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ANALYSIS OF THE DYNAMICS OF LAMINATED GLASS COMPOSITE PANELS UNDER IMPACT LOADING

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Summary. *The study presents the results of analysis of the laminated glasses composites dynamic state under impact loading. The paper investigates modelling of a rigid ball drop on laminated glasses with different thicknesses of polyvinyl butyral (PVB) interlayers. The aim of the paper is to study the dependence of laminated glasses dynamic deformation on the velocity of free ball fall. The study performs computations using a finite element method (FEM) in modern computer-aided engineering (CAE) software within a 3D modelling and explicit dynamics approach. The investigation includes a mesh-size convergence analysis. The work carries out the dynamic strains and stress state analysis in laminated glasses under different loading conditions.*

Key words: *laminated glass, impact loading, polyvinyl butyral interlayer, mesh-size convergence, explicit dynamics, dynamic deformed state.*

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Introduction. Laminated glass panels are widely used in modern technology. These are portholes, car windows, external parts of solar panels, elements of building structures, etc. [1–4]. Their function is to protect other sensitive elements from external factors. Laminated glass consists of two or more glasses laminated together with one or more layers of polymer film (interlayers). The intermediate layer improves mechanical properties: impact strength, fracture toughness, noise insulation, thermal insulation, etc. Polyvinyl butyral (PVB) film, ethyl vinyl acetate (EVA), ionoplast polymers, cast in place (CIP) liquid resin and thermoplastic polyurethane (TPU) are most commonly used as interlayer materials [5–7]. Laminated glass composites generally experience impulse or impact loads caused by the entry of strange objects during their operation [1–4]. Destructive forces can cause significant harm, disable the systems in which they are installed, or substantially impair their functional characteristics [8].

The impact strength of laminated glass is higher than that of a glass plate of the same thickness. Study of dynamic behavior of glass laminated composites under the impulse and / or impact loading is an important practical task, the results of which provide recommendations on the internal structure, requirements on operating modes, limits of use, and so forth.

The impact destructive behavior of the laminate is complex. The combined effects of the glass fragility, the non-linear interlayer characteristic and the adhesive compound significantly complicate behavior of the laminated glass damage. The analysis of the failures of laminated glasses usually carried out experimentally with further numerical modeling or vice versa [9, 10].

Experimental studies are very expensive due to high fragility, optical transparency, high lubricity of the glass surface, and therefore have significant limitations on the possibilities of using experimental equipment [11]. Preliminary computational modelling reduces the number of necessary experimental studies, formulate practical recommendations, and define limitations.

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The problem statement. The aim of this work is to study the dynamic response of laminated glass composites resulting from the impact effect of a rigid ball drop and to analyze the dependence of the level of dynamic deformations, arising in the elements of the composite from the conditions of impact.

The objectives of the study are following:

1) to develop a computer-based mathematical model that makes it possible to investigate the impact interaction of a spherical rigid body with a three-layer glass composite;

2) to verify the calculation studies, to assess the accuracy level and provide recommendations on the parameters of the calculation model;

3) to carry out a series of theoretical studies to determine the pattern of influence of the ball drop parameters on the composite.

In this work, the three-layer laminated glass under the impact of a smooth solid steel ball of 83 mm in diameter (2.3 kg) was considered. The composite is a combination of two glass plates with a thickness of 5 mm each and with an interlayer of PVB having a thickness of 0.38 mm, 0.76 mm and 1.52mm (effective thicknesses of interlayers) in between. The plates are 305 × 305 mm in size.

The properties of the glass material and interlayer are taken from the data of the manufacturers and verified by the initial properties discussed in Chang et al. [12] and shown in Table 1. The geometric model is shown in Figure 1.

Table 1

Material properties

Material	Density, ρ (kg/m^3)	Young's modulus, E (Pa)	Poisson ratio, ν
Steel	7850	$2{\cdot}10^{11}$	0.3
Glass	2500	$7{\cdot}10^{10}$	0.23
PVB	1100	$2.2{\cdot}10^{8}$	0.495

Development of a computational model and its verification. The behavior of laminated glass samples with PVB interlayer was modelled as transient analysis in 3D statement of explicit dynamic formulation of finite element method (FEM). Hexagonal FE with 8 nodes with 3 degrees of freedom in each was used.

As boundary conditions, laminate was fixed on both sides, and the ball drop was simulated at the center of the plate, as shown in Figure 1. The ball was modeled as a rigid body. The composite was modeled in a three-dimensional setting as part of a physical linear-elastic setting. The interaction of the ball and the composite was carried out within the framework of achieving the objective of one-way contact according to the algorithm «surface to surface». The air resistance during the impact was ignored.

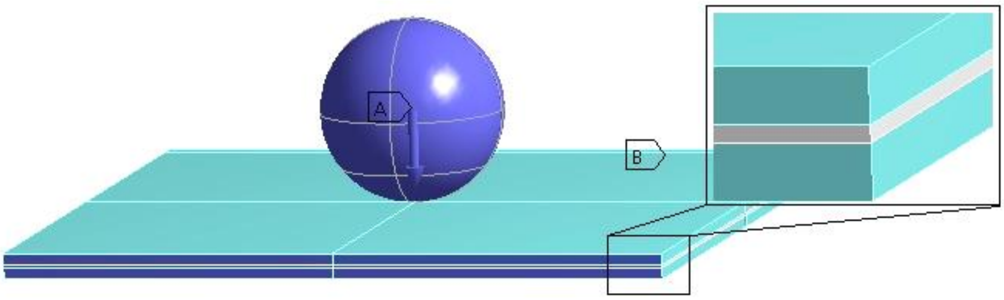

Figure 1. Boundary conditions
(A – Vector of Initial Velocity, B – Fixed Support of Composite)

The FE meshes with elements of different size have been created for the investigated model. For each mesh size, maximum total deformation (u_{max}) and maximum equivalent (von-Mises) stress (σ_{vMmax}) have been calculated to determine computational accuracy. A laminated glass model with a 1.52 mm PVB interlayer and a different velocity of ball free-fall (v_{bff}) was used. The results of the calculations are given in Table 2. The FE mesh model is shown in Figure 2.

Table 2

Dependence of the results on model mesh size

FE mesh size (mm)	Number of nodes	v_{bff} (m/s)	u_{max}(mm)	σ_{vMmax}(MPa)
10	0.04825×10^5	3	2.8742	69.393
		4.85	4.6048	118.31
		5.3	5.786	116.15
		6	6.5234	128.84
5	0.17322×10^5	3	3.1283	105.01
		4.85	4.6652	191.33
		5.3	5.0141	213.11
		6	5.2102	244.06
2	2.06294×10^5	3	1.8548	287.73
		4.85	2.9584	472.18
		5.3	3.2234	518.53
		6	3.6403	590.02

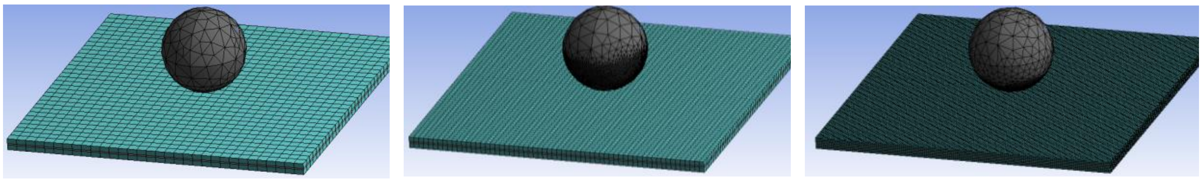
A B C

Figure 2. Mesh size of the model (A – 10 (mm), B – 5 (mm), C – 2 (mm))

Additional calculations with different mesh sizes were performed and the results for deformations were received (Table 3).

Table 3

Dependence of the mesh sizes on nodes and total deformation

FE mesh size (mm)	Number of nodes	u_{max} (mm)
5	$0.17322 \cdot 10^5$	5.2102
4	$0.39793 \cdot 10^5$	3.9519
3	$0.69080 \cdot 10^5$	3.8332
2.5	$0.98814 \cdot 10^5$	3.7835
2	$2.06294 \cdot 10^5$	3.6403
1.5	$4.93677 \cdot 10^5$	3.5793
1	$13.10812 \cdot 10^5$	3.5364

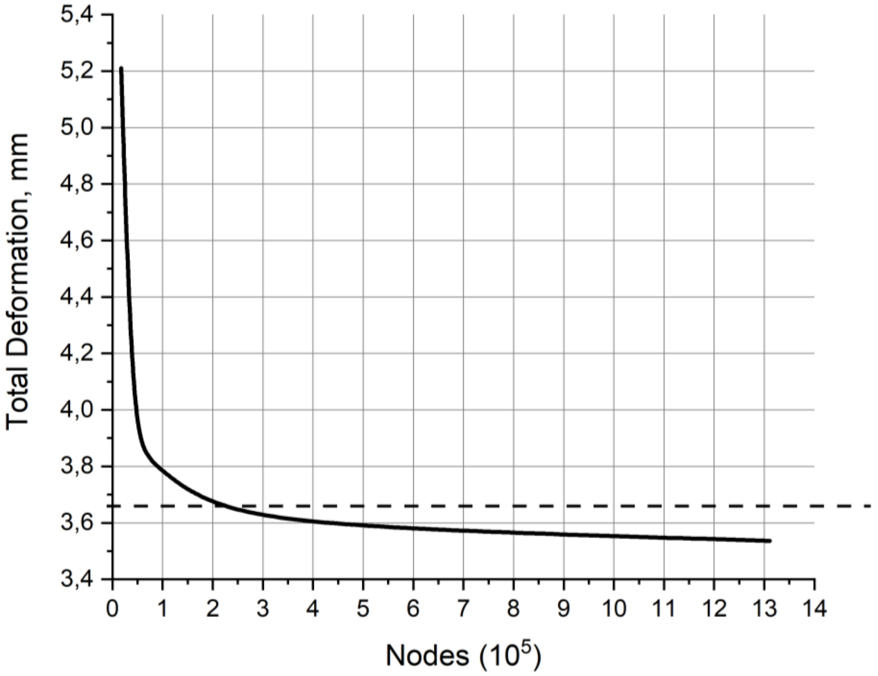

Figure 3. Dependence of the total deformation on mesh size

Similar estimation studies for the composite with the same size and conditions have been made in Vedernama and Pavar [5]. A comparison of the results shows good consistency with the results. The dependence of deformations on the mesh size (specified in the nodes) is shown in Figure 3, where the dotted line indicates the value in Article [5]. The closest mesh size is 2 mm. It can be seen that at first the accuracy between the bend values of the meshes, which have FE with dimensions of 5 mm and 4 mm, is quite large and constitutes 24%, but later it noticeably decreases to 3% between meshes of 4 and 3 mm, and between 2 mm and 1 mm it measures 2.8%.

Calculation of non-linear dynamics of laminated glass. The impact load of the steel ball on laminated glasses with different thickness of the PVB interlayer and the velocity of ball drop were calculated. The results of maximum total deformation, equivalent (von-Mises) stress at characteristic points (Figure 4) at the moment of time t_0 (which corresponds to maximum deformation) and t_{max} (which corresponds to the maximum stress value at all period of time) are available. Similarly, results have been derived for maximum principal elastic strain (ε_{max}). The selected point *H* is the point where the largest maximal deformation and high stress localization occur, but there is no singularity of stress concentration, as at the point where the laminate directly interacts with a perfectly rigid ball. At the place of fixed support of the composite there is the singularity of the stress, which should decrease rapidly as the distance from this part increases according to Saint-Venan’s principle. Therefore, the point *D*, which is behind the singularity, was chosen to analyse the stress state of the model. The values obtained from the calculation are shown in Table 4.

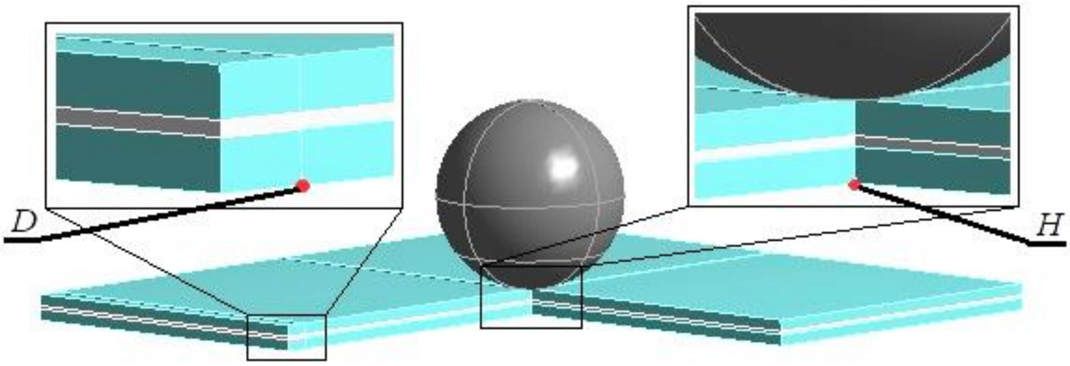

Figure 4. Main investigated points of the model

Table 4

Simulation results

Interlayer thickness (mm)	FE mesh size (mm)	v_{bff} (m/s)	u_{max} (mm)	Point	σ_{vMmax} in t_0 (MPa)	σ_{vMmax} in t_{max} (MPa)	ε_{max} 10^{-3} in t_0	ε_{max} 10^{-3} in t_{max}
0.38	2	3	1.696	D	83.102	94.987	0.37902	0.41464
				H	173.5	273.24	2.151	3.1823
		4.85	2.6953	D	133.11	150.32	0.59302	0.65365
				H	321.66	454.34	3.947	5.2613
		5.3	2.936	D	144.79	163.22	0.64481	0.70853
				H	350.88	497.92	4.3092	5.7838
		6	3.3086	D	162.49	182.84	0.72393	0.7917
				H	396.42	565.66	4.8751	6.5987
0.76	2	3	1.7823	D	79.974	88.442	0.36653	0.39811
				H	197.15	257.78	2.4027	2.9184
		4.85	2.833	D	127.06	140.08	0.56057	0.66492
				H	342.47	430.13	4.179	4.8495
		5,3	3.0856	D	138.44	152.25	0.60941	0.73599
				H	374.43	471.92	4.5724	5.3179
		6	3.4756	D	155.94	170.63	0.68446	0.84899
				H	424.68	536.57	5.1912	6.0884
1.52	2	3	1.8789	D	73.665	81.156	0.33234	0.40361
				H	198.67	227.88	2.4001	2.6745
		4.85	2.9755	D	113.62	127.69	0.49426	0.70324
				H	333.3	382.16	4.0551	4.448
		5.3	3.2372	D	124.48	138.8	0.53808	0.77419
				H	365.07	418.2	4.4471	4.8939
		6	3.6405	D	141.08	155.32	0.6072	0.90358
				H	414.69	473.21	5.0612	5.5909

Figure 5 shows the total deformation in laminated glass with 0.38 mm PVB interlayer under the impact loading of the ball free-fall velocity with 3 m/s. For laminated glasses with other interlayer thicknesses and the velocities of the steel ball, it was evaluated in the same way.

The maximum deformation is observed in the impact zone and the minimum deformation is observed on the fixed edges of the model. Maximum deformations increase with impact height and layer thickness (Figure 6). Between the velocity of 3 m/s and 4.85 m/s the deformation increased by 37%, between 4.85 m/s and 5. m/s by another 8%, between 5.3 m/s and 6 m/s by 11% with a fixed interlayer thickness. Similarly for the case of a fixed velocity of ball fall, but different thicknesses of the PVB interlayer should also tend to increase: between the thicknesses of the layer 0.38 mm and 0.76 mm the deformation increased by 4.8%, and between 0.76 mm and 1.52 mm by 5.1% with a velocity of 3 m/s.

The maximum principal elastic strain in the laminated glasses occurs in its fixed sides, decreases to the centre of the impact and then increases (Figure 7). In the PVB interlayer, the maximum strain is distributed at the centre of the model and the minimum strain can be observed at the edges of the model (Figure 8).

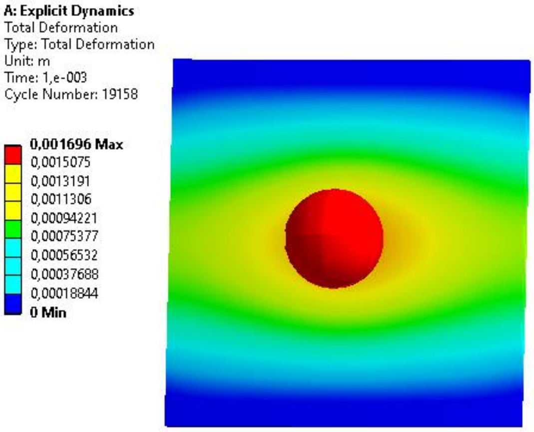

Figure 5. Total Deformation of LG with 0,38 (mm) PVB interlayer with the ball free-fall velocity 3 (m/s)

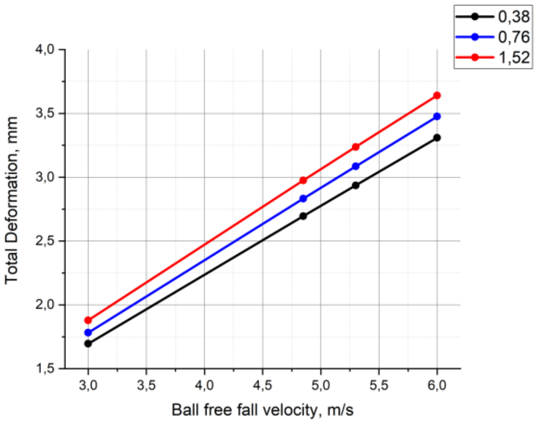

Figure 6. Dependence of maximum Total Deformation on the ball free-fall velocity

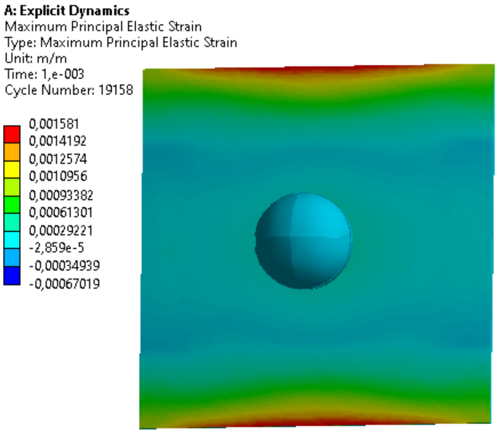

Figure 7. Maximum Principal Elastic Strain of LG with 0,38 (mm) PVB interlayer with the ball free-fall velocity 3 (m/s)

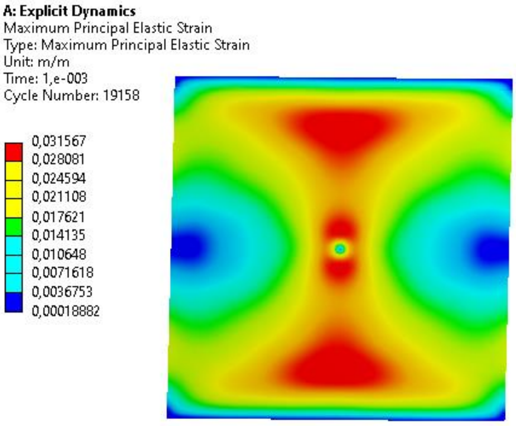

Figure 8. Maximum Principal Elastic Strain of 0,38 (mm) PVB interlayer with the ball free-fall velocity 3 (m/s)

The equivalent (von Mises) stress distribution indicates that the maximum values are on the fixed side of the glass composite and in the centre of impact in the LG (Figure 9). The stress increases with the increase of the ball free-fall velocity. But as the thickness of the interlayer increases, the equivalent stress decreases (Figure 10). With a fixed interlayer thickness between velocities of 3 m/s and 4.85 m/s the stress increased by 37%, between 4.85 m/s and 5.3 m/s by 8%, between 5.3 m/s and 6 m/s by another 11%. In the case of a fixed velocity of ball drop, but different thicknesses of the PVB interlayer, the stress decreased by 3.7%, with the velocity of 3 m/s between the thicknesses of the layer 0.38 mm and 0.76 mm, and between 0.76 and 1.52 mm the stress decreased by 8%.

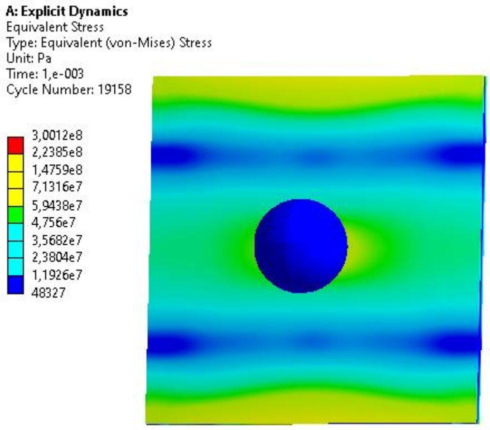

Figure 9. Equivalent (von-Mises) Stress of LG with 0,38 (mm) PVB interlayer with the ball free-fall velocity 3 (m/s)

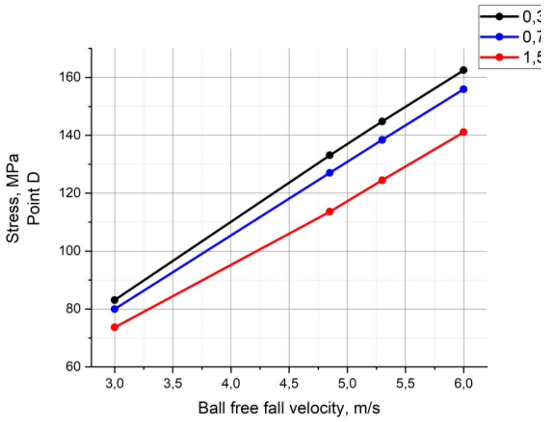

Figure 10. Dependence of Equivalent (von-Mises) Stress at point *D* at t_0 on the ball free-fall velocity

Conclusions. Dynamics of stress-strain state of laminated glass consisting of two glasses 5 mm thick laminated together with a PVB interlayer with 0.38 mm, 0.76 mm and 1.52 mm gap thickness were investigated. Dynamic excitation was formed as a result of the impact on the composite, modelled as a dynamic one-way interaction with a rigid body of spherical shape with a diameter of 83 mm (2.3 kg) to simulate a ball impact on a composite at a different rate of free-fall velocity.

The computer mathematical model was developed within FEM in a three-dimensional setting with explicit dynamic modelling of each structural element of the composite. Verification of the calculation studies was carried out. FE meshes with elements ranging in size from 5 mm to 1 mm were constructed. Comparison of the results with those provided in studies showed that for the selected 2 mm mesh, the accuracy of the deformation values of meshes with FE of 2 mm and 1 mm, measures 2.8%.

The thickness of the PVB interlayer and the velocity of the ball free-fall varied. The results of maximum deformations, equivalent (von Mises) stresses and maximum principal elastic strains have been calculated and analyzed. The results showed that the dependence of the deformations and stresses on the ball velocity was linear. Within the velocities of 3 m/s and 4.85 m/s the deformation increased by 37%, between 4.85 m/s and 5.3 m/s by another 8%, within 5.3 m/s and 6 m/s by 11% with a fixed interlayer thickness. Similar to a fixed free-fall velocity, but different thicknesses of the PVB interlayer there is also a tendency of increasing: within 0.38 mm and 0.76 mm layer thickness the deformation increased by 4.8%, and within 0.76 mm and 1.52 mm – by 5.1% with the velocity of 3 m/s.

With the fixed thickness of the interlayer within the velocities of 3 m/s and 4.85 m/s, the stress increased by 37%., within 4.85 m/s and 5.3 m/s by 8%., and within 5.3 m/s and 6 m/s by another 11%. In the case of a fixed velocity of the ball free-fall, but different thicknesses of the PVB interlayer we have the tendency of decreasing: the stress decreased by 3.7%, with the ball free-fall velocity of 3 m/s within the thicknesses of the layer of 0.38 mm and 0.76 mm, and between 0.76 and 1.52 mm by 8%.

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АНАЛІЗ ДИНАМІЧНОГО СТАНУ ЛАМІНОВАНИХ СКЛЯНИХ КОМПОЗИТНИХ ПАНЕЛЕЙ ПРИ УДАРНОМУ НАВАНТАЖЕННІ

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Резюме. *Наведено представлені результати аналізу динамічного стану композитів ламінованих стекол при ударному навантаженні. Розглянуто моделювання падіння абсолютно твердої гладкої сталевої кулі на ламіноване скло з різною товщиною полівініл-бутирального (PVB) прошарку. В якості граничних умов зафіксовано ламінат з двох сторін, а удар кулі змодельовано у центрі пластини. Композит змодельовано в тривимірній постановці в рамках фізичної лінійно-пружної постановки. Взаємодію кульки та композиту проведено у рамках розв'язання задачі одностороннього контакту за алгоритмом «поверхня до поверхні». Опором, що надається повітрям під час удару, знехтувано. Метою роботи було вивчення залежності прогинів, напружень та деформацій ламінованих стекол від швидкості вільного падіння кулі. Поведінка впливу зразків ламінованого скла з PVB прошарком змодельованоза допомогою перехідного аналізу. Дослідження проведено з використанням методу скінченних елементів (МСЕ) із використанням гексагонального 8 вузлового скінченного елемента зі 3 ступенями вільності в кожному, в рамках 3D-моделювання та явного динамічного підходу в сучасному програмному забезпеченні комп'ютерного інженерного аналізу (CAE). Виконано аналіз збіжності розміру сітки. Створено скінчено-елементні сітки з елементами різного розміру та для кожного розміру сітки проведено розрахунки прогинів і напружень. Також проведено верифікацію розрахункових досліджень, що дозволило оцінити рівень похибок та рекомендації щодо параметрів розрахункової моделі. У статті проаналізовано динамічні деформації та напружений стан у ламінованих стеклах за різних умов навантаження, виведено результати прогинів, деформацій та напружень у характерних точках в різні моменти часу, побудовано графіки залежностей прогинів та напружень від швидкості вільного падіння кулі.*

Ключові слова: *ламіноване скло, ударне навантаження, полівініл-бутиральний прошарок, збіжність розмірів сітки, явна динаміка, напружено-деформований стан.*

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