Numerical simulation of damage to the deformed state of the coating slab of a special structure

Anna A. Yatsenko[1], *Mikhail V.* Chernyshov[1], and *Karina E.* Savelova[1*]

[1] Baltic State Technical University «VOENMEH», 190005 Saint-Petersburg, Russian Federation

Abstract. In this paper, we strived to the goal to ensure various special structures against damage factors of high-explosive blast. Together with application of combined blast protection devices, we considered reinforcement of constructive elements and simulated the impact and interaction of detonating projectile with reinforced concrete wall. Various packages of computational mechanics which belong to ANSYS family were applied to numerical simulations, as well as the developed numerical model of reinforced media which can be effective in development of combined blast-protective structures for urban environment. Protection devices based of developed blast-protective structures combine influence of blast-absorbing multiphase media with durability of rigid reinforced base constructions, so the numerical simulation of blast wave reflection and projectile impact are also necessary for their research and development. Our computational results, achieved in this study, have shown that, owing to reinforcement, the considered coating slab retained its integrity, though some cracking and ejection of concrete really occurred. Keywords**:** blast wave, reinforced concrete, deformed state, blast protection

1 Introduction

To ensure trouble-free operation of various special structures, a modern monitoring system for the operational condition of special structures is needed, which could automatically record the parameters of damage, residual strength and residual deformations and issue recommendations for determining limit states for serviceability.

One of the main elements of this system is the modeling of the impact of emergency loads and impacts on special structures. Numerical methods implemented in software packages: ANSYS, ROBOT, DLUBAL, etc. provide ample opportunities for assessing damage parameters and assessing the stress-strain state of load-bearing structures.

The above-mentioned reinforced structures can help us not only to strengthen buildings, but also to develop the combined blast protection devices (so-called blast inhibitors [1-3]) which combine energy-absorbing features of multiphase relaxation media [4-6] with durability of solid materials [7-10].

* Corresponding author: karinkamurz@yandex.ru

2 Numerical simulation program

Analysis and modeling of the behavior of concrete under the influence of a contact emergency explosion shows that concrete, when exposed to the loads of an explosion of explosive charges, exhibits a complex stress-strain state. One of the software packages capable of performing this kind of calculations is ANSYS AUTODYN.

The ANSYS AUTODYN module is a program designed for highly nonlinear problems that involve buckling, complex contact, and/or failure of bodies. At the same time, implementing an implicit integration scheme, the advantage of which is the stability of integration and conservation of energy, is very difficult or completely impossible. In the case of an implicit scheme, time is a parameter for incrementing loads. In an explicit integration scheme, time is explicitly involved; at each integration step, the solver calculates the time step size using a corollary to the Courant-Friedrichs-Lévy criterion. In this case, the maximum time step is limited by the time during which the elastic wave travels a distance equal to the smallest element in the system.

3 Equation of state P-α for a solid body

Although compression models provide good results for low stress levels and low α materials, it is highly desirable to obtain a unified porous material modeling formulation that provides good representation over a wide range of stresses and different materials.

Such a model was derived by Hermann (1969) and is available in explicit dynamics.

Hermann's P-alpha model uses a phenomenological approach to develop a representation that gives correct behavior at high stress levels, while at the same time providing a sufficiently detailed description of the compression process at low stress levels.

The basic assumption is that the specific internal energy of a porous material is the same as the same material at solid density under the same pressure and temperature conditions. Then porosity α is determined by expression (1)

The process of propagation of air blast wave and HE detonation products is determined by the laws of conservation of mass, momentum and energy in the form

$$\alpha = \frac{v}{v_s}. \qquad (1)$$

where v is the specific volume of the porous material, and v_s is the specific volume of the material in the solid state at the same pressure and temperature (note that v_s is only $1/\rho_s$ at zero pressure). Porosity parameter α becomes equal to one when the material is compacted to a solid state. If the equation of state of a solid material without taking into account the effects of shear strength is

$$p = f(v,e) \qquad (2)$$

then the equation of state (2) of the porous material has the form:

$$p = f\left(\frac{v}{\alpha}, e\right), \qquad (3),$$

The function (3) can be any of the equations of state that describe the compressed state of the material; in other words, Linear, Polynomial and Impact, but not those that describe the extended state. To complete the description of the material, the porosity α must be specified as a function of the thermodynamic state of the material

$$\alpha = g\left(p,e\right). \qquad (4)$$

Usually the available data is insufficient to fully determine the function *g(p,e)*, but fortunately most of the problems of interest involve shock compression of a porous material, i.e. the area of interest is on or near the Hugoniot adiabat. In Hugoniot equation, pressure and internal energy are related by the Rankine-Hugoniot conditions, so equation (4) can be expressed as it follows:

$$\alpha = g(p)\,, \quad (5)$$

with an implicitly assumed change in energy. This equation (5) is assumed to remain valid in the vicinity of the Hugoniot (assuming that the compressive strength is insensitive to small changes in temperature when extrapolating small distances from the Hugoniot). The general behavior of a densifying porous material has been described previously, and the *P-α* model is constructed to reproduce this behavior. The *P-α* dependence (Figure 1) that achieves this performance is shown schematically in the figure below. The material is deformed elastically before the onset of plastic compression (compaction) α_p, and subsequent deformation is plastic until the material is completely compressed at pressure p_s.

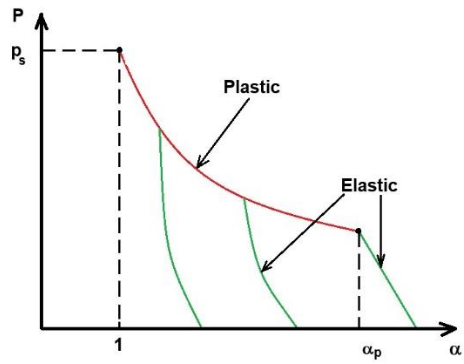

Fig. 1. Dependence of P on α

Intermediate unloading and overloading are elastic up to the plastic loading curve.

The choice of a suitable function *g(p)* is somewhat arbitrary as long as it satisfies some simple analytical properties listed by Herrmann in his original paper, and several forms of it have been used by different researchers. A simple form found to be adequate for porous iron is the quadratic one, but cubic and exponential forms have also been proposed and the parameters adjusted according to experimental data.

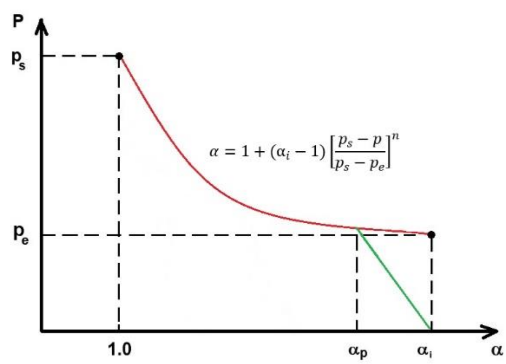

Fig. 2. Dependence of P on α (standard version)

The following plastic compaction (compression) curve options are available:

- Standard (Fig. 2).

This is the default option, where the plastic compression curve is determined by the solid compression pressure p_s at full compression, the initial compression pressure pe at porous compaction α_i, and the compression ratio n.

- Alpha Plastic (AUTODYN component system only, see Figure 3)

The plastic compaction curve is determined by the solid compaction pressure p_s at full compaction, the initial compaction pressure p_e at the beginning of plastic compaction α_p and the compaction degree index *n*.

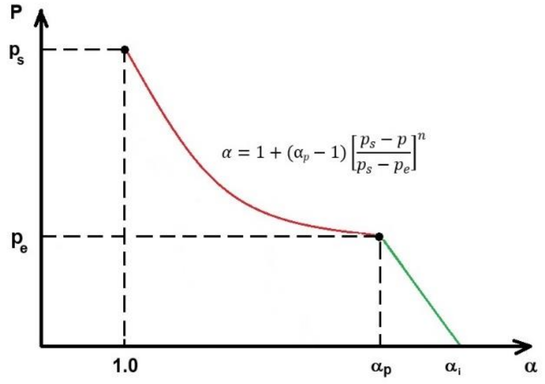

Fig 3. Dependence of P on α (Alpha Plastic option)

Carroll and Holt modified the porous material equation of state to obtain expression (6)

$$p = \left(\frac{1}{\alpha}\right) f\left(\frac{v}{\alpha}, e\right). \qquad (6)$$

Here the factor *1/α* was included to account for their argument that the pressure in the porous material is almost *1/α* times the average pressure in the matrix material. It is this form of the model that is available in explicit dynamics.
Note. The solid equation of state is defined using the following property:
- *Polynomial equation of state.*

When calculating the effective deformation, Poisson's ratio is assumed to be zero

4 Modeling damage to a concrete slab

4.1 Statement of the problem

A concrete wall is 1.2 m thick, 10 m high. It is exposed to the impact of a contact explosion of a projectile with a power of 200 kg of explosives, modeled as a spherical charge with a radius of 266 mm. The computational domain filled with air is a structured mesh with square cells with a side of 10 mm; length 5400 mm, height 5000 mm. Concrete wall with a width of 1200 mm, a height of 5000 mm and a cell size of 5 mm. The boundary conditions are a rigidly fixed wall and free flow of air and combustion products at the remaining boundaries. As a result of the calculation, pressure and deformation fields of the concrete wall were obtained, as well as pressure graphs at the following points – the center of detonation, 0.5 m, 1 m, 1.5 m, 2 m, 2.5 m, 3 m, 3.5 m, 4 m, 4.5 m, 5 m.

4.2. Calculation results

The calculation results for class B20 concrete are presented in Figure 4-10.

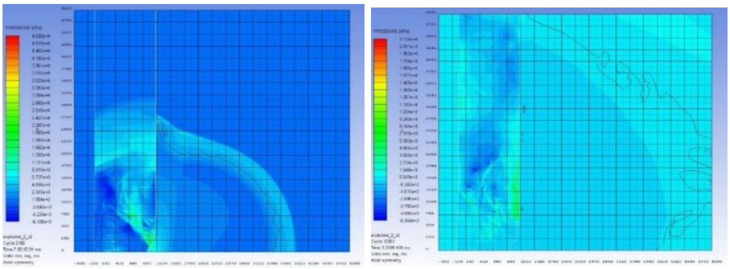

Fig. 4. Pressure fields at 0.75, 2.3 μs

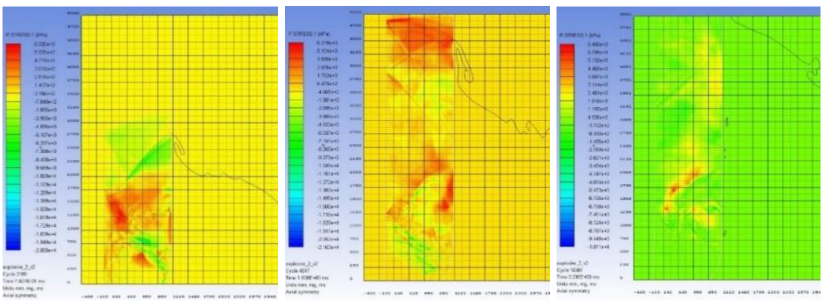

Fig. 5. Principal stress fields in the coating slab at 0.75, 1.5 and 2.3 μs

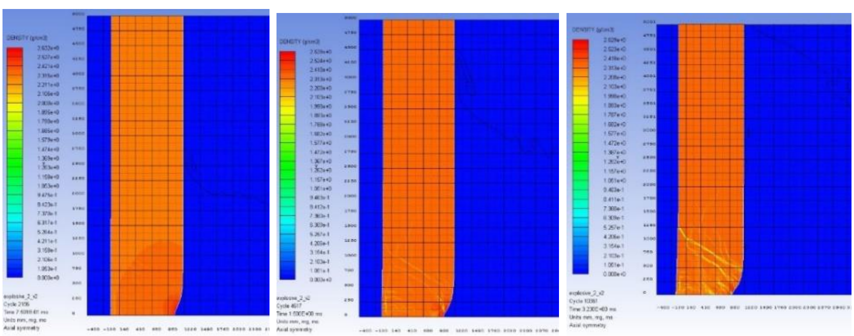

Fig. 6. Density fields in the coating slab material at 0.75, 1.5 and 2.3 μs

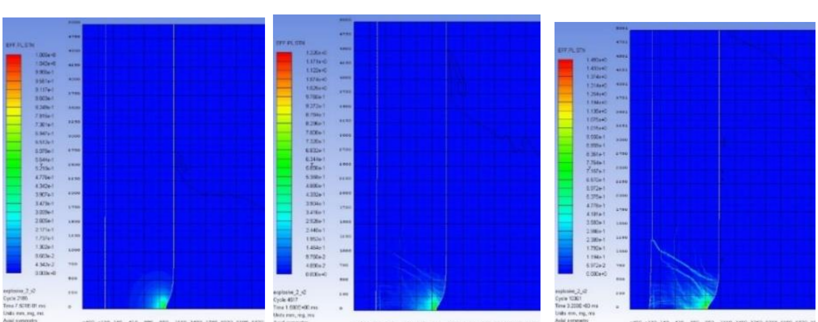

Fig. 7. Effective plastic deformation fields in the coating slab material at 0.75, 1.5 and 2.3 μs

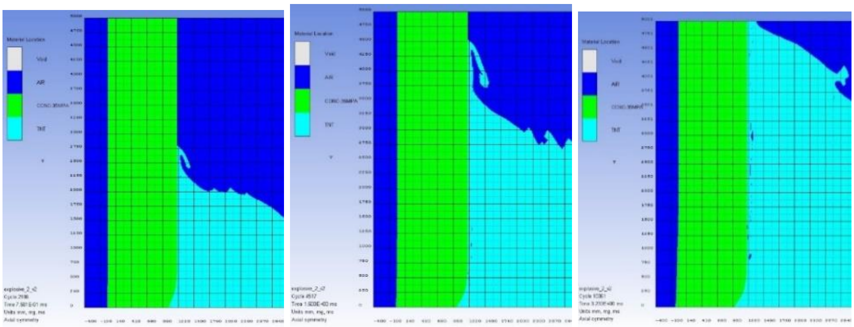

Fig. 8. Displacement fields of the coating slab material at 0.75, 1.5 and 2.3 μs

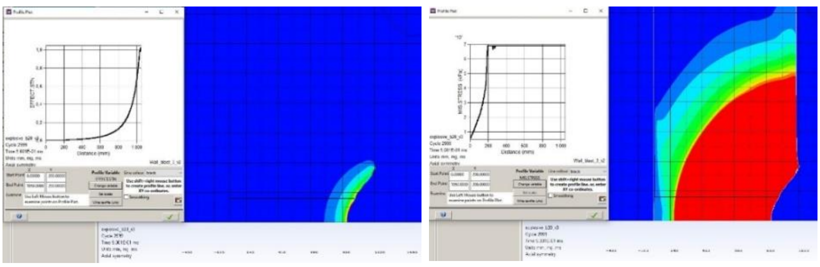

Fig. 9. Effective deformations and principal stresses in the slab at a depth of 200 mm

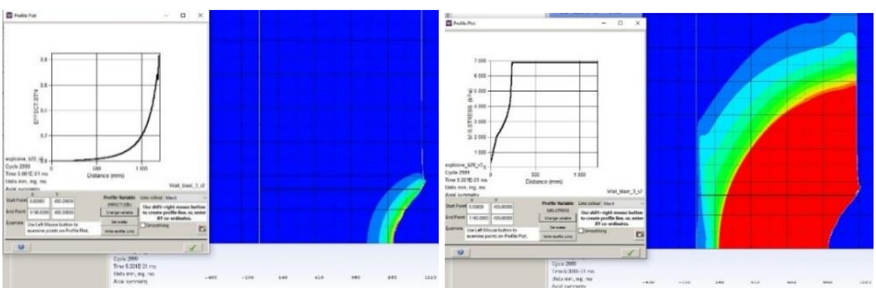

Fig. 10. Effective deformations and principal stresses in the slab at a depth of 400 mm

5 Conclusion

The calculation results have shown that within the explosive charge, destruction and ejection of concrete material from the coating slab occur. The effective deformation fields show that through cracking occurs in the coating slab at a distance of 1.25 m from the explosion epicenter. The maximum stress in the coating slab is 6.45 MPa, which leads to significant damage in the coating slab, including in the compression zone.

Acknowledgments

The study was carried out at the expense of a grant of the Russian Science Foundation No. 22-29-20269, https://rscf.ru/en/project/22-29-20269/, and a grant from the St. Petersburg Science Foundation in accordance with the agreement dated April 15, 2022 No. 57/2022.

References

1. R. Braimah *Blast Mitigation Techniques*. Ottawa, Canada, **21** (2006)
2. M. Silnikov, A. Mihaylin, N. Vasiliev, V. Ermolaev, V. Shishkin *Liquid blast inhibitors: technology and applications* in Detection and Disposal of Improvised Explosives. Saint Petersburg NATO Seminar Proceedings (Springer Verlag, 97-103, 2006)
3. M.V. Chernyshov, A.S. Kapralova *Brief Review of Modern Devices for Blast Mitigation* in International Science and Technology Conference "Earth Science". IOP Conference Series: Earth and Environmental Science, **666**, 022082 (2021)
4. B.E. Gelfand, M.V. Sil'nikov *The selection of an efficient blast-reduction method when detonating explosives* in Doklady Physics, **47**, 3, 192-194 (2002)
5. A.D. Resnyansky, T.G. Delaney *Experimental Study of Blast Mitigation in a Water Mist* in Australian Government. Department of Defense, DSTO TR 1944 (2007).
6. M.V. Silnikov, A.I. Sadyrin, A.I. Mikhaylin, A.V. Orlov *Shock wave overpressure evaluation at blast detonation inside a destructible container* in Materials Physics and Mechanics, **20**, 2, 175-185 (2014)
7. B.E. Gel'fand, A.V. Gubanov, E.I. Timofeev *Reflection of shock waves by a wall in two-phase gas-bubble-liquid media with variable mass concentration of the gas* in Fluid Dynamics, **17**, 299-302. (1983)
8. K. Takayama, M.V. Silnikov, M.V. Chernyshov *Experimental study of blast mitigating devices based on combined construction* in Acta Astronautica, **126,** 541-545 (2016)
9. M.V. Silnikov, M.V. Chernyshov, N.A. Danilov, I.A. Melnikov, A.I. Mikhaylin., A.S. Pankov, V.N. Shishkin, N.N. Vasilyev *Analysis and Testing of Combined Blast Inhibitors* in Proceedings of the 30th International Symposium on Shock Waves (ISSW30). Tel Aviv, Israel, 2015, Springer International Publishing AG, **2**, 1361-1365 (2017)
10. M.V. Chernyshov, A.S. Kapralova, S.A. Matveev *Combined device for suppression of damaging effects of detonation of the condensed media* in Journal of Physics: Conf. Series. **1214**, 012002 (2019)