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SIMULATION OF SHOCK WAVE ACTION FROM AN EXPLOSIVE DEVICE ON A PROTECTIVE SHELL

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The numerical approach to investigate the protective shell behavior under shock wave from an explosive device was presented. Comparison of shock wave characteristics from different explosive devices that were obtained experimentally and by Sadovsky's analytic formulas was made. The hemispheric geometrical model of shock wave and two finite element models of the cylindrical steel protective shell were created using NASTRAN software. The shock wave from an explosive device with a TNT equivalent of explosive mass 250 kg was considered. Overpressure was given as the evenly distributed load which depended on the distance from explosion epicenter to the shell surface areas. Shell behavior from the static action of overpressure was investigated in the nonlinear formulation by the Newton-Raphson method and compared with the results of the linear static and buckling analysis. The positive impulse was presented in the shape of a triangle with a certain time of action. The dynamic behavior of the two shell models was investigated by the fourth-order Runge-Kutta method. The results of static and dynamic analysis allowed to assess the impact of shock wave action from the explosive device on the stressed deformed state of the protective shell.
Keywords: protective shell, explosive device, shock wave, finite element method, static and dynamic analysis.

Introduction. At the present time there are domestic and foreign methodological approaches on the issue of modeling shock wave and designing of the special protective constructions in the different explosive devices [1-7].

As a result of military operations in Ukraine for prevention of people deaths, damages of military technique and live ammunitions there was a necessity to create a new probabilistic approach for the estimation of vitality of protective military and civil infrastructures taking into account damages from an explosion and fragments of explosive devices. The probabilistic approach for the estimation of vitality of the military protective thin shell constructions with damages from explosive devices using of calculable procedures of NASTRAN software [8-10] of finite element analysis was created by the authors. The new probabilistic multiparametric model of shell surface damages from shock influence of explosion and fragments of explosive devices was formed. The first stage of research involved the creation of numerical approach to investigate the protective shell behavior under positive phase of shock wave from an explosive device, the hemispheric geometrical modeling of shock wave and the creation of finite element model of shell with the surface areas which had certain values of overpressure and positive impulse; the static and dynamic analysis to assess the stressed deformed state of shell. In the article the research of protective shell from the action of shock wave was executed taking into account safe distance (higher and lower distances threshold) for people.

1. Comparison of shock wave characteristics from different explosive devices that were obtained experimentally and by Sadovsky's formulas

The shock wave experimental characteristics from different categories of explosive devices were presented in the document that had limited access. We presented them in graphical form (Fig. 1).

In this article the comparison of shock wave characteristics from different explosive devices that were obtained experimentally and by Sadovsky's analytic formulas was made.

Normalized distance threshold Z was calculated by formula

$$Z = R/\sqrt[3]{M} , \tag{1}$$

where R, Z – a distance (m), a normalized distance (m/kg$^{1/3}$) between the explosion epicenter and the shell; M – TNT equivalent of explosive substance mass (kg).

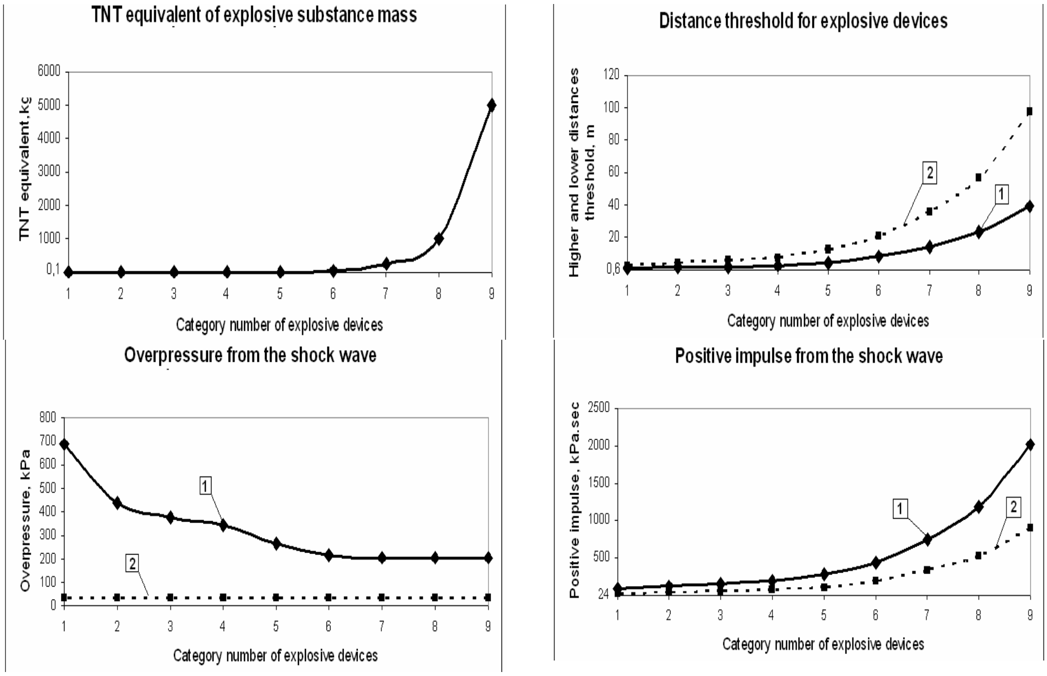


Fig. 1. The shock wave experimental characteristics depending on higher(1) and lower (2) distances threshold for different categories of explosive devices

Overpressure from shock wave ΔP (MPa) was modeled in the hemispere form and calculated by Sadovsky's formula

$$\Delta P = 0,1\frac{\sqrt[3]{M}}{R} + 0,43\frac{\sqrt[3]{M^2}}{R^2} + 1,4\frac{M}{R^3}. \quad (2)$$

Positive impulse from shock wave I (kPa-sec) was calculated by Sadovsky's formula

$$I = 6,3\frac{\sqrt[3]{M^2}}{R}. \quad (3)$$

Time of positive impulse from shock wave τ (s) was calculated by Sadovsky's formula and showed in Fig. 2.

$$\tau = 1,7\cdot 10^{-3}\sqrt[6]{M}\cdot\sqrt{R}. \quad (4)$$

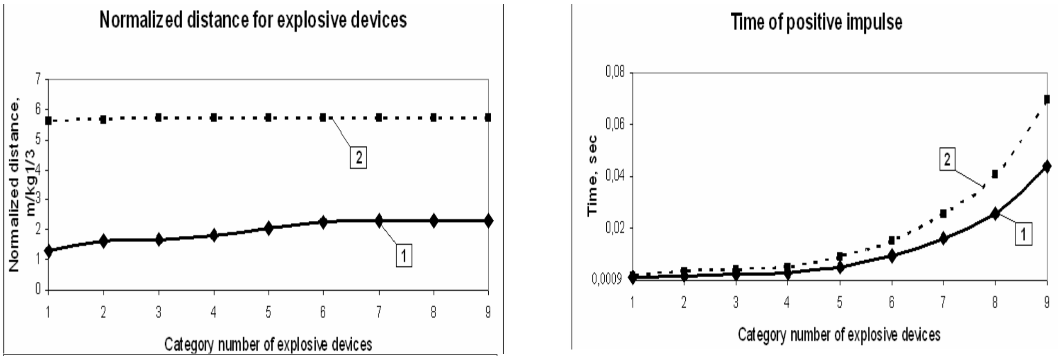
The shock wave characteristics that were obtained by Sadovsky's formulas for different category explosive devices depending on higher (1) and lower (2) distance threshold were presented in Fig. 2 and Tab. 1.

2. Static analysis of the two shell models from action of overpessure

Research contained the modeling of a cylindrical shell as an aggregate of three-cornered shell finite elements with six degrees of freedom at the nodes; creation of hemispheric geometrical model of shock wave; determination of the areas on the shell surface with certain values of overpressure and positive impulse depending on a distance to explosion epicenter.

The cylindrical steel shell was presented as thin-walled shell segment with a height 5 m, a width 17,32 m, a length 36 m and a thickness 0,015 m. Steel had mechanical characteristics: E=2,06·10^{11} Pa, G=0,792·10^{11} Pa, ρ =7850 kg/m^3, μ=0,3.

As an example, the positive phase of shock wave from category number seven of the explosive devices with a TNT equivalent of explosive mass 250 kg was considered. The higher and lower distances threshold were 14,5 m (2,302 m/kg$^{1/3}$) and 36 m (5,715 m/kg$^{1/3}$) respectively. We chose the most dangerous location of the shell to the explosion epicenter. Overpressure was given as the evenly distributed load with the certain values which depended on the distance from explosion epicenter to the shell surface areas. The geometry model of shell under the influence of shock wave (Fig. 3) were generated in the NASTRAN software [10].



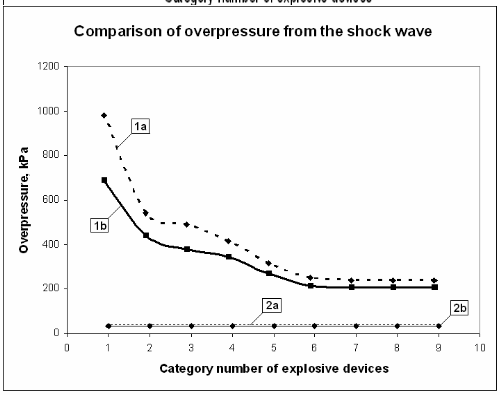


Fig. 2. The shock wave characteristics for different category explosive devices depending on higher (1) and lower (2) distance threshold: Sadovsky's formula (a), experiments (b)

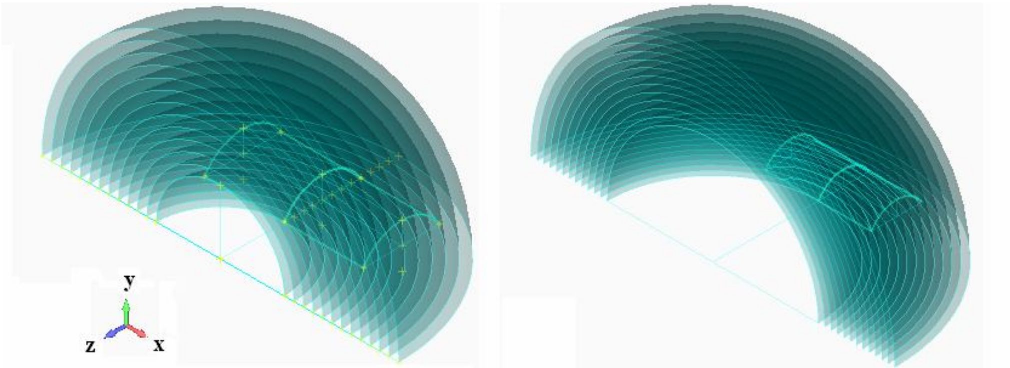
Table 1

The analytical characteristics of shock wave

Category number of explosive devices	Higher distance threshold			Lower distance threshold		
	Normalized distance, m/kg$^{1/3}$	Normalized positive impulse, kPa·s/kg$^{1/3}$	Time of positive impulse, s	Normalize d distance, m/kg$^{1/3}$	Normalized positive impulse, kPa·s/kg$^{1/3}$	Time of positive impulse, s
9	2,298	15,625	0,0441	5,708	6,291	0,0695
8	2,300	9,130	0,0257	5,700	3,684	0,0406
7	2,302	5,747	0,0162	5,715	2,315	0,0256
6	2,253	3,434	0,0094	5,700	1,357	0,0149
5	2,042	2,215	0,0052	5,709	0,792	0,0088
4	1,826	1,449	0,0029	5,715	0,463	0,0051
3	1,700	1,235	0,0022	5,700	0,368	0,0041
2	1,638	1,017	0,0017	5,669	0,294	0,0032
1	1,293	0,754	0,0009	5,602	0,174	0,0019

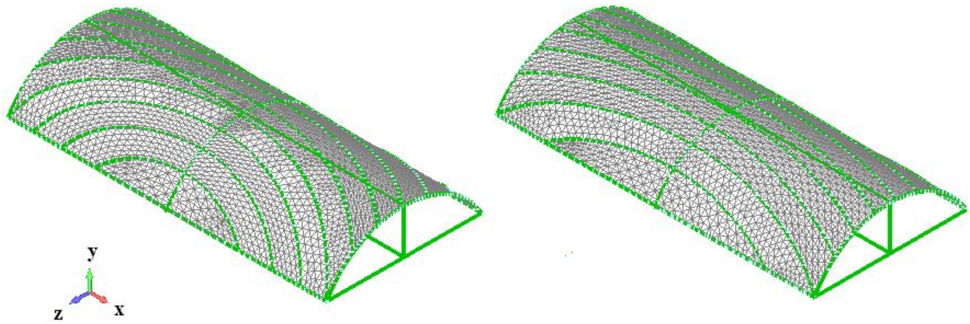
The finite element models of the shell for two geometrical models (Fig. 3) were created. The nodes of four shell edges were fixed. The shell surface areas with certain values of overpressure and positive impulse from shock wave were showed in Fig. 4.

Distance from explosion epicenter to the shell surface areas, corresponding overpressure and time positive impulse were calculated by Sadovsky's formulas and given in Tab. 2.



(a) (b)

Fig. 3. The geometrical models of cylindrical shell under action the shock wave: the distances 14,5 m (a), 36 m (b)



(a) (b)

Fig. 4. The shell surface areas with certain values of the overpressure and positive impulse: the distances 14,5 m (a), 36 m (b)

Table 2

Number of shell surface areas	Higher distance threshold			Lower distance threshold		
	Distance, m	Over-pressure, kPa	Time of positive impulse, s	Distance, m	Over-pressure, kPa	Time of positive impulse, s
1	14,500	239,415	0,0162	36,000	38,168	0,0256
2	16,665	174,869	0,0174	38,165	34,518	0,0264
3	18,830	134,005	0,0185	40,330	31,447	0,0271
4	20,995	106,539	0,0196	42,495	28,835	0,0278
5	23,160	87,189	0,0205	44,660	26,591	0,0285
6	25,325	73,031	0,0215	46,825	24,645	0,0292
7	27,490	62,345	0,0224	48,990	22,946	0,0299
8	29,655	54,068	0,0232	51,155	21,450	0,0305
9	31,820	47,515	0,0241	53,320	20,126	0,0312
10	33,985	42,228	0,0249	55,485	18,946	0,0318
11	36,150	37,893	0,0257	57,650	17,889	0,0324

Shell behavior from the static action of overpressure was investigated (Fig. 5) in the nonlinear formulation (*Nonlinear Static*) by the Newton-Raphson method and compared with the results of the linear static analysis (*Linear Static*) and buckling one (*Buckling*).

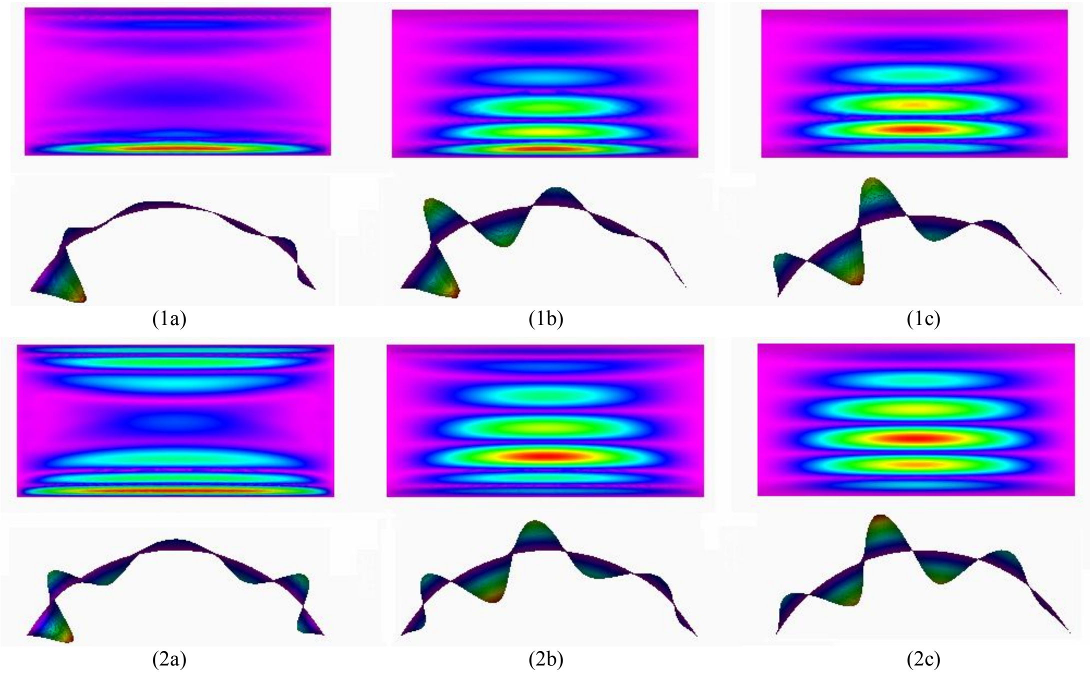


Fig. 5. The deformed shell state from static action of overpressure at the distances of 14,5 m (1) and 36 m (2): linear (a), nonlinear (b) and buckling (c) analyses

Solving the buckling and nonlinear static problems were obtained the critical load coefficients. When there was the distance 14,5 m, they respectively had values 0,0872 (11757 Pa) and 0,0794 (10703 Pa); the distance 36 m – 0,3071 (10597 Pa) and 0,292 (10079 Pa). Static characteristics of the shell under critical overpressure were presented in Tab. 3.

Table 3

Static characteristics of the critical stressed deformed shell state

Static characteristics of the shell	Distance 14,5 m		Distance 36 m	
	Linear Static	Nonlinear Static	Linear Static	Nonlinear Static
Total translation, m	0,1731	0,0577	0,0263	0,0435
VonMises Stress, kPa	625 543	140 138	162 922	82 752
VonMises Strain	0,0027	0,0005	0,0007	0,0003

The overpressure load curves of the shell were obtained solving the nonlinear statics problem and showed in Fig. 6. The control three nodes were located along symmetrical axis *Z* in the direction of shock wave action on the frontal (node 1), back (node 3) shell sides and the highest point (node 2).

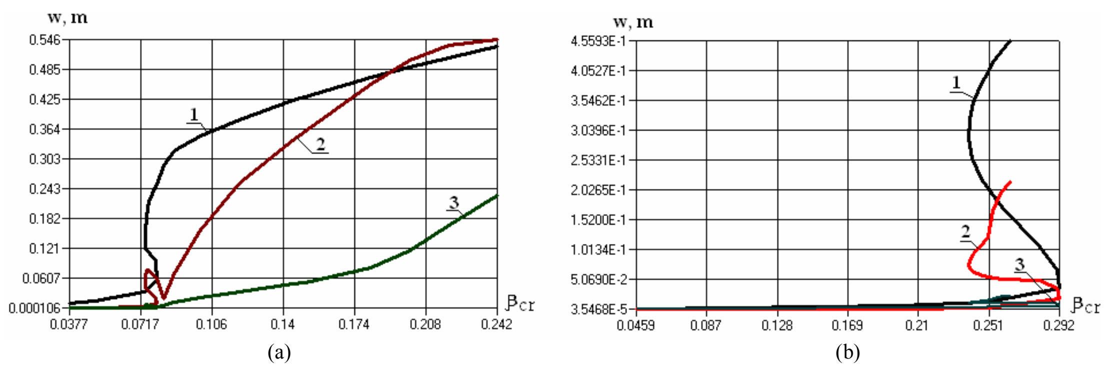
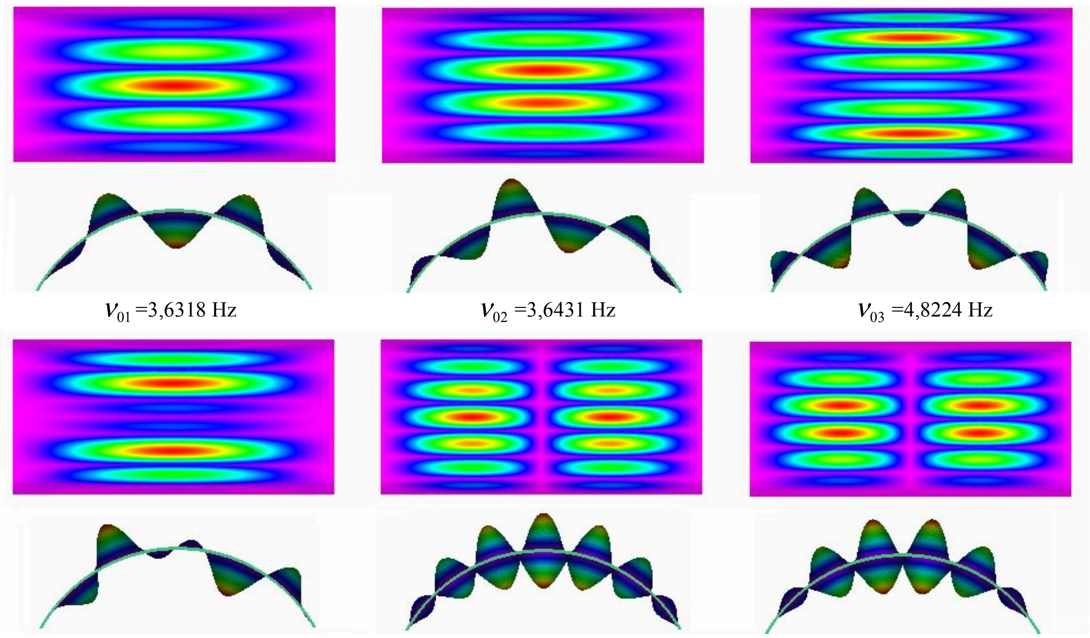


Fig. 6. Overpressure load curve of the shell at the distances of 14,5 m (a) and 36 m (b) (nonlinear static analysis)

The investigation showed that the shell behavior (Fig. 6) was different and depended on the distance to explosion epicenter. The influence of overpressure from the considered explosive device on two shell models were significant and stability condition of the shells was violated.

3. Shell behavior under the influence of the positive impulse

The first step of the dynamic investigation was modal analysis of shell using the Lanczos method (*Normal Modes*) [10]. The first six natural modes were the same views for two shell models and showed in Fig. 7. The values of natural frequencies for two shell models differed by 1 %.



ν_{01} =3,6318 Hz ν_{02} =3,6431 Hz ν_{03} =4,8224 Hz

ν_{04} =5,2889 Hz ν_{05} =5,7076 Hz ν_{06} =5,7730 Hz

Fig. 7. The first six forms of shell natural oscillations

Influence of positive impulse of shock wave on the dynamic behavior of the shell models was investigated by the fourth-order Runge-Kutta method of direct integration (*Direct Transient*) [10]. The positive impulse was presented in the shape of a triangle with a time of action τ_{imp} and given in Tab. 2 with appropriate delay time for each shell surface areas. The largest period of shell natural oscillations $T_{01} = 1/\nu_{01} = 0,2753$ s was taken account. Step of integration time was taken equal $\Delta t = 0,005\tau_{min}$.

The dependence of the nodal translations *u*, *v*, *w* (respectively along *X*, *Y*, *Z*- axes) and VonMesis stresses in the shell elements on time of positive impulse were presented in Fig. 8 and Fig. 10.

The deformed shell state at the different time of positive impulse was showed in Fig. 9 and Fig. 11.

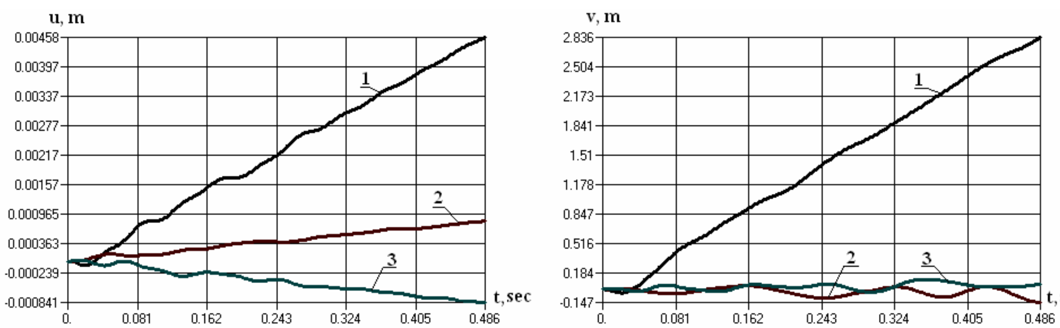


Fig. 8 (1). The dependence of the nodal translations and VonMesis stresses in the shell elements on time (the distance 14,5 m)

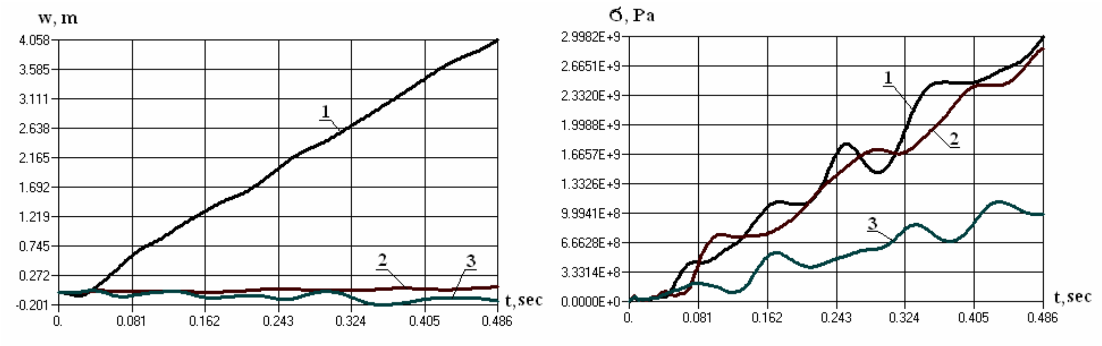
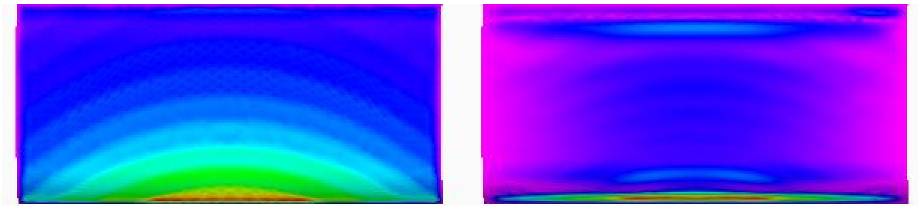
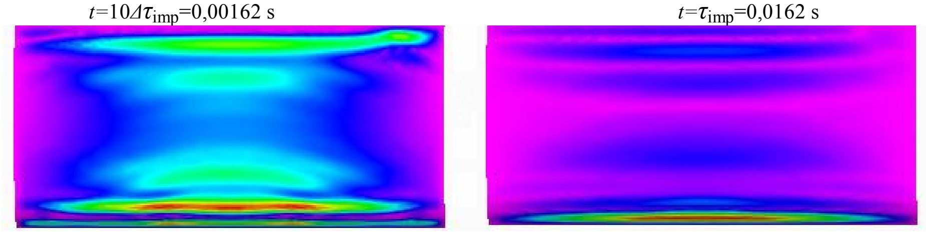


Fig. 8 (2). The dependence of the nodal translations and VonMesis stresses in the shell elements on time (the distance 14,5 m)



$t=10\Delta\tau_{imp}$=0,00162 s $\qquad$ $t=\tau_{imp}$=0,0162 s



t=0,03564 s $\qquad$ $t=1{,}8T_{01}$=0,486 s

Fig. 9. The deformed shell state at the different time of positive impulse (the distance 14,5 m)

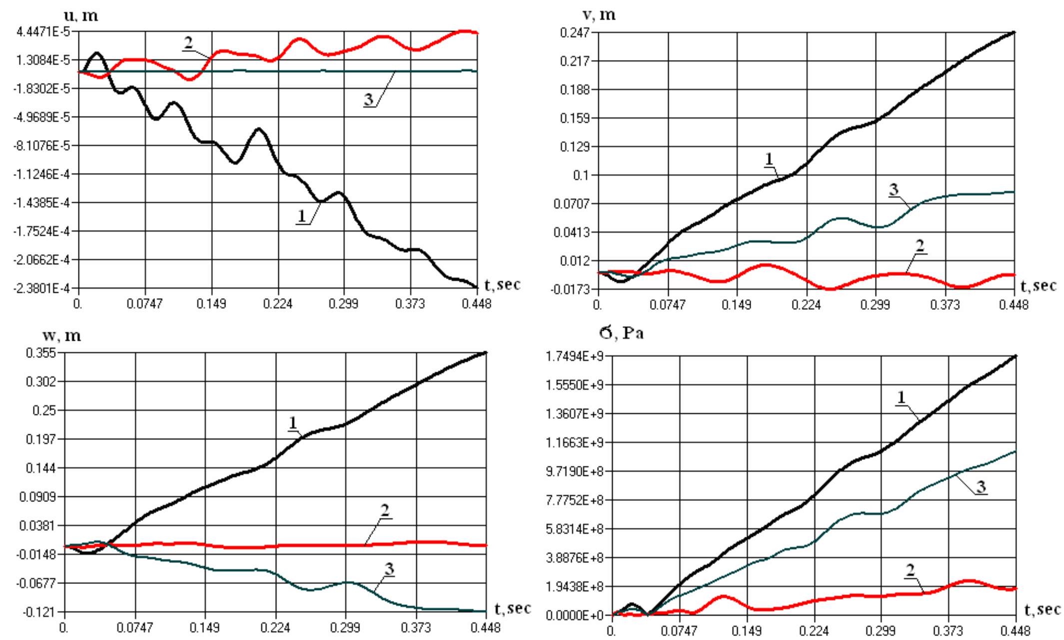
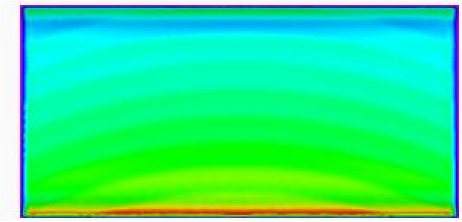
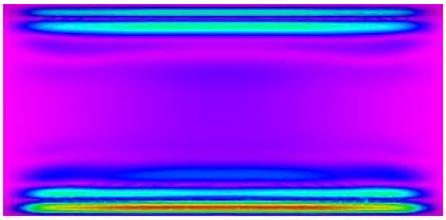
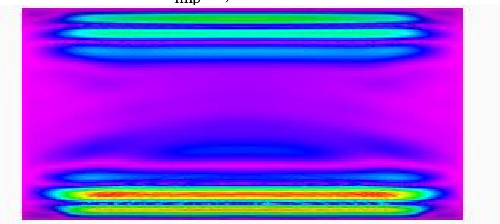


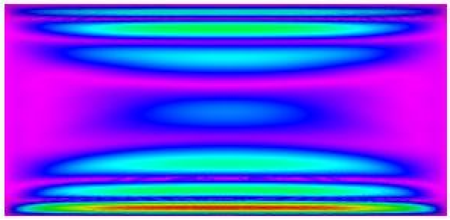
Fig. 10. The dependence of the nodal translations and VonMesis stresses in the shell elements on time (the distance 36 m)





$t=10\Delta\tau_{\text{imp}}$=0,00256 s $\quad$ $t=\tau_{\text{imp}}$=0,0256 s





t=0,03564 s $\quad$ $t=1{,}8T_{01}$=0,486 s

Fig. 11. The deformed shell state at the different time of positive impulse (the distance 36 m)

The dynamic investigation showed that the behavior of the two shell models from positive impulse was different and depended on the distance to explosion epicenter. The back and frontal shell sides had the different stressed deformed states. The dynamic coefficient during the impulse duration was no more than 0,58 which corresponding to the ratio of τ_{imp} to T_{01} [11]. The influence of positive impulse from the considered explosive devise on two shell models was destructive.

Conclusion. The numerical approach allowed to investigate the stressed deformed state of shell under shock wave from explosive device using static and dynamic analysis in finite element formulation. The shell was damaged, therefore, it is necessary to investigate the shell with new geometric or mechanical properties.

REFERENCES

1. *Jacob N., Nurick G.N., and Langdon G.S.* The effect of stand-off distance on the failure of fully clamped circular mild steel plates subjected to blast loads // Engineering Structures, 2007. – Vol. 29, No. 10. – pp. 2723-2736.
2. *Tuhut L.I., Ghicioi E.* Computational simulation of shock wave generated by the detonation of explosives for civil use // SESAM 2019, MATEC Web of Conferences 305, 2020, 00019.
3. *Aune V., Valsamos G., Casadei F., Larcher M, Langseth M., and Borvik T.* Numerical study on the structural response of blast-loaded thin aluminium and steel plates // International Journal of Impact Engineering, 2020. – Vol. 99. – pp. 131-144.
4. *Xu Q.P., Li Z.R., Ding G., Su J.J., Liu Y., and Huang F.L.*Numerical simulation of the influence of ditch landform on shockwave propagation // Engineering Blasting, 2020. – Vol. 26, No. 6. – pp. 23-27.
5. *Al-Yacoby A.M., Hao L.J., Liew M.S., Ratnayake R.M.S., Samarakoon S.M.K. Thin*-Walled Shell Storage Tank under Blast Impacts: Finite Element Analysis // Materials, 2021. – Vol. 143. – 7100.
6. *Hafskjold B., Bedeaux D. and Kjelstrup S.* Theory and simulation of shock waves: Entropy production and energy conversion // PoreLab, Department of Chemistry, Norwegian University of Science and Technology (NTNU), Trondheim, Norway, Physical Review E 104, 2021, 014131.
7. *Mykhailovsky D.V., Shliakov I.O.* Methods of calculation and engineering protection of critical infrastructure objects and other strategic facilities against long-range projectiles // Strength of Materials and Theory of Structures, 2023. – Вип. 111. – С. 155-171.
8. *Bazhenov V.A., Lukianchenko O.A., Vorona Yu.V., Vabyshchevych M.O.* The influence of shape imperfections on the stability of thin spherical shells // Strengh of Materials, 2021. – Vol. 53, №6. – P. 842-850.
9. *Lizunov P.P., Lukianchenko O.O., Geraschenko O.V., Kostina O.V.* Dynamic stability of a hemispherical shell with shape imperfections // Strength of Materials and Theory of Structures. – 2023. – Issue. 110. – P. 97-107.
10. *Jaecheol Koh* Siemens NX Nastran: Tutorials for Beginners and Advanced Users. – ASIN: B0B19ZBZCM, 2022. – 566 p.
11. *Ray W. Clouph, Joseph Penzien* Dynamics of Structures. – New York, 1975. – 634 p.

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Лук'янченко О.О., Геращенко О.В., Костіна О.В.
МОДЕЛЮВАННЯ ДІЇ УДАРНОЇ ХВИЛІ ВІД ВИБУХОВОГО ПРИСТРОЮ НА ЗАХИСНУ ОБОЛОНКУ

Представлено чисельний підхід до дослідження поведінки захисної оболонки при дії ударної хвилі від вибухового пристрою. Виконано порівняння експериментальних характеристик ударної хвилі від різних вибухових пристроїв з аналітичними значеннями, отриманими за формулами Садовського. За допомогою програми NASTRAN створені геометрична модель ударної хвилі у вигляді півсфери та дві скінченно-елементні моделі циліндричної сталевої оболонки із зонами, що мали конкретні значення надлишкового тиску і позитивного імпульсу. Як приклад, розглянута позитивна фаза ударної хвилі від вибухового пристрою з TNT еквівалентною масою тротилу 250 кг. Надлишковий тиск подано у вигляді рівномірно розподіленого навантаження, значення якого залежало від відстані між епіцентром вибуху та конкретної зони поверхні оболонки. Поведінка оболонки від статичної дії надлишкового тиску досліджена в нелінійній постановці методом Ньютона-Рафсона і порівняна з результатами лінійної задачі статики та задачі втрати стійкості. Отримано коефіцієнти критичного навантаження та статичні характеристики оболонки. Першим кроком динамічного дослідження був модальний аналіз оболонки із застосуванням методу Ланцоша. Позитивний імпульс представлено у вигляді трикутника з конкретним значенням часу його дії. Враховано максимальний період власних коливань оболонки. Досліджено вплив позитивного імпульсу на динамічну поведінку двох моделей оболонки методом прямого інтегрування Рунге-Кутти. Представлено стан оболонки в різний час дії позитивного імпульсу. Результати статичного і динамічного аналізів дозволили оцінити вплив дії ударної хвилі від вибухового пристрою на напружено-деформований стан захисної оболонки.

Ключові слова: захисна оболонка, вибуховий пристрій, ударна хвиля, метод скінченних елементів, статичний і динамічний аналіз.

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Keywords: protective shell, explosive device, shock wave, finite element method, static and dynamic analysis.

УДК 539.3
Лук'янченко О.О., Геращенко О.В., Костіна О.В. **Моделювання дії ударної хвилі від вибухового пристрою на захисну оболонку** // Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА. 2025. – Вип. 115. – С. 33-42.
Представлено чисельний підхід до дослідження поведінки захисної оболонки при дії ударної хвилі від вибухового пристрою. Виконано порівняння експериментальних характеристик ударної хвилі від різних вибухових пристроїв з аналітичними значеннями, отриманими за формулами Садовського. За допомогою програми NASTRAN створені геометрична модель ударної хвилі у вигляді півсфери та дві скінченно-елементні моделі циліндричної сталевої оболонки із зонами, що мали конкретні значення надлишкового тиску та позитивного імпульсу. Наведено результати статичного і динамічного аналізів, що дозволили оцінити напружено-деформований стан оболонки.
Табл. 3. Іл. 11. Бібліогр. 11 назв.

UDC 539.3
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The numerical approach to investigate the protective shell behavior under shock wave from an explosive device was presented. Comparison of shock wave characteristics from different explosive devices that were obtained experimentally and by Sadovsky's formulas was made. The hemispheric geometrical model of shock wave and two finite element models of cylindrical steel shell with the surface areas that had certain values of overpressure and positive impulse were created using NASTRAN software. The results of static and dynamic analysis allowed to assess of the stressed deformed state of shell.
Tab. 3. Fig. 11. Refs. 11.

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