DOI: 10.18721/JPM.12315
УДК 534

STRENGTH OF REINFORCED CONCRETE STRUCTURES UNDER EXTREME MECHANICAL IMPACTS

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The article deals with feasibility studies of the strength of reinforced concrete structures under extreme mechanical impacts. The focus is on the interaction of the structure's outer containment with a heavy aircraft. Modern physical models and methods of direct numerical simulation of processes are used with taking into account nonlinear behavior of materials. These approaches are verified on original model problems. The impact of a heavy transport aircraft on an undeformed reinforced concrete wall is determined. The thickness values of the outer containment of the reactor building are varied. The strength of structures with taking into account the pliability of soil bases on which reinforced concrete structures are located is also studied.

Keywords: structural strength, extreme mechanical impacts, ferroconcrete, finite element method

Citation: Modestov V.S., Strength of reinforced concrete structures under extreme mechanical impacts, St. Petersburg Polytechnical State University Journal. Physics and Mathematics. 12 (3) (2019) 162–171. DOI: 10.18721/JPM.12315

ПРОЧНОСТЬ ЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ПРИ ЭКСТРЕМАЛЬНЫХ МЕХАНИЧЕСКИХ ВОЗДЕЙСТВИЯХ

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В статье рассмотрены вопросы обоснования прочности ответственных железобетонных конструкций при экстремальных механических воздействиях. Главное внимание уделяется взаимодействию внешней защитной оболочки конструкции с тяжелым самолетом. Используются современные физические модели и методы непосредственного численного моделирования процессов с учетом нелинейного поведения материалов. Эти подходы верифицируются на оригинальных модельных задачах. Определяется воздействие тяжелого транспортного самолета на недеформированную железобетонную стену. Варьируются значения толщины внешней защитной оболочки реакторного здания. Исследуется прочность конструкций с учетом податливости грунтовых оснований, на которых расположены железобетонные сооружения.

Ключевые слова: прочность железобетонной конструкции, экстремальное механическое воздействие, железобетон, метод конечных элементов

Ссылка при цитировании: Модестов В.С. Прочность железобетонных конструкций при экстремальных механических воздействиях // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2019. Т. 3 № .12. С. 177–187. DOI: 10.18721/JPM.12315

Introduction

Maintaining the safety of industrial and civil facilities in normal and emergency conditions is the problem of utmost importance. Even more stringent requirements are imposed for nuclear facilities with additional standards for nuclear and radiation safety. Strength calculation of reinforced concrete structures under extreme mechanical stresses is a crucial related issue. Such impacts include atmospheric vortices (tornadoes, whirlwinds, hurricanes), and technological disasters (collapse of heavy structure, aircraft crash, etc.). Aircraft crashing onto the outer containment of a nuclear reactor is a particular risk.

Numerous publications have considered the behavior of reinforced concrete structures under extreme mechanical stresses. Major advances in solving this problems were made by Birbrayer, Roleder [1, 2] and Volkodav [3]. The latter used quasistatic methods to describe the deformation of barriers upon aircraft crash, introducing a dynamic coefficient that characterizes the degree to which the dynamic load on the obstacle exceeds the static one. A classical expression (the so-called Riera formula [4]) was obtained by developing a viscoelastic model of colliding bodies for the load on a fixed barrier from crashing aircraft.

Unfortunately, the majority of studies on this subject are based on considerable assumptions and limitations that are not necessarily substantiated. Moreover, engineering calculation techniques are typically used. Calculations of reinforced concrete structures are commonly performed by linear methods for determining the stress-strain state. In this case, the state of concrete is assessed first, and only then is the reinforcement of the structure selected. This method is unsuitable for assessing the stress-strain state of reinforced concrete under extreme impacts, when non-linear local stresses and strains evolving in the regions where concrete interacts with reinforcing steel start to have a pronounced effect. In fact, no solution has been found as yet for the problem in this statement.

Modern physical models and methods of direct numerical simulation have been used in this study to substantiate the strength analysis for reinforced concrete structures under extreme mechanical stresses, taking into account non-linear behavior of materials and flexibility of foundation soils where reinforced concrete structures are built.

Methods and algorithms for analysis of extreme mechanical stresses

Diverse methods have been developed for numerically simulating the behavior of reinforced concrete structures under extreme mechanical stress, taking into account the nonlinear physical and mechanical properties of concrete and reinforcement. Many models typically involve a universal approach for describing nonlinear strength characteristics of concrete (i.e., the concrete matrix makes the transition from elastic to plastic stage) using the yield criterion F_f:

$$\sqrt{I_2} = F_f\left(I_1, \theta, \kappa\right), \qquad (1)$$

where

$$I_1 = 3p = \sigma_1 + \sigma_2 + \sigma_3, I_2 = = \frac{1}{2} tr\left(S^2\right), I_3 = \frac{1}{3} tr\left(S^3\right)$$

are the invariants of the stress tensor (σ_i are the elements of the stress tensor σ), p is the mean normal stress); $\boldsymbol{\kappa}$ is the vector of internal variables of the material; θ is the Lode invariant (in cylindrical coordinates); S in the formula for I_2 is the deviatoric stress tensor,

$$S = \sigma - pE$$

(E is the unit tensor).

Nearly all models of reinforced concrete can account for reinforcement. Different techniques are used, from adding distributed stiffness in the directions of reinforcement to direct simulation of individual rebars, reinforcing mesh, etc.

From a mechanical standpoint, the properties of a composite matrix consisting of concrete are mainly described by the following parameters:

nonlinear load-deformation curve;

Young's compressive and tensile moduli; the tensile strength is lower than the compressive strength by tens of times;

cracking and resulting deformation anisotropy, cracks evolving and growing in the regions where the concrete matrix contacts the reinforcement.

The Concrete Damage Plasticity (CDP) model was used in this study, offering a wide range of options to simulate the properties of concrete and other quasi-brittle materials in all types of structures (beam, shell and solid). This model is based on describing the elastoplastic properties of concrete, accounting for its damage and different tensile and compressive behaviors. The CDP model can also be used for simple concrete, but it is primarily intended for analysis of reinforced concrete structures. Elements simulating reinforcement can be added to the finite element model of the given material. This model is designed to calculate structures under monotonous, cyclic and dynamic loads. The model combines the law for non-associated plastic flows and the laws of hardening and elastic deformation with irreversible damage, allowing to simulate crack formation. The CDP model used is also convenient because it can account for concrete recovering its stiffness under alternating cyclic loads and for the dependence of material properties on the strain rate.

Concrete is assumed to be linearly elastic under tension, up to a stress value equal to tensile strength, which corresponds to onset of microcracking in the material. The behavior of concrete after reaching tensile strength is described with the descending branch of the load-deformation curve, generating localized stresses in the structure. Concrete under uniaxial compression typically exhibits linear behavior until the yield point is reached. The plastic phase of deformation is characterized by a hardening region up to the ultimate compressive strength with a subsequent descending segment of the curve. The load-deformation curves are given in [5] and describe the main parameters of unreinforced concrete.

Reinforcement of concrete structures is generally simulated using special beam elements, which can be set individually or in oriented layers. An elastic-plastic model is commonly used for material deformation. The effects arising from interaction of concrete with reinforcement, such as sliding or dowel action, are simulated approximately by adjusting the stress–strain relationship for concrete in order to account for the propagation of stresses in cracked concrete by means of reinforcement.

Developing and testing the procedure for simulating reinforced concrete structures with nonlinear behavior of materials

We used the methods and algorithms described above, as well as those given in [5–15], to simulate reinforced concrete structures under extreme mechanical stresses.

As noted above, there are other methods for modeling reinforcement in concrete in finite element calculations than direct solid modeling. In particular, the discrete, embedded and distributed models are used.

The nodes of reinforcing bars coincide with the nodes of the solid mesh for concrete in the discrete model.

The nodes of reinforcing elements and concrete do not coincide in the embedded model, and concrete grids do not coincide, but are related by compatibility equations.

Finally, the distributed model assumes that reinforcement is evenly distributed over the elements of the finite element mesh for concrete.

We used the ABAQUS software system, applying embedded and distributed reinforcement. Solving the problem of static loading on a reinforced concrete beam, we compared the results yielded by the calculations using these two methods for modeling reinforcement. We found that the stresses obtained at a specific point in the structure and the strain energies for both embedded and distributed reinforcement coincide with an accuracy sufficient for engineering calculations.

It could be concluded by considering a similar model problem on dynamic loading of a concrete slab with reinforcing loops (joints proposed by Perederiy) that the bearing capacity of such structures mainly depends on radial cracks propagating along the contour of the loop joints, rather than primary cracks on the bottom surface of the slab under the loaded regions, which is the case with simple longitudinal reinforcement. Mathematical simulation predicted diagonal cracks in the horizontal plane between adjacent loop joints. It was also confirmed that transverse (interlocked) reinforcement inside the loop joints positively (and substantially) affects the bearing capacity of reinforced concrete slabs and, in particular, delays cracking.

The procedure was tested for the model problem of a reinforced concrete slab interacting with a deformable metal impactor. Reinforcement of the plate was given both by direct simulation of reinforcement bars with beam elements, and using the technology of distributed reinforcement in the ABAQUS software.

Calculations confirmed that the distributions of the concrete damage parameter d for two reinforcement models (rebars and distributed reinforcement) yield qualitatively similar results. On the other hand, the von Mises equivalent stresses expectedly produce a “smeared” picture for distributed reinforcement compared with bar reinforcement (Fig. 1). Besides, the von Mises equivalent stresses are lower for the distributed reinforcement model than for the bar reinforcement model. Calculations also

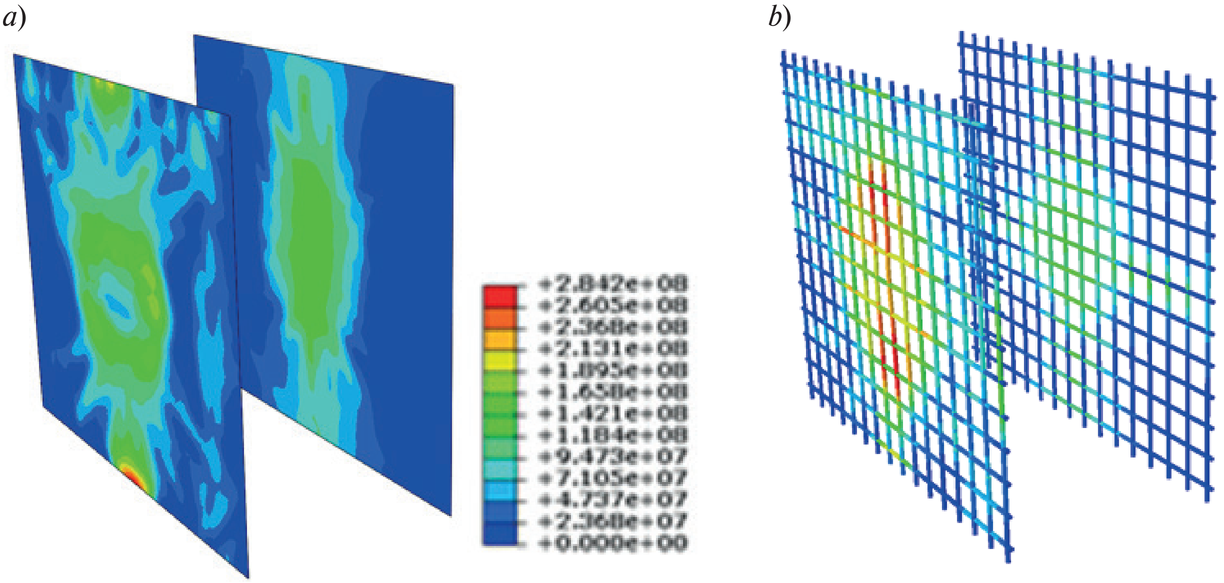

Fig. 1. Field of von Mises equivalent stresses in rebars for two reinforcement models: distributed (*a*) and beam (*b*)

established that the time dependences obtained for the R_z component of the slab's total reaction force and the u_z component of the displacement vector for the central node on the bottom surface of the slab almost completely coincide for the two reinforcement models. This circumstance made it possible to perform subsequent calculations with the model of distributed reinforcement, which requires the least amount of resources, for the regions far from the impingement surface.

Considering the given problem of a reinforced concrete slab penetrated by a deformable metal impactor, we applied the expanded Drucker–Prager model, allowing to set several criteria for progressive damage and fracture of the material, and the so-called element deletion function. In terms of the finite element method, this function allows to gradually exclude elements whose degree of damage exceeds a preset value from the simulation model.

Impact simulation for aircraft colliding with non-deformable reinforced concrete slab

We used the procedure described in the previous section to numerically simullate the collision of a wide-body aircraft with a rigid reinforced concrete slab.

The load on a rigid wall from crashing aircraft was found by the formula proposed by Riera [4]:

$$R(t) = P\left[\xi(t)\right] + \dot{\xi}^2(t)\mu\left[\xi(t)\right]. \qquad (2)$$

In this case, the aircraft model was a rigid plastic beam with mass μ (ξ) per unit length and ultimate load *P*(ξ), distributed along the length ξ. The data given in literature for Boeing 707 were used for the μ(ξ) and *P*(ξ) distributions. The corresponding dependences for wide-body airplanes Boeing 737, Boeing 747, Airbus A380 were determined by scaling. We assumed that the rigid wall was made of grade B40 concrete, and the physical and mechanical properties of the reinforcement corresponded to standards for A400 steel. The classical von Mises elastic-plastic model with isotropic hardening was used in collision simulations for reinforcement and aircraft materials.

CAD models and sketches of Airbus A380, available online, were taken as the basis for the geometric model of the wide-body passenger airplane. A finite-element model of the aircraft was constructed, containing 72,354 linear shell three- and four-node elements providing 434,124 degrees of freedom.

We carried out a comparative study for the collision of an Airbus A380 with a rigid wall using the simplified Riera analytical method and explicit finite-element modelling according to the procedure we developed. The speed of the aircraft colliding with the wall was taken equal to 110 m/s. The collision was considered at zero values of heading, elevation and bank angles.

Fig. 2 shows simulated fracture of the airplane upon collision with a rigid wall at time t = 0.5 s. The reaction force of the rigid wall was calculated and compared with the solution by the Riera method [4].

Fig. 2. Fracture of aircraft upon collision with rigid wall at time $t = 0.5$ s, obtained by FEM

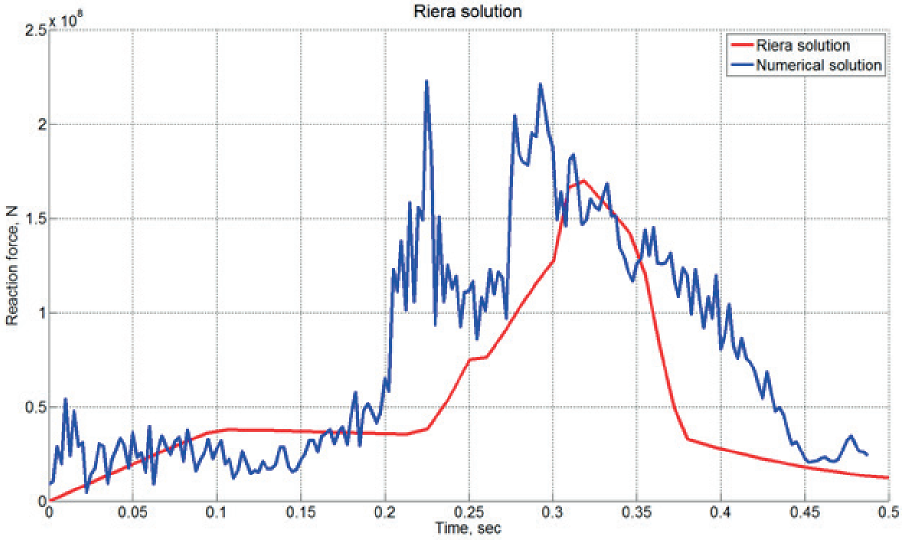

Fig. 3. Analytical and numerical solutions for reaction force of reinforced concrete wall depending on time upon collision with aircraft

Fig. 3 shows a comparison of the numerical and analytical solutions for the reaction force of a reinforced concrete wall. Analysis of these data reveals the expected qualitative differences in the shape of the curve for the reaction force depending on time. Setting the load by the Riera method produces a smooth solution, and using the finite element model yields two numerical extrema.

The first extremum in Fig. 3 corresponds to the time when the wings of the aircraft contact the wall, the second to the time when the engines crash. Notably, the maximum reaction force found through numerical calculation is 2.25 MN, and that found through approximate calculation by the Riera method 1.7 MN.

Thus, analysis of the results confirms that the developed finite element model of the aircraft is applicable to simulating collision with NPP buildings.

Impact simulation for aircraft colliding with reactor building of NPP

As an airplane collides with an industrial structure, in particular, with the reactor building of a nuclear power plant, this generates extreme loads on these structures [1]. For this reason, strength calculations should include not only the strength of individual structures but also the strength and stability of the entire building and its foundations.

Extreme mechanical impacts have a pronounced dynamic character, so strength calculations under the loads these impacts generate should be carried out either by dynamic methods or with a quasistatic load found using the dynamic load coefficient.

The above-described method was used for numerical simulation of aircraft colliding with the reactor building of the nuclear power plant taking into account nonlinear behavior of materials.

We constructed a geometric and a finite element model of the power plant developed, including models of the reactor building, the safety building, and models of the steam cell, complying with design documentation of a typical nuclear power plant. We assumed that the safety buildings and the steam cell were made of shell elements with a linear elastic material model with the properties set equivalent to those of B40 concrete. Contact interaction conditions were imposed between the containment of the reactor building, the safety buildings and the steam cell. The containment was assumed to consist of external and internal parts. The finite element mesh was condensed in the region where the greatest deformations were expected.

We considered three material models within the finite element model of the reactor building:

linear, with the properties of B40 concrete (model 1);

nonlinear, for a CDP or Drucker–Prager material with the properties of B40 concrete (model 2);

the same as model 2, but with the properties of B60 concrete (model 3).

An elastic plastic material model with the properties of reinforcing steel A 400 was used for reinforcement. The total number of nodes in the finite element model of the reactor building was 1,373,769 and the number of degrees of freedom was 4,221,307.

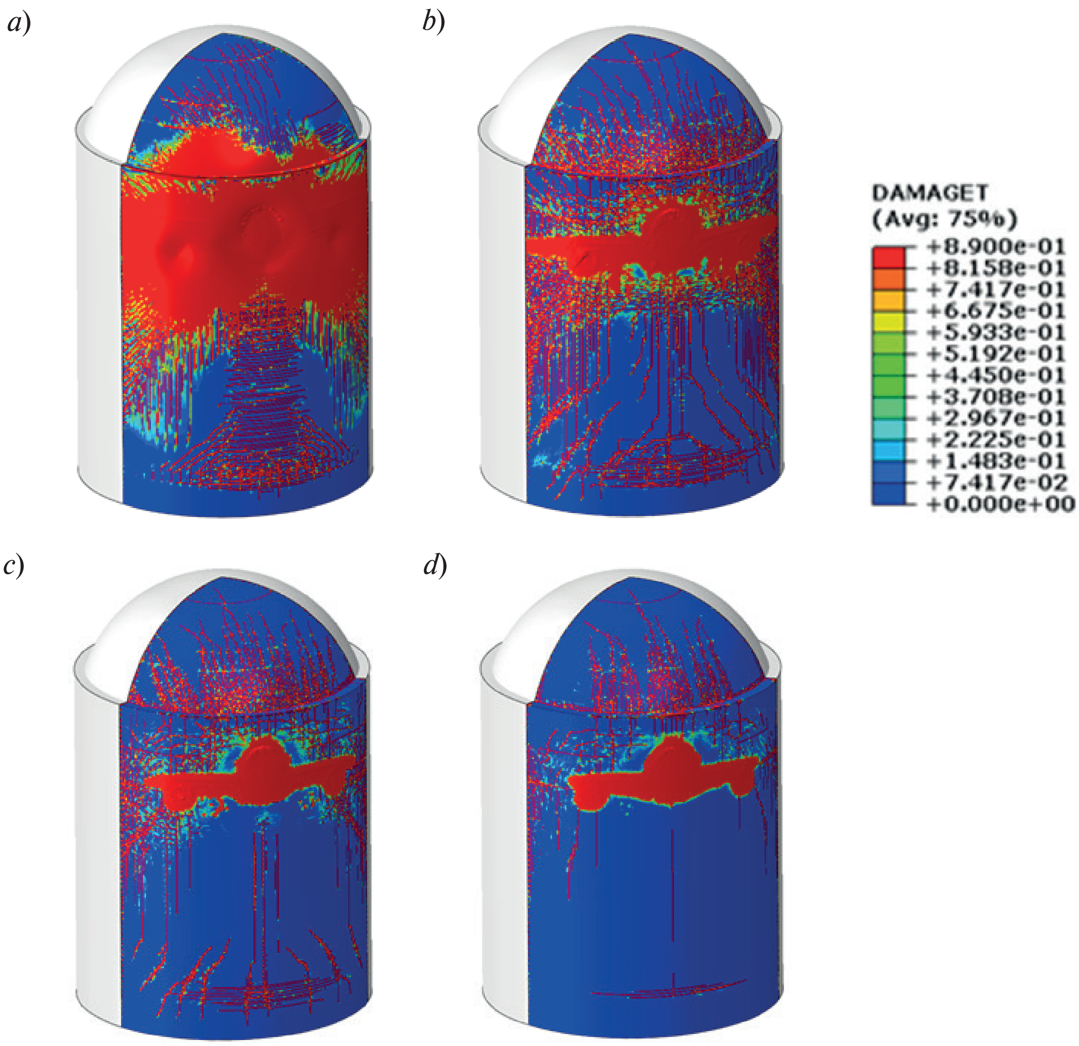

Fig. 4. Distribution of damage parameter d_t (%) for concrete on outer containment of NPP reactor, for different thicknesses T, m: 0.6 (*a*), 1.5 (*b*), 2.0 (*c*), 2.5 (*d*)

Numerical simulation of the problem was carried out in a wide range of thicknesses T of the outer containment: from 0.6 to 2.5 m.

Fig. 4 shows the distribution of concrete damage parameter d_t in the reactor building after collision with the aircraft for different thicknesses T.

Analysis of the data shown in Fig. 4 led us to conclude that the main cracks emanating in the longitudinal direction form on the outer containment for all wall thicknesses except $T = 2.5$ m. If $T = 0.6$ m, the resulting cracks penetrate almost the entire surface of the containment (with the exception of the dome and the area near the foundation). The size of the affected area decreases with increasing containment thickness, and the damaged region has a local nature at $T = 2.5$ m, repeating the shape of the crashed airplane. Main cracks initiate in the circular direction of the outer containment in all cases.

Calculations showed that the maximum values of the displacement vector of the containment points, amounting to about 1.8 m, are observed for the containment thickness of 0.6 m. These displacement are catastrophic, destroying the containment. It follows that containment thickness $T = 0.6$ m is unacceptable for the given parameters of collision with aircraft. Considering the requirements of the standards and based on the simulation results, we can argue that the minimum allowable thickness of the outer containment is 1.5 m.

Simulation of aircraft collision with reactor building of NPP with flexible soil foundation

Constructing an algorithm for solving this problem, we simulated the soil foundation using a simplified approach, consisting in replacing the spatial soil model with equivalent springs and dampers related to the nodes of the finite element mesh of the building foundation. We used both a model of a rigid foundation and a simplified model of a deformable foundation using elastic damping elements. The values of equivalent stiffness and damping of the soil foundation were determined by the formulas of both the ASCE and the NIST standards.

Next, we considered the impact of an aircraft against a cylindrical shell whose geometry approximately corresponded to the outer containment of the reactor building. The calculations were carried out in the ABAQUS/EXPLICIT software. The number of finite elements was 17,613.

Fig. 5 shows the calculated displacements of a point on the surface of the containment near the impingement surface in the direction of the Ox axis depending on time. Apparently, the solutions for the absolutely rigid foundation model and the simplified flexible foundation model are considerably different. Calculations by ASCE and NIST standards yielded fairly close results.

The calculated data indicate a significant difference between the algorithms accounting for soil flexibility (ASCE and NIST standards) and the rigid foundation algorithm (excluding soil flexibility).

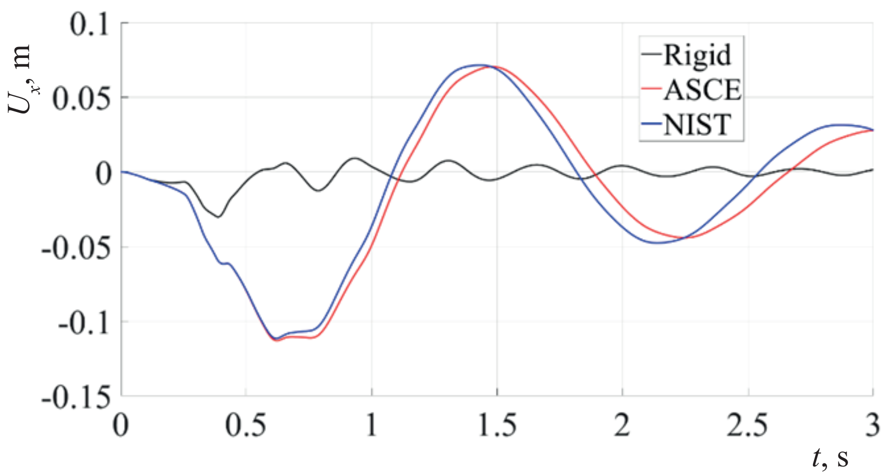

Fig. 5. Displacements of a point in containment of NPP reactor building near impingement surface, in the direction of Ox axis. Simulations by ASCE and NIST standards were run for an absolutely rigid foundation and for a flexible foundation

This result emphasizes that it is important to take into account the flexibility of the soil foundation in constructing a procedure for calculating the interaction between an airplane and the reactor building of a nuclear power plant.

Conclusion

We have studied the strength of reinforced concrete structures under extreme mechanical stress, obtaining the following results.

1. We have developed a simulation technique and solved the problem of impact interaction between a reinforced concrete slab and a deformable metal impactor; the ABAQUS software system was used to account for embedded and distributed reinforcement.

2. We have carried out a comparative study of interaction of an Airbus A380 aircraft with a rigid wall using direct numerical dynamic calculation by finite element modeling and by the simplified Riera method. We have found that the constraint force of the wall as a function of time has two extrema: when the aircraft wings contact the wall and when the engines crash against it.

3. We have constructed finite element models of the NPP, consisting of a reactor building, a safety building, and a steam chamber, based on the design documentation of a typical NPP.

4. We have run numerical simulation of the interaction of aircraft with the reactor building of the NPP based on the calculation methods tested in the study, taking into account the nonlinear behavior of the materials. We have found that the minimum allowable thickness of the outer containment of the NPP is 1.5 m for the given model.

5. We have come up with a procedure for calculating the collision of an airplane with the reactor building of an NPP taking into account the flexibility of the soil on which the NPP is located.

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Received 10.06.2019, accepted 19.08.2019.

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Статья поступила в редакцию 10.06.2019. принята к публикации 19.08.2019.

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