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LINEAR DYNAMIC PROPERTIES IN CURVED LAMINATED GLASSES

The study presents the results of linear dynamics of laminated glass panels with different curvatures. This is an actual task in the field of mechanical engineering, aviation, shipbuilding, energy, architecture, etc. Such composites are durable, easy to care for and have a wide range of design options. The aim of the work is to study the influence of the curvature parameter on the frequencies and modes of composites. The paper considers the linear characteristics for laminated glass with polyvinyl butyral interlayer. The article considers behavior of the triplex and the propagation of elastic waves in the linear state. The paper performs calculations using the finite element method in the framework of modal analysis in a three-dimensional formulation in the framework of a physical linear-elastic formulation. The study uses hexagonal finite element with 8 nodes with 3 degrees of freedom in each. This work model laminated glass with a curvature parameter ranging from 0 mm to 250 mm. The composite consisted of three layers: two glass layers thickness of each was 3 mm, and a polyvinyl butyral interlayer with 0.38 mm thickness. The size of the plates was 500×500 mm. As a boundary condition, the laminate was fixed on two opposite sides. The article performs mesh size convergence analysis. The results of natural frequencies in accordance with the curvature parameter are derived. The graphs of natural vibration modes are also shown, that give a clear view about the state of composites.

Keywords: laminated glass, polyvinyl butyral interlayer, linear dynamics, curvature parameter, modal analysis, mesh-size convergence.

У дослідженні представлені результати лінійної динаміки ламінованих скляних панелей з різною кривизною. Це актуальне завдання у сфері машинобудування, авіаційної промисловості, суднобудування, енергетики, архітектури тощо. Такі композити є довговічними, простими в догляді та мають широкі конструктивні можливості. Метою роботи є вивчення впливу параметра кривизни на частоти та форми композитів. У роботі розглядаються лінійні характеристики для ламінованих стекол з полівініл-бутиральним прошарком. Було розглянуто поведінку триплексу та розповсюдження в ньому пружних хвиль у лінійному стані. У даній статті виконано обчислення з використанням методу скінченних елементів в рамках модального аналізу в тривимірній постановці у рамках фізичної лінійно-пружної постановки. Використовувався гексагональний скінченний елемент з 8 вузлами із 3 ступенями волі в кожному. У роботі моделювалися ламіновані стекла з параметром кривизни, що варіювався від 0 мм до 250 мм. Композит складався з трьох шарів: два скляних шара, товщиною 3 мм кожен, та полівініл-бутирального прошарку, товщиною 0,38 мм. Розмір пластин складав 500×500 мм. В якості граничних умов, ламінат був закріплений з двох протилежних сторін. Виконано аналіз збіжності розміру сітки. Виведено результати власних частот в залежності від параметра кривизни. Також показані графіки власних форм коливань, що дають наглядне уявлення про стан композитів.

Ключові слова: ламіноване скло, полівініл бутиральний прошарок, лінійна динаміка, параметр кривизни, модальний аналіз, збіжність розміру сітки.

В исследовании представлены результаты линейной динамики ламинированных стеклянных панелей с различной кривизной. Это актуальная задача в сфере машиностроения, авиационной промышленности, судостроения, энергетики, архитектуры и т.д. Такие композиты являются долговечными, простыми в уходе и имеют широкие конструктивные возможности. Целью работы является изучение влияния параметра кривизны на частоты и формы композитов. В работе рассматриваются линейные характеристики для ламинированных стекол с поливинил-бутиральной прослойкой. Было рассмотрено поведение триплекса и распространение в нем упругих волн в линейном состоянии. В работе выполнены вычисления с использованием метода конечных элементов в рамках модального анализа в трехмерной постановке в рамках физической линейно-упругой постановки. Использовался гексагональный конечный элемент с 8 узлами с 3 степенями свободы в каждом. В данной статье моделировались ламинированные стекла с параметром кривизны, который варьировался от 0 мм до 250 мм. Композит состоял из трех слоев: два стеклянных шара, толщиной 3 мм каждый, и PVB прослойки толщиной 0,38 мм. Размер пластин составлял 500×500 мм. В качестве граничных условий, ламинат был закреплен с двух противоположных сторон. Выполнен анализ сходимости размера сетки. Выведены результаты собственных частот в зависимости от параметра кривизны. Также показаны графики собственных форм колебаний, которые дают наглядное представление о состоянии композитов.

Ключевые слова: ламинированное стекло, поливинил-бутиральний слой, линейная динамика, параметр кривизны, модальный анализ, сходимость размера сетки.

Introduction. In the modern world, laminated glass is mainly used in mechanical engineering, aircraft industry, shipbuilding, energetics, commercial buildings, architecture, design etc. [1]. Strength and stability are the advantages of triplex. Such glasses are durable, easy to care for and have wide design possibilities [2]. Noise and heat insulation qualities are higher than that of tempered glass. Tempered glass (single layer) is cheaper, since fewer resources are required to manufacture [3]. Laminated glass is multilayer, consists of two or more separate glasses, between which there is special glue (interlayer) [4]. The choice of such a material is good for safety purposes use. Thus, this excludes damage by fragments, the risk of a person falling out through the glass. So laminated glass provides a high level of protection against hurricanes, bombs, bullets, it blocks UV radiation, preventing the inner filling from fading [5].

There are several types of laminated glass, differing in production technology, which gives different results in the output: PVB, liquid rubber and PVC lamination etc. PVB-glass is the most widely used and tested glass for over 60 years, capable of providing maximum safety. PVB, or Polyvinyl Butyral, is a thermoset, one-component, polymerizing glue. PVB lamination process is complex and requires proper quality control. It is important to note that laminated glass alone does not provide high quality thermal protection, so heat-regulating PVB has to be used [6, 7].

Curved laminated glass is increasingly being used in modern architecture to construct free-form roofs and facades. It is also widely used in windshields of cars, trains, planes. Curved glass is traditionally produced through hot-forming processes [8].

The article is devoted to studying dynamic behavior of laminated glass. It is an important practical task, the results of which are recommendations on internal structure, technical instructions on the operating modes, limits of use, etc.

Formulation of the problem. The aim of the work is to study the linear dynamics of laminated glasses with different curvatures to consider the linear characteristics for triplex. Natural frequencies and vibration modes are investigated to consider the behavior of laminated glass and distributed elastic waves over it in a linear state.

The following tasks are set in this study: to develop a computer-based mathematical model of a three-layer laminated glass with different curvatures; to carry out a series of theoretical studies to determine the pattern of influence of the curvature parameter on the frequencies and modes of composites.

In current work, the different curvatures of three-layer LG have been modelled. The curvature parameter has been varying from 0 mm to 250 mm (i.e. from flat LG up to the curved as cylindrical shell with radius equal to half the side length). The laminate is a combination of two skin glass layers of thickness 3 mm each with a PVB interlayer of 0.38 mm thicknesses. The size of plates is 500×500 mm. The material properties of the glass and interlayers are taken from manufacturer's data tables and verified by the initial properties considered in Zhang et al. [9] and shown in Table 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	$7 \cdot 10^{11}$	0.23
PVB	1100	$2.2 \cdot 10^{11}$	0.495

Simulation model. The behavior of laminated glass samples with PVB interlayer was modelled by modal analysis in 3D modelling and a finite element method (FEM). Hexagonal FE with 8 nodes with 3 degrees of freedom in each was used (Figure 1) [10].

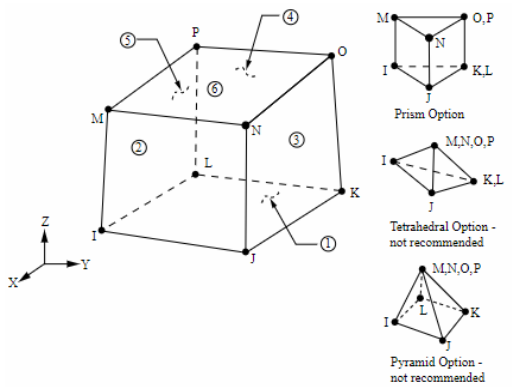


Figure 1 – Finite 3-D Structural Solid Element

The natural value and vector problem needs to be solved for mode-frequency analyses. It has the form of (1)–(2):

$$[M]\{\ddot{q}\} + [K]\{q\} = 0 \qquad (1)$$

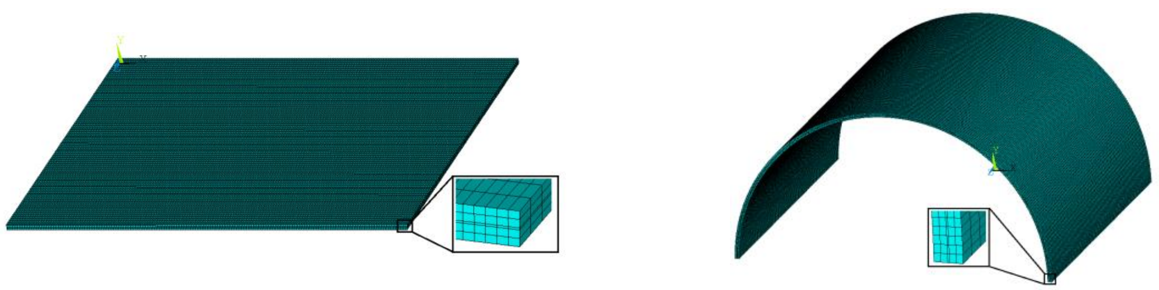
$$[K]\{q\} - \lambda[M]\{q\} = 0 \qquad (2)$$

where M – mass matrix, K – stiffness matrix, q – nodal displacement vector, λ – natural values.

As boundary conditions, laminate was fixed on two opposite sides. The composite was modeled in a three-dimensional state as part of a physical linear-elastic state. The geometric models with FE mesh are shown in Figure 2.

For the studied straight laminated glass, FE mesh with elements of different sizes was created. For each mesh size, the calculations of frequencies were performed to determine the computational error. The value of the mesh size is chosen 2 mm. The error between the values of frequencies for calculations with FE meshes decreases and between values of 2 mm and 1 mm is less than 2%.

Calculation of linear dynamics of curved laminated glasses. Modal analysis was carried out for laminated glasses with different curvatures. The frequencies and vibration modes of the composites were obtained (table 3). The Figure 3 shows Natural Vibration modes that can be resonated in dynamic studies.



A B

Figure 2 – Mesh models of laminated glass (A – straight laminated glass, B – curved laminated glass)

Table 2 – Dependence of laminated glass mode frequency on curvature

Curvature (mm)	Frequency (Hz)									
	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	f_{10}

c = 0	139.6	165.6	279.3	369.3	404.4	523.5	527.8	691.7	727.9	750.4
c = 31.25	387.8	506.2	577.1	599.7	727.5	738.5	886.9	904.5	917.9	979.6
c = 39.06	372.7	530.8	600.9	629.9	791.5	823.8	994.9	1005.6	1048.8	1059.8
c = 46.88	361	560.4	602.3	633.7	857.12	869.9	1085	1117	1125.2	1145.7
c = 62.5	338.3	584.5	616.4	621.4	928.8	967.1	1029.1	1135.2	1286	1291.4
c = 93.75	295.9	534.3	562.6	698.2	934.3	1039.2	1065.6	1153	1288.9	1312.1
c = 125	249.9	467.5	490.9	680.6	818.3	1084.6	1113.6	1155.6	1176.3	1191
c = 187.5	165.8	334.1	347.4	535.1	593.5	863.6	879.1	1100.8	1108.2	1112.9
c = 250	109.7	235.6	240.7	397.8	426.5	635.6	647.3	861.2	892.1	1079.6

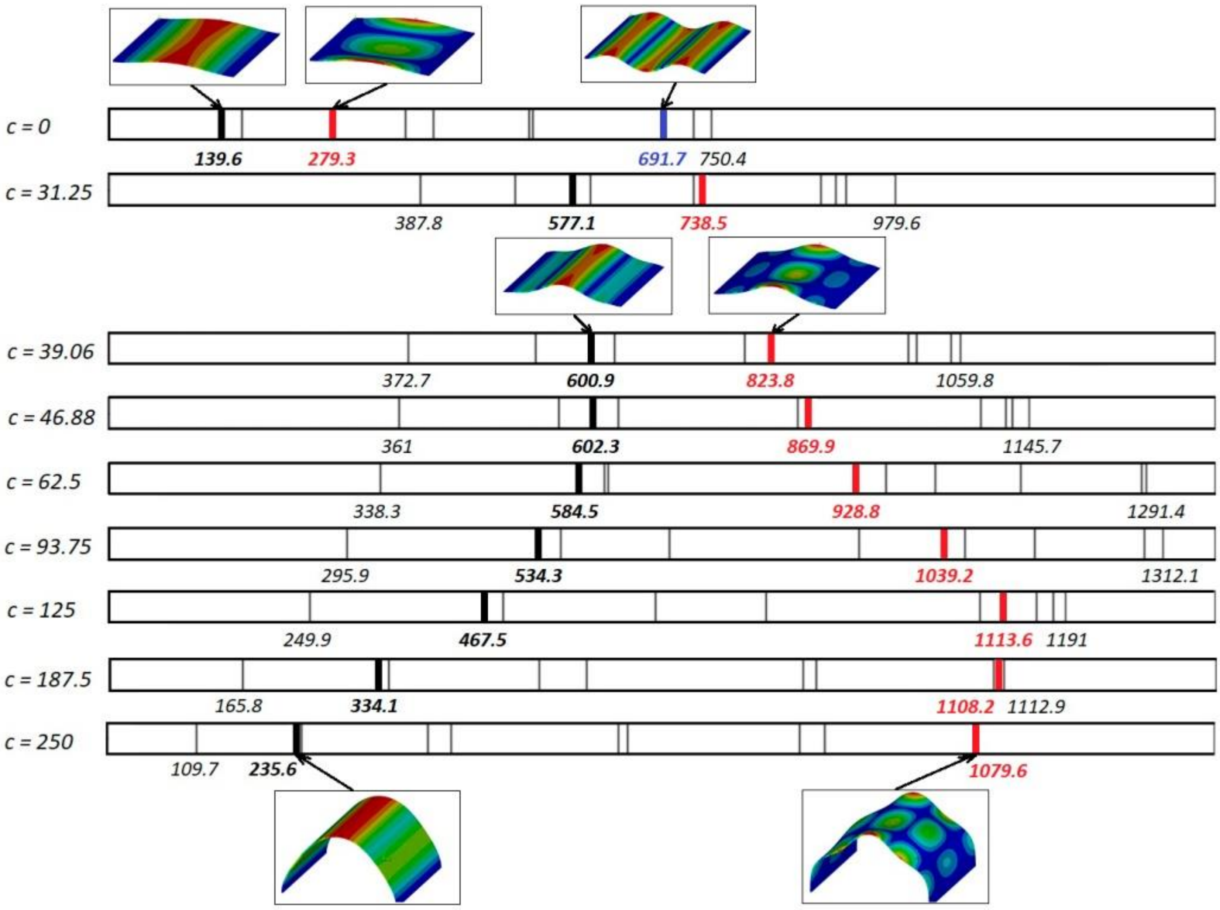


Figure 3 – Laminated glass mode frequency

With increasing curvature to a value of 48.88 mm, the first Natural frequency increases from 139.6 Hz to 602.3 Hz, then its value decreases to 235.6 Hz (highlighted in black). The wave is distributed over the plate, which can be seen in Figure 2. The second Natural frequency of straight laminated glass increases from 279.3 Hz to 1113.6 Hz with increasing curvature to 125 mm (highlighted in red). Elastic waves distributed over the laminated glass are clearly seen in Figure 2.

Conclusions. This article investigates the linear dynamics of the laminated glass with different curvatures, which consisted of two glasses with a thickness of 3 mm, laminated together with PVB interlayer thickness of 0.38 mm. The curvature parameter has been varying from 0 mm to 250 mm (i.e. from straight LG up to the curved as cylindrical shell with radius equal to half the side length).

The computer model was developed within the FEM in a three-dimensional setting with explicit dynamic modeling of each structural element of the composite.

The modal analysis was performed to determine the pattern of influence of the curvature parameter on the frequencies and modes of composites. The results showed that with increasing curvature to a value of 48.88 mm, the first Natural frequency increases from 139.6 Hz to 602.3 Hz, and then its value decreases to 235.6 Hz. The second Natural frequency of straight laminated glass increases from 279.3 Hz to 1113.6 Hz with increasing curvature to 125 mm.

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