Numerical simulation of deformation and fracture of space protective shell structures from concrete and fiber concrete under pulse loading

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Abstract. This paper presents results of numerical simulation of interaction between aircraft Boeing 747-400 and protective shell of nuclear power plant. The shell is presented as complex multilayered cellular structure comprising layers of concrete and fiber concrete bonded with steel trusses. Numerical simulation was held three-dimensionally using the author's algorithm and software taking into account algorithms for building grids of complex geometric objects and parallel computations. The dynamics of stress–strain state and fracture of structure were studied. Destruction is described using two-stage model that allows taking into account anisotropy of elastic and strength properties of concrete and fiber concrete. It is shown that wave processes initiate destruction of shell cellular structure—cells start to destruct in unloading wave, originating after output of compression wave to the free surfaces of cells.

1. Introduction

Shell structures find wide application in different fields: oil and gas pipelines, containers of different kinds used for materials storage and transportation, different types of aircrafts: planes, ballistic missiles; special building structures intended for protection of objects from natural and man-made impacts. While designing new structures along with analyzing behavior of separate elements under different impacts the overall structural behavior should be also analyzed. Full-scale experiments in this case would generally imply large material costs though the required result will not always be obtained. This significantly concerns dynamic processes requiring information on particular parameters at different periods. Thus, the need arises in models and methods enabling to perform analysis and predict structural behavior under different operational loads and possible abnormal situations. Proper definition of structural behavior should take into account 3D nature of the stress–strain state specified by several factors:

- presence of elements leading to geometrical asymmetry;
- consideration of the real loading conditions generally being non-symmetrical;
- anisotropy of physical-mechanical properties of materials that structural elements are made of.

In case one of the given factors takes place, it defines carrying 3D analysis. This complex task implicates developing adequate model describing structural behavior as well as real consideration of geometry and spatial configuration of different elements of structure. The paper presents numerical modeling results of interaction between aircraft Boeing 747-400 and protective shell structure of nuclear power plant. The shell was presented as complex multilayered cellular structure comprising layers of concrete and fiber concrete bonded with steel trusses.

2. Description of protective shell design model

Studies devoted to destruction of concrete and reinforced concrete structures are commonly conducted under static loading, whereas structural behavior under dynamic loading is understudied. Generally, engineering techniques are used for the research, though they do not take into consideration many factors, which are crucial during dynamic loads testing. In the present work, concrete structure behavior is described three-dimensionally [1]. For numerical calculations authors software and algorithm enabling performing parallel calculations with high performance are used [2], software is based on finite element method modified for solving dynamic tasks [3]. Destruction of concrete and fiber concrete under dynamic loading is described by means of two-stage model allowing taking into account anisotropy of elastic and strength properties of concrete and fiber concrete [1], using Hoffman criterion, considering differences in ultimate compressive strength and ultimate tensile strength of concrete and fiber concrete:

$$\begin{aligned} f(\sigma) = C_1(\sigma_2-\sigma_3)^2 + C_2(\sigma_3-\sigma_1)^2 + C_3(\sigma_1-\sigma_2)^2 + \\ C_4\sigma_1 + C_5\sigma_2 + C_6\sigma_3 + C_7\sigma_4^2 + C_8\sigma_5^2 + C_9\sigma_6^2 \geq 0. \end{aligned} \tag{1}$$

Here coefficients C_{1-9} are found from the following equations:

$$\begin{aligned} C_1 = [(Y_tY_c + Z_tZ_c)^{-1} - X_tX_c)^{-1}]/2, \\ C_2 = [(X_tX_c + Z_tZ_c)^{-1} - Y_tY_c)^{-1}]/2, \\ C_3 = [(X_tX_c + Y_tY_c)^{-1} - Z_tZ_c)^{-1}]/2, \\ C_4 = X_t^{-1} - X_t^{-1}, C_7 = S_{yz}^{-2}, \\ C_5 = Y_t^{-1} - Y_t^{-1}, C_8 = S_{zx}^{-2}, \\ C_6 = Z_t^{-1} - Z_t^{-1}, C_9 = S_{xy}^{-2}, \end{aligned} \tag{2}$$

where X_t, X_c—ultimate tensile and compressive strength along X axis, Y_t, Y_c—ultimate tensile and compressive strength along Y axis, Z_t, Z_c—ultimate tensile and compressive strength along Z axis, S_{xy}, S_{yz}, S_{zx}—ultimate shear strength along the corresponding axes. Validity of the model is proved by experimental studies [4].

The general layout of protective shell in given in figure 1. The upper and lower cover of shell present three-layered structure. The upper layer material is fiber concrete 50 mm thick, the central layer material is concrete 200 mm thick and the lower layer material is fiber concrete 50 mm thick. In the given case due to complex geometry of structure the reinforcing elements were not defined clearly, their presence was accounted through elastic and strength properties of material.

Figure 2 presents cellular structure of shell made of fiber concrete. The shell generally consists of eight segments with steel trusses placed in between them. Physical-mechanical properties of materials are given in table 1.

Contact impact on the shell was replaced in calculations by impulse in accordance with the scheme given in [5]. The impulse direction coincided with falling of aircraft under angle of 10 degrees towards horizon. The areas of applied impulse are given in figure 3. The area loaded by aircraft body is marked dark color. Maximum impulse value is 250 MN. The conditions of aircraft-to-shell interaction corresponded with the parameters given in [5]. Time-dependent load distribution along the impact area is given in figure 4.

Table 1. Physical-mechanical properties of materials.

Material	ρ, kg/m^3	Sound velocity C_s, m/s	Poisson ratio	Tensile strength, MPa	Compressive strength, MPa	Shear strength, MPa	Young modulus E, GPa
Concrete	2450	4500	0.2	1.75	22	3.4	26
Fiberconcrete	2450	4500	0.2	3.4	41	6.5	41
Steel A400	7850	5930	0.3	400	400	400	204


a

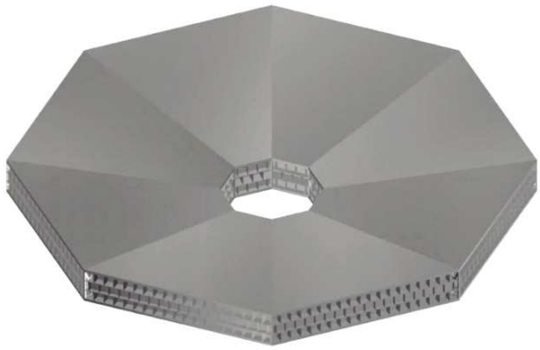

b

Figure 1. General layout of protective shell: a) top view, b) bottom view.

It should be noted that major concern while calculations of structures comprising large amount of different elements is making 3D finite-element grid. It is essentially a separate task and accuracy of calculations and time for its solving are dependent on that.

3. Results of dynamic calculations of protective shell of cellular structure to the loads of falling aircraft

Numerical studies of stress–strain state dynamics and fracture of protective shell under impulse action have been carried out. Analysis of stress–strain state shows that the area of tensile stress is being formed along the perimeter of impulse application area and inside the shell on the free surface of cellular structure thus leading to destruction of shell cellular structure. Tensile stress occurs because of compression wave output into free surface of cell that they reflect from by unloading waves. Existence of free surfaces inside the shell decreases the degree of compression stress on the one hand, while on the other hand leads to formation of tension areas where the destruction of cellular structure initiates and crack formation begins.

The dynamics of shell destruction can be observed in figure 5; destruction areas occurring on the front surface of shell can be seen at different periods. Destruction occurs directly in the area of impulse application and due to tensile stress action; cracks occur along the perimeter of load application and then propagate over the shell surface. Steel trusses deflect but destruction does not occur. It should also be noted that trusses are stress raisers due to sufficient difference in elastic and strength properties of steel and fiber concrete.

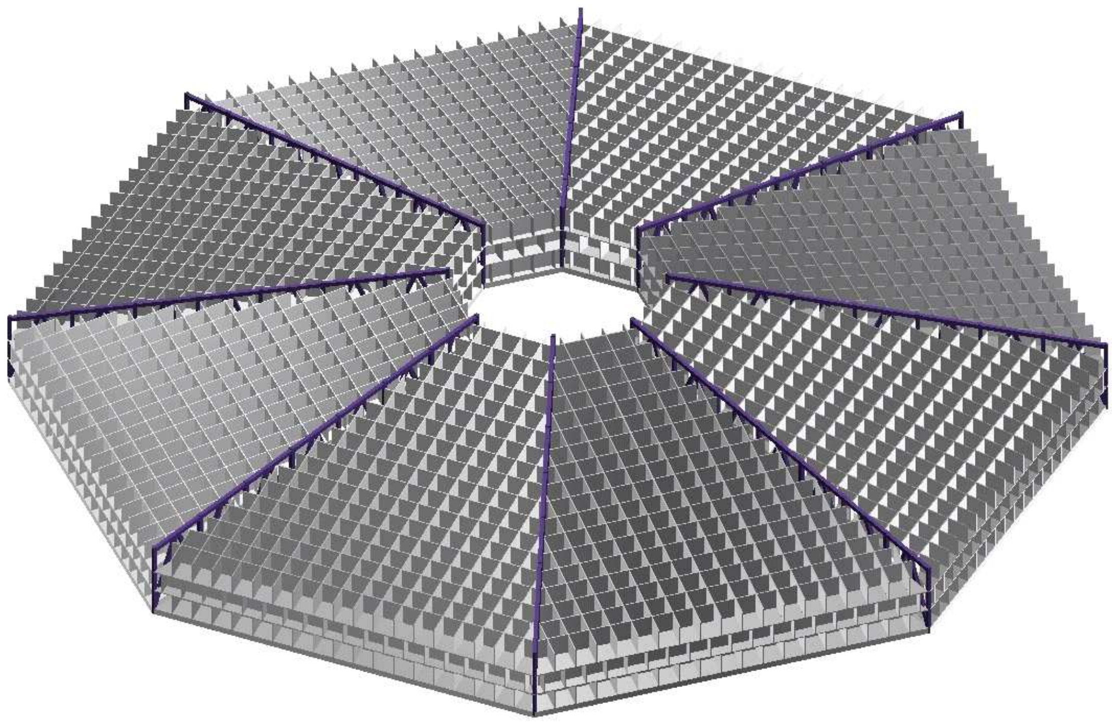


Figure 2. Inner cellular structure of shell.

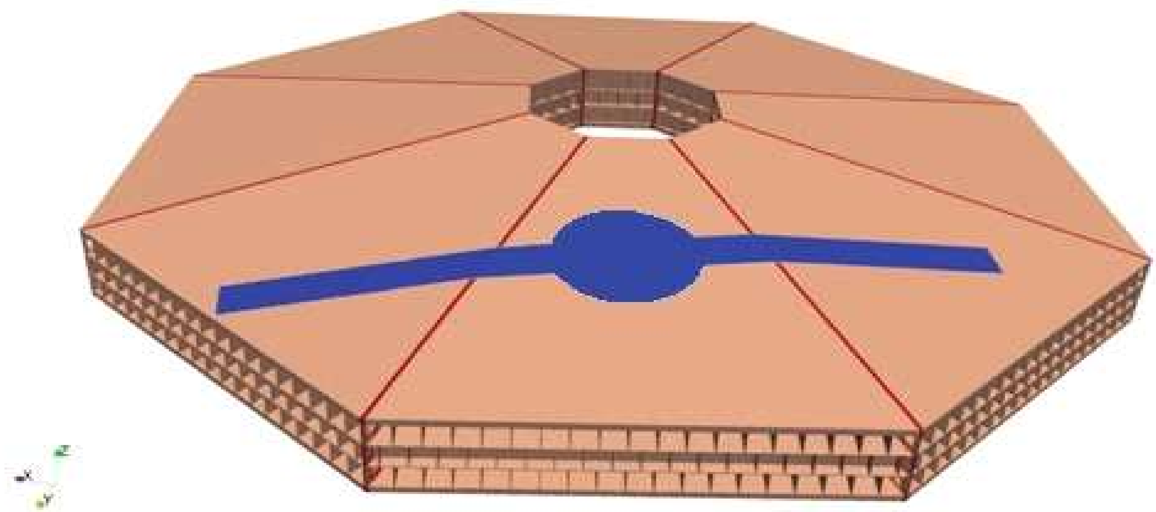


Figure 3. Scheme of impulse application.

By the period of 160 ms additional load of aircraft wings occurs and the increase in degree

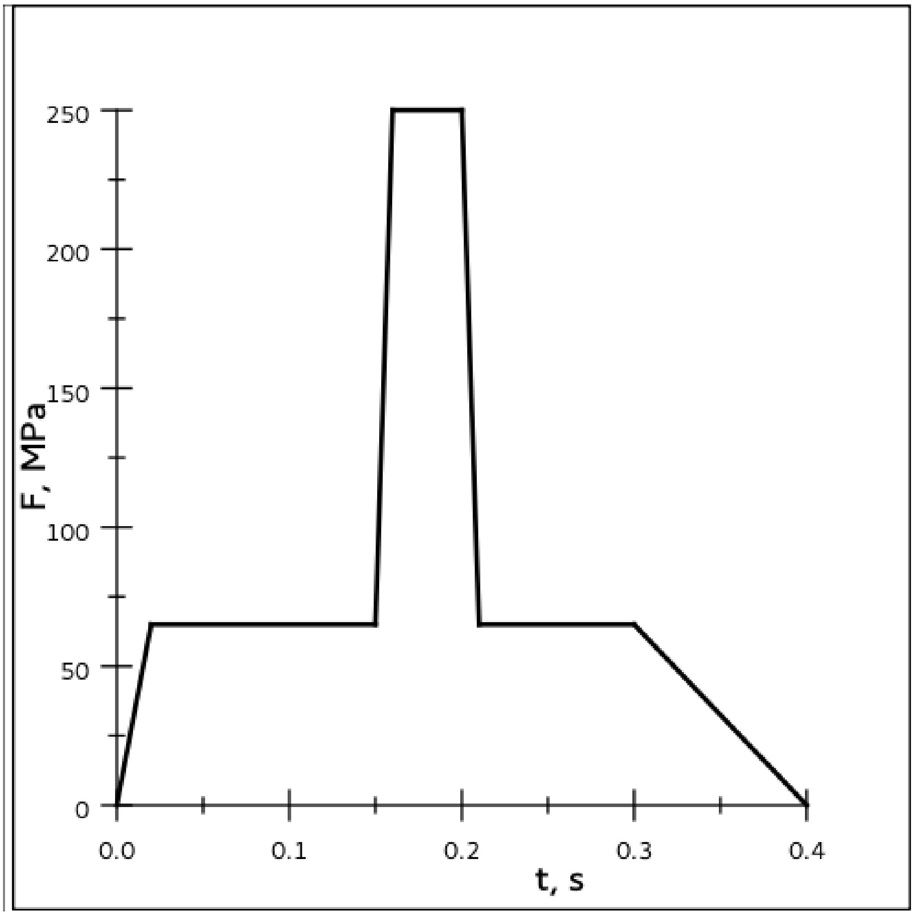
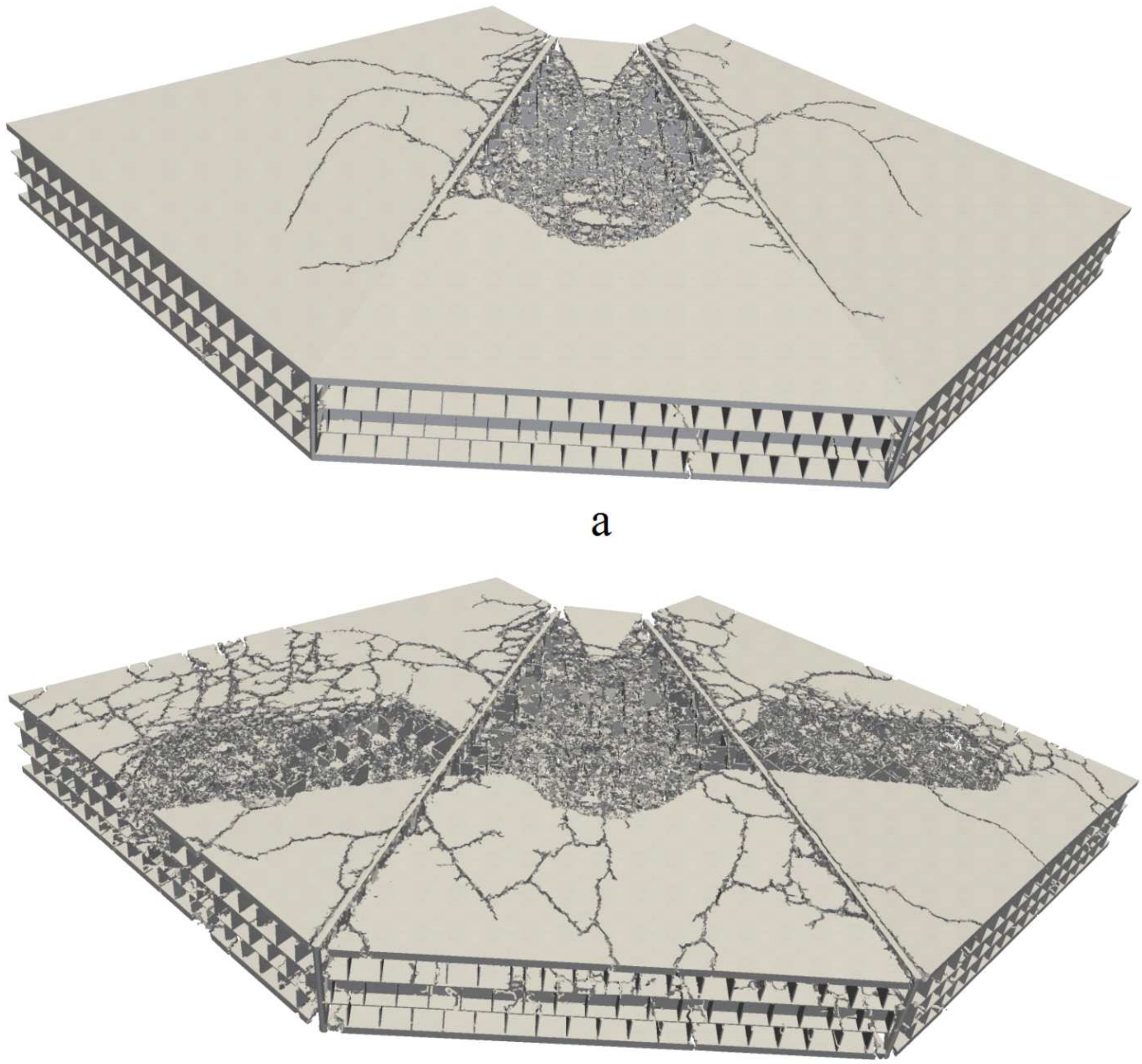


Figure 4. Load while impact of aircraft Boeing 747-400.

of destruction in the shell is observed. Fracture propagation on the back surface of the shell is shown in figure 6. As could be seen from the figures cracks form on the back surface to the shell and afterwards propagate over the shell surface. Cracks result from impact of tensile stress occurring at the compression wave output on the back surface and then stay the same for the period of impulse load action. Destruction of shell along its thickness is shown in figure 7, cross-section of shell along median surface passing through the areas of load application at the sequential periods. Initially fracture is observed in circular area of load from the aircraft body and then in the areas of impulse from wings.



a

b

Figure 5. Shell destruction. Top view. a) $t = 20$ ms, b) $t = 300$ ms.

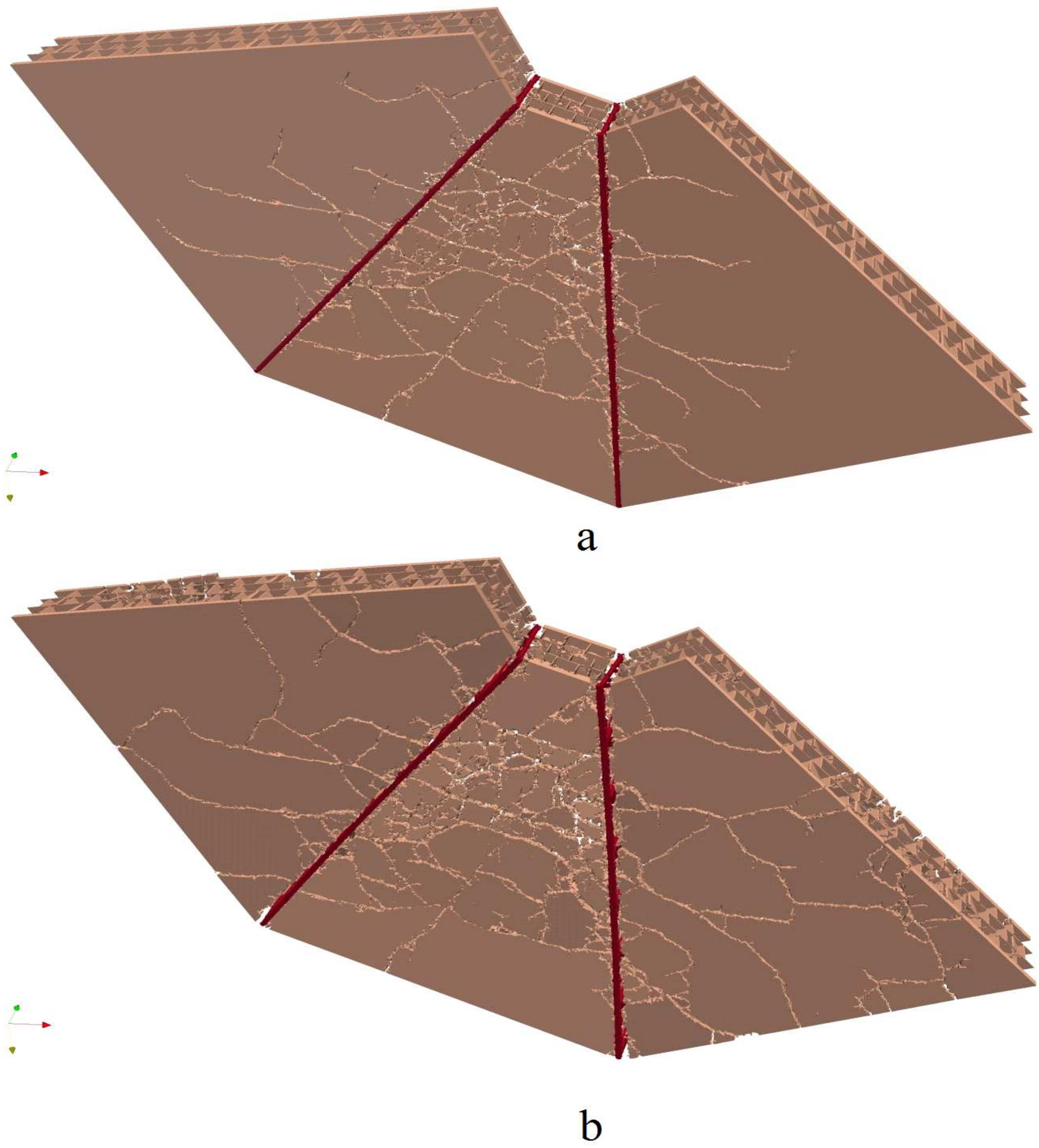


Figure 6. Shell destruction. Bottom view. a) $t = 20$ ms, b) $t = 300$ ms.

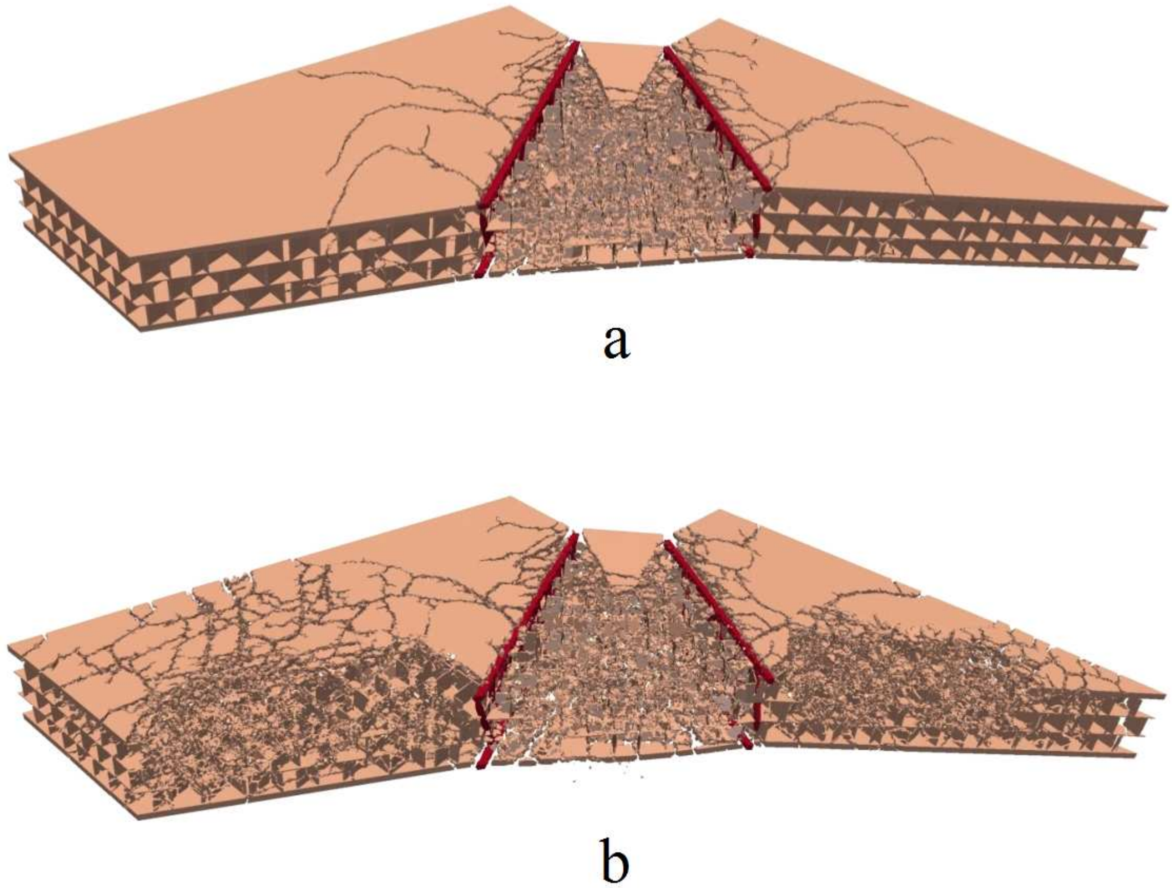


Figure 7. Shell destruction. Cross section. a) $t = 20$ ms, b) $t = 300$ ms.

4. Conclusion
The results of numerical simulations can be concluded as follows.

- The model and calculation methodology was developed within phenomenological approach of continuum mechanics for shell structures with complex inner structure under intensive dynamic loadings. Methodology is realized in 3D version based on modified finite element method.
- The developed methodology allows performing numerical simulations with wide range of parameters to choose optimal structural solutions.
- The dynamics of stress–strain state and destruction of protective shell of nuclear power plant with cellular inner structure under impulse action was studied numerically.
- Destruction of cellular structure initiates in the areas of tensile stress occurring at the moment of compression wave output into free areas of the cells. Further development of fracture follows as a result of impulse load.

- Cracks occur in the upper and lower covers of the shell due to tensile stress and then propagate in radial directions.

References

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