsymbol{u}}_i$ and acceleration $\ddot{\boldsymbol{u}}_i$ are then approximated by means of the central difference method as:

$$\dot{\boldsymbol{u}}_i = \frac{\boldsymbol{u}_{i+1}-\boldsymbol{u}_{i-1}}{2\Delta t} \tag{3.1}$$

$$\ddot{\boldsymbol{u}}_i = \frac{\boldsymbol{u}_{i+1}-2\boldsymbol{u}_i+\boldsymbol{u}_{i-1}}{\Delta t^2} \tag{3.2}$$

The system of equations of motion can be written using (3.1) and (3.2) in the form[2]:

$$\left(\frac{1}{\Delta t^2}\boldsymbol{M}+\frac{1}{2\Delta t}\boldsymbol{C}\right)\boldsymbol{u}_{i+1} = \boldsymbol{F}_i - \left(\boldsymbol{K}-\frac{2}{\Delta t^2}M\right)\boldsymbol{u}_i - \left(\frac{1}{\Delta t^2}\boldsymbol{M}-\frac{1}{2\Delta t}\boldsymbol{C}\right)\boldsymbol{u}_{i-1} \tag{3.3}$$

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 $\boldsymbol{C} = \alpha\boldsymbol{M}$ [8], Raileigh damping (3.4) 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.

$$\boldsymbol{C} = \alpha\boldsymbol{M} + \beta\boldsymbol{K} \tag{3.4}$$

The explicit method is conditionally stable. It means that a stability condition (3.5) has to be satisfied.

$$\Delta t < \Delta t_{crit} \tag{3.5}$$

$$\Delta t_{crit} = \frac{2}{\omega} \qquad \text{or} \qquad \Delta t_{crit} = \frac{l}{c} \tag{3.6}$$

where ω is the lowest element natural frequency, l is the characteristic length of the smallest element and c is the wave speed [6] [7]. 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 described e.g. in [8].

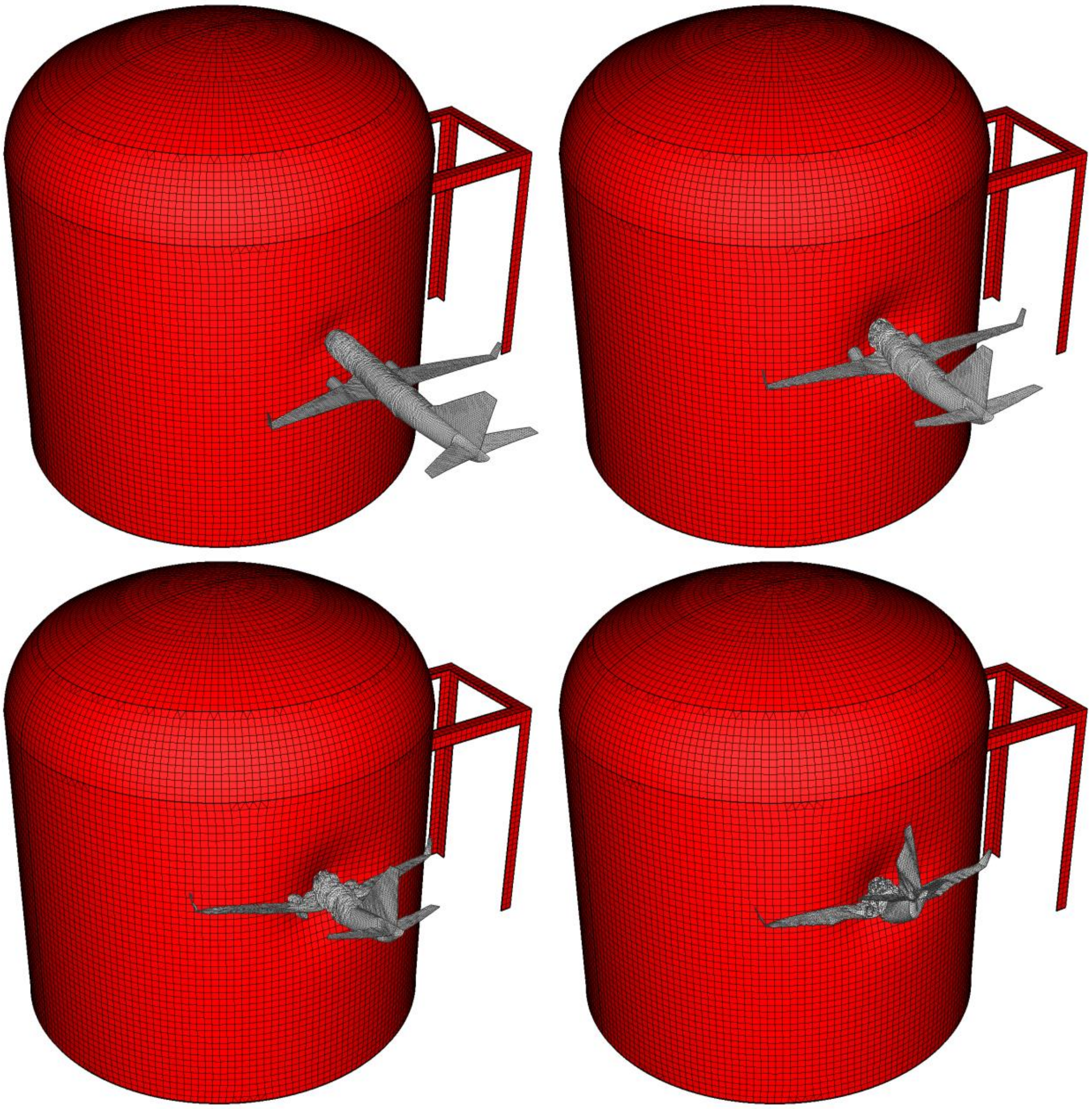

Fig. 3.1 Impact of the airliner into the containment structure in real time
(0.05 s, 0.13 s, 0.25 s and 0.6 s)

IV. THE RESULTING DAMAGE

A series of calculations of varying thicknesses of the steel and reinforced concrete containments were performed. Permanent damage, particularly permanent deformations and plastic strains, were investigated.

The results of several calculations are presented below. Permanent deformations and plastic strains for three containments with thicknesses 0.6 m, 1.0 m and 1.4 m representing the series of calculations for reinforced concrete are displayed in the Fig. 4.1.

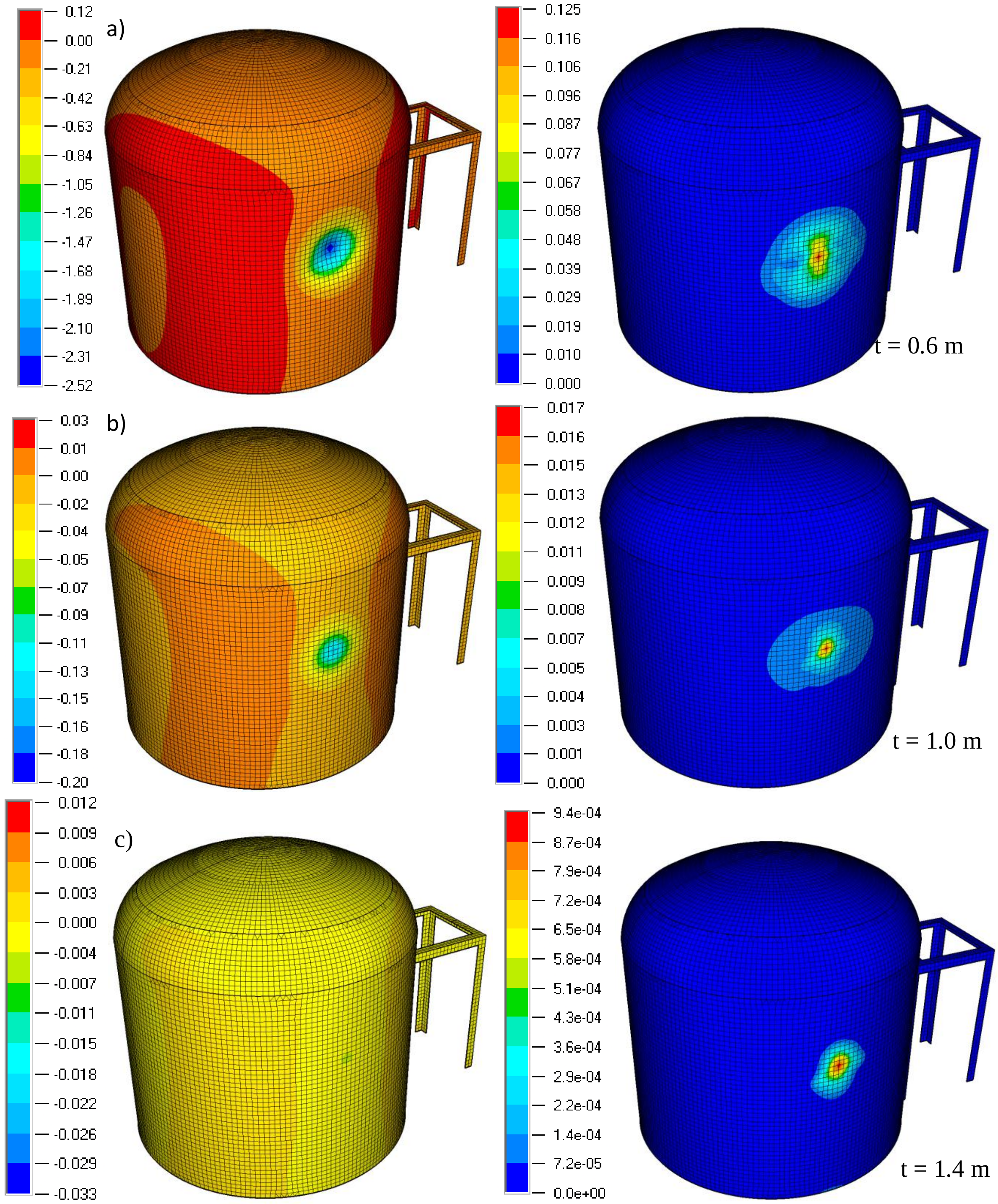

Fig. 4.1 Permanent deformations and plastic strain extension for reinforced concrete containments

The results for steel containments are presented analogously to the above. Permanent deformations and plastic strains for three containments with thicknesses of 0.06 m, 0.10 m and 0.14 m representing the series of calculations for steel are displayed in the Fig. 4.2.

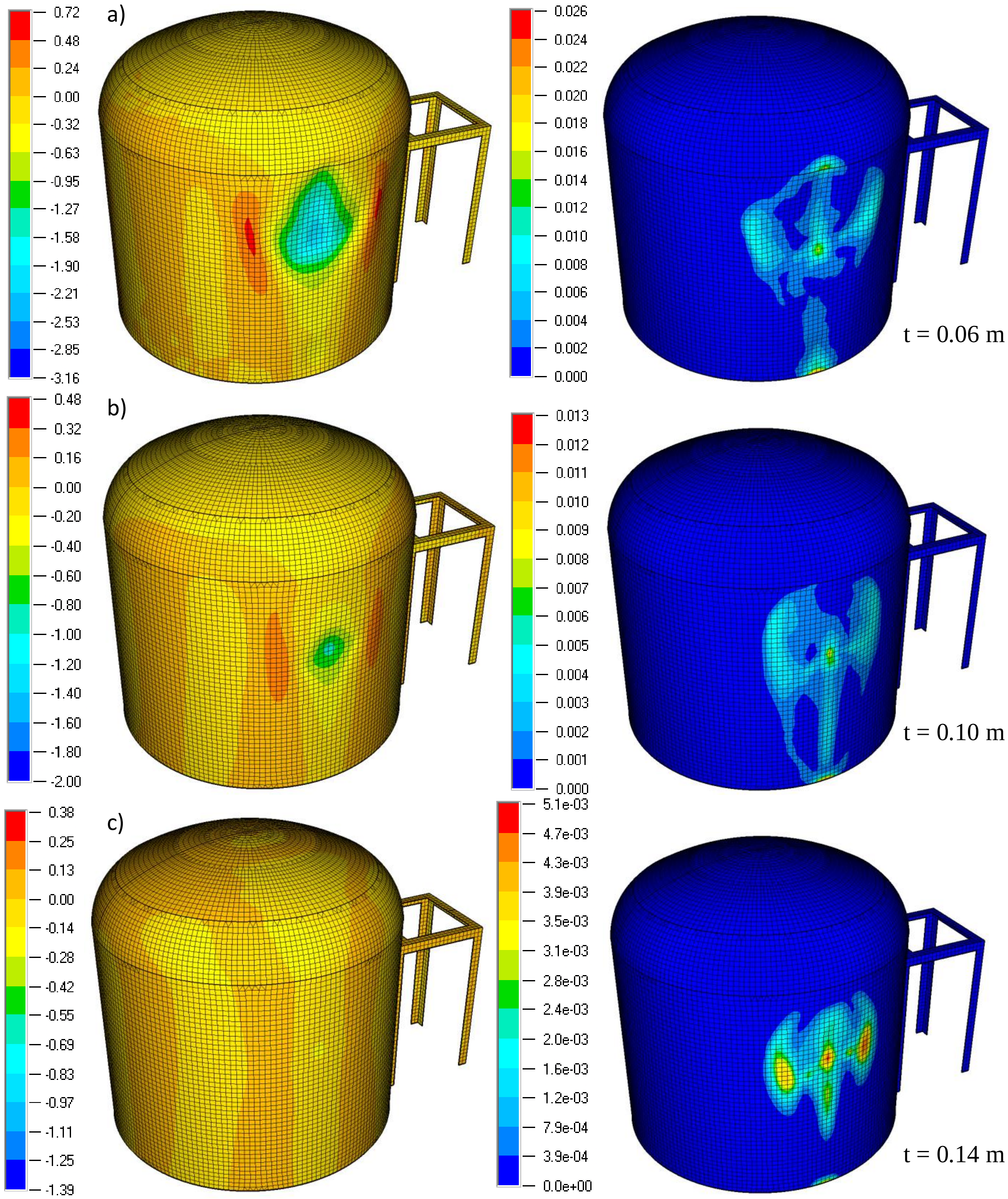

Fig. 4.2 Permanent deformations and plastic strain extension for steel containments

Qualitatively different deformation shapes can be observed, when comparing the two types of containments i.e. reinforced concrete and steel. In case of reinforced concrete the permanent displacement shapes are approximately circular in correspondence with the plastic yielding shapes. Contrarily shapes pertinent to steel containment are irregular and also the impact of engines is more perceptible. The circular deformation shapes which occur in the series of reinforced concrete containments are caused by the much higher bending stiffness of reinforced concrete in comparison with steel. This qualitative difference in deformation and plastic yielding patterns is caused by the fact that these two materials have different ratios between bending and membrane stiffnesses since membrane stiffness increases linearly with thickness whereas bending stiffness increases with the third power of thickness.

Figures characterizing the extent of permanent damage, particularly maximum displacement and maximum von Mises plastic yielding, for different containment thicknesses are introduced in the tables 4.1 and 4.2.

Wall thickness [m]	0,6	0,7	0,8	0,9	1	1,1	1,2	1,3	1,4
Displacement [m]	2,43E+0	1,70E+0	9,90E-1	4,26E-1	1,37E-1	3,96E-2	1,61E-2	7,84E-3	4,01E-3
Plastic yielding	1,25E-1	1,10E-1	8,00E-2	5,00E-2	1,70E-2	6,00E-3	2,70E-3	1,50E-3	9,40E-4

Table 4.1 Maximum displacements and maximum plastic strain for reinforced concrete containments

Wall thickness [m]	0,05	0,06	0,07	0,08	0,10	0,12	0,14	0,16
Max displacement [m]	2,80+0	2,13E+0	1,57E+0	1,03E+0	8,71E-1	2,35E-1	1,73E-1	1,47E-1
Plastic yielding	2,58E-2	2,60E-2	2,56E-2	1,80E-2	1,30E-2	7,20E-3	5,10E-3	5,87E-3

Table 4.2 Maximum displacements and maximum plastic strains for steel containments

V. 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. Calculations were performed utilizing the RFEM program applying the explicit finite element method. The aim of the calculations was to determine the extent of damage, mainly the magnitudes of permanent deformations. For the thickest containments in the series only insignificant plastic yielding was detected. Thus the behavior of these structures could be considered as elastic with no occurrence of permanent damage to the structures. Contrarily, where the lowest thicknesses were applied a massive plastic yielding occurred with massive damage.

As regards the reinforced concrete containments for thicknesses greater than 1.4 m permanent damage is negligible. For thicknesses lower than 1.0 m considerable plastic strains occurred. On opposite surfaces of the containment shell different signs of strain are obtained with the negative sign prevailing. Even if on the shell surfaces severe damage and cracking might appear the inner part of the body near the neutral axis could remain without substantial damage preventing possible leaks of radioactive material. However, more detailed analyses of specific particular stiffnesses and reinforcements should be performed.

Concerning the steel containments we have presented in this paper (with thicknesses 0.06, 0.10 and 0.14 m) some plastic yielding and permanent deformations occurred. However, a maximal obtained plastic yielding (value 0.026) should not lead to a steel rupture leading to a leakage of radioactive material.

The results of the parametric study could either serve for estimating the damage caused by the impact of a plane to any particular nuclear power plant containment or assist in assesment of calculations of other similar containments. This parametric study was performed in consideration of a flight speed of 500 km/h. Further research incorporating maximum airliner speed will be forthcoming.

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