In this study, massive, glulam, and cross-laminated timber beams of rectangular cross-section were examined under a concentrated impulse loading (impact).

The task addressed was to determine and compare the deformation and dynamic characteristics of beams made of different types of timber under short-term impact.

During experimental studies, dependences of displacements over time were established; oscillation oscillograms were constructed; spectral analysis was performed, and the frequencies of free oscillations ($f_{MT, exp}$ = 75 Hz, $f_{GLT, exp}$ = 73 Hz, $f_{CLT, exp}$ = 67 Hz) and logarithmic damping decrements ($\beta_{MT, mean}$ = 0.222, $\beta_{GLT, mean}$ = 0.100, $\beta_{CLT, mean}$ = 0.092) were determined for each type of beam. It was found that a cross-laminated timber beam is characterized by the lowest deformation resistance and the lowest oscillation damping rate. Glue-laminated timber (glulam), in comparison with solid timber, demonstrates a smaller maximum displacement and a lower oscillation damping rate.

The results are attributed to the peculiarities of internal structure of the materials, the orientation of the fibers, the presence of adhesive layers, and the nature of the interlayer interaction, which significantly affect the stiffness, damping properties, and distribution of impact energy.

A distinctive feature of the findings is the experimentally confirmed comparison of the dynamic response of beams made of different wooden based materials under the same loading conditions, which made it possible to reasonably assess their effectiveness under the action of impulse influences and solve the research problem.

This study's results could be used in the design of timber load-bearing elements of buildings and structures subjected to dynamic or impact loads, as well as to refine calculation models, determine dynamic coefficients, and assess the effectiveness of using solid, glued, and cross-glued wood

Keywords: timber beams, natural vibrations, damping decrement, impact, dynamic loading

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EFFECT OF CONCENTRATED IMPULSE LOADING (IMPACT) ON MASSIVE, GLULAM, AND CROSS-LAMINATED TIMBER BEAMS

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1. Introduction

In the current context of sustainable construction, materials with a reduced carbon footprint and increased environmental efficiency are becoming paramount. In this regard, timber – as a traditional, naturally renewable material – is increasingly being considered as a structural element with high potential due to its high strength-to-weight ratio.

The current development of timber construction, in particular the use of glulam and cross-laminated timber, necessitates an in-depth study on the operation of structural elements and the possibility of their modification.

The use of wood-based materials in load-bearing elements such as beams, columns, wall panels, and floor slabs is particularly relevant as they compete with metal and concrete. In this context, the following basic materials can be distinguished: massive timber , glued-laminated timber (glulam), and cross-laminated timber (CLT) – each one has its own characteristic structure, production technology, physical and mechanical properties, and behavior under load.

Expanding scope of application of timber structures necessitates an in-depth study on their operation not only under static but also dynamic loads. Unlike static loading, the action of concentrated impulse loading is accompanied by high deformation rates and the occurrence of oscillatory processes, which can lead to a fundamentally different response of the elements.

In this regard, an experimental study on the effect of concentrated impulse loading on beams made of massive, glulam, and cross-laminated timber is relevant in order to compare their dynamic behavior.

2. Literature review and problem statement

In [1], an engineering methodology for calculating glued-laminated timber elements reinforced with composite tapes is described. The author shows that such reinforcement is effective under static loads, but issues related to the behavior of beams under dynamic influences remain unresolved. The likely reason is the orientation of the methodology towards normative calculations, which are traditionally based on static models.

This direction is further developed in [2], in which the stress-strain state of glued-laminated timber beams reinforced with composite tapes was experimentally determined.

It is shown that composites improve the performance of timber , but the studies are limited to quasi-statics. The reason may be objective difficulties associated with the need to use specialized equipment to record dynamic processes.

In thesis [3], a thorough study of bending elements made of glued-laminated timber with combined reinforcement was performed. The influence of the type of reinforcement on the stress-strain state and crack resistance of beams was shown. At the same time, dynamic loading modes, in particular impact, remained outside the scope of the study, which is explained by its focus on the mechanisms of failure with a gradual increase in load.

In work [4], the need to use deformation models in the calculation of timber structures is justified, which allows for a more accurate description of their nonlinear behavior. However, the authors consider mainly static loads, while the influence of the deformation rate is not analyzed. This can be explained by the fundamental impossibility of fully adapting static deformation models to impulse loads. An option for overcoming the difficulties may be to conduct a series of specialized dynamic tests.

Analysis of the stress-strain state of glulam beams reinforced with composite tapes, reported in [5], confirms the effectiveness of combined structural solutions. However, the results are focused on statics, and the expense of preparing large-scale dynamic tests probably made the corresponding studies impractical at that time.

In [6], an engineering methodology for calculating elements made of glued-laminated timber reinforced with composite reinforcement is proposed, based on taking into account the features of the stress-strain state of such elements. The methodology is focused on the operation of elements under static loads and does not take into account the specifics of the dynamic operation of beams.

In [7], a method for calculating prefabricated buildings made of cross-laminated timber is proposed. The structural efficiency of such buildings and the possibility of their application in modern construction are shown. At the same time, the dynamic behavior of individual elements is not the subject of detailed analysis. This is due to the author's focus on the operation of the building as a single system, and not on local impact effects.

In work [8], numerical modeling and calculation of buildings made of cross-laminated timber are performed, taking into account the spatial operation of the panels. The author expanded the approaches to modeling CLT structures, but most attention is paid to static calculation schemes. The probable reason is the significant computational complexity in modeling prefabricated buildings from CLT panels under the action of dynamic loads.

Some current studies have already addressed the dynamic behavior of timber elements. For example, in [9], the effect of impact loading on glulam beams reinforced with CFRP strips was experimentally investigated. It was shown that the impulsive nature of the loading significantly changes the stress-strain state and the failure mechanism of the beams. However, the results apply only to glulam timber and do not allow for comparison with other types of wood-based materials. The reason may be the multiple increase in the number of test specimens and the time spent on further research.

In [10], the bending and vibration behavior of composite CLT-steel beams was analyzed, which confirms the relevance of studying the natural frequencies and vibration characteristics of timber structures, but the issue of concentrated impact remained unresolved. This may be due to the different physical nature of vibration and impact processes.

Work [11] studied the influence of the type and rate of loading on glued-laminated timber beams during bending. The author shows that with increasing loading rate, the stiffness and nature of element failure change. However, impulse loads with high energy concentration (impact), characterized by an ultra-short duration of action and significant peak force, were not considered, presumably due to the need to use impulse installations.

An important aspect of the dynamic operation of timber structures is the action of wind and other variable loads in high-rise buildings. In [12], the behavior of a 30-story building made of cross-laminated timber was analyzed taking into account dynamic wind effects. It was shown that for CLT structures in high-rise construction, the dynamic characteristics (natural frequencies, amplitudes of oscillations, damping) can be decisive in assessing the performance, but the local operation of individual elements, in particular beams, under the action of short-term impulse loads is not considered in the work.

In study [13], a significant effect of wind vortex excitation on the stress-strain state of steel structures with a solid section was established. Although the work considers steel elements, the results emphasize the general problem of the dynamic sensitivity of structures to impulse effects.

The issue of concentrated impulse loading was directly considered in [14], in which the effect of impact on steel roof trusses was investigated. The complexity of the redistribution of forces is shown; at the same time, similar studies for beams made of timber and wood-based materials are practically absent.

Separate attention should be paid to analysis of the regulatory framework for taking into account dynamic effects. In particular, the Eurocode [15] provides an approach to determining the logarithmic decrement of damping for the fundamental bending mode, in particular based on the parameters of structural damping. However, the standard provides generalized damping ranges for entire structures, and not for individual elements, in particular beams.

Thus, despite a large body of research into the static operation of beams made of massive, glulam, and cross-laminated timber [1–8], as well as individual studies concerning dynamic and vibration effects [9–14], issues related to their dynamic response under a concentrated impulse load (impact) remain unresolved.

This gives grounds to argue that it is advisable to conduct a comprehensive study aimed at determining the effect of a concentrated impulse load (impact) on beams made of massive, glued-laminated, and cross-laminated timber with subsequent comparison of their dynamic responses.

3. The aim and objectives of the study

The purpose of our study is to establish the dynamic characteristics and damping properties of beams made of massive, glued-laminated, and cross-laminated timber under the action of a concentrated impulse load (impact). The results will contribute to increasing the validity of the choice of the type of material of timber structural elements operating under dynamic and impact loads. On their basis, it is possible to refine the engineering methodology for calculating the behavior under the influence of dynamic loading and the damping properties of timber beams.

To achieve the goal, the following tasks were set:

– to conduct a series of experimental studies on the vibration process of beams made of massive, glulam, and cross-laminated timber under impact loading and obtain time-displacement dependences;

– to analyze the obtained experimental data: to determine the natural vibration frequencies, logarithmic damping decrements; to perform a comparison with theoretically calculated frequencies.

4. Materials and methods

The object of the study is massive, glued-laminated, and cross-laminated timber beams of rectangular cross-section, subjected to a concentrated impulse loading (impact).

The principal hypothesis of the study assumes that with the same geometric parameters of the beams and the same parameters of the impulse (ball mass, lift height, speed before impact), the dynamic response of massive, glulam, and cross-laminated timber beams will differ in the following characteristics:

– displacement amplitude in the middle of the span;

– natural frequency;

– damping decrement.

It is assumed that these differences arise from the difference in:

– elasticity modulus E;

– shear modulus G;

– density ρ;

– internal structure of the material (solid, layered, cross-oriented).

Based on preliminary calculations, the expected displacements are within ±2 mm, and the required minimum recording time is approximately 0.2 s. Based on these assumptions, an digital displacement sensor was used that allowed us to cover the amplitude of ± 5 mm (sensitivity 0.023 mm), with an approximate recording time of 0.52 s (reading interval 0.127 ms).

The following simplifications were adopted in the research process:

1. The pendulum motion is considered without energy losses, the friction of the ball against the air, the friction in the upper block of the pendulum, deformations and cable tension are neglected.

2. The beam supports are considered ideal hinged, the friction in the support nodes is neglected.

3. The beam material is considered to be free of initial defects; the natural imperfections of the sample materials are neglected.

4. The impact is considered to be an instantaneous concentrated impulse load applied exactly in the middle of the span without repeated contact after the ball rebounds.

Performed experimental study is a continuation of a series of studies aimed at investigating and comparing the behavior of massive, glued-laminated, and cross-laminated timber beams, described in [16–18]. The physical and mechanical characteristics, namely the elasticity modulus, shear modulus, and density for the three types of beams reported in this study are taken from experiments conducted earlier (Table 1).

Impulse loading, namely impact, was generated using a pendulum mechanism. The impact occurred on the front face of the element in the middle of the span. The displacement of the beam in the middle of the span was measured online by a digital sensor.

Table 1

Physical and mechanical properties of the studied beam samples

Design span	l_{ef}	1854	mm
Beam height	h	145	mm
Beam width	b	90	mm
Mean modulus of elasticity	$E_{MT,mean}$	7.658	GPa
	$E_{GLT,mean}$	7.292	
	$E_{CLT,mean}$	6.108	
Mean shear modulus	$G_{MT,mean}$	0.479	GPa
	$G_{GLT,mean}$	0.456	
	$G_{CLT,mean}$	0.382	
Density	ρ_{MT}	0.462	t/m^3
	ρ_{GLT}	0.490	
	ρ_{CLT}	0.486	

A test rig was designed, manufactured, and installed to conduct experimental research. The rig was designed for testing beam elements in a horizontal position according to a single-span scheme with left fixed and right movable supports (Fig. 1).

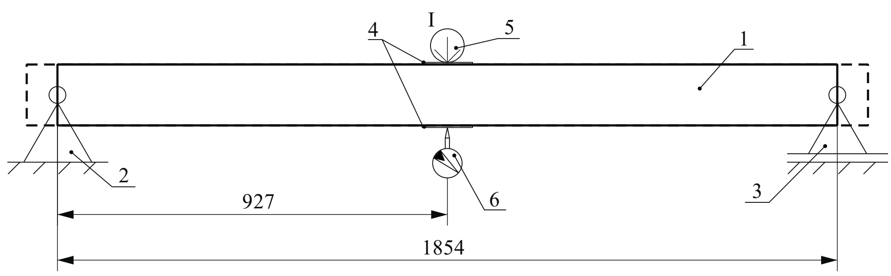


Fig. 1. Layout of the test setup elements: 1 — beam; 2 — hinged-fixed support; 3 — hinged-movable support; 4 — distribution plate; 5 — pendulum “payload”; 6 — digital sensor

To achieve an impact without repeated contact after the rebound of the “payload”, a lateral impact model was adopted using a pendulum mechanism. The pendulum was made of a steel cable and a steel ball with a diameter of 80 mm, the beam face was placed at the point of the pendulum’s equilibrium position, taking into account the dimensions of the ball.

To verify the hypothesis, data collection was performed during the tests (mid-span displacement (δ) and the corresponding time (t)), data cleaning was performed, and checked for missing values, anomalies, or erroneous entries. For the convenience of further analysis, the data were structured in tables. Oscillograms of vibrations were constructed for visual analysis.

Methods for processing the obtained experimental data of the displacement δ – time t for each type of timber under study (massive, glulam, cross-laminated):

– construction of vibration oscillograms for each type of timber;

– determination of maximum displacements;

– spectral analysis using the discrete Fourier transform method and determination of the natural vibration frequency;

– calculation of logarithmic damping decrements;

– construction of exponential envelopes of damped vibrations.

Previously, at the first stage of the study, the experimental data collection was provided, which included the following parameters: the mass of the ball (m_b), the drop height (h_{imp}), and the theoretical speed of the ball immediately before impact (v_{imp}) was determined, given in Table 2.

To determine the speed of the ball immediately before impact, the law of conservation of energy was applied, which means that during the fall, the potential energy of the ball at drop height h_{imp} is converted into kinetic energy and is completely transferred from one form to the other at the lowest point (the pendulum's equilibrium position) [19]:

$$h = h_{imp} \rightarrow U = \max; \quad K = 0,$$

$$h = 0 \rightarrow U = 0; \quad K = \max,$$

$$U = K, \tag{1}$$

where K – kinetic energy; U – potential energy.

At the point of maximum elevation above the equilibrium point, the ball's velocity is zero, and the potential energy U is maximum and equal to

$$U = m_b g h_{imp}, \tag{2}$$

where m_b – mass of the ball; g – gravitational acceleration; h_{imp} – drop height (height of the ball rise above the pendulum equilibrium position).

At the equilibrium position, the ball's velocity is maximum, and accordingly the kinetic energy K is equal to

$$K = \frac{m_b v_{imp}^2}{2}, \tag{3}$$

where m_b – mass of the ball; v_{imp} – velocity of the ball immediately before impact.

The law of conservation of energy (1) takes the form

$$\frac{m_b v_{imp}^2}{2} = m_b g h_{imp}.$$

Accordingly, the speed of the ball immediately before impact v_{imp} is equal to

$$v_{imp} = \sqrt{2 g h_{imp}}. \tag{4}$$

Table 2

Impulse loading (impact) output data

Ball mass	m_b	2.104	kg
Drop height	h_{imp}	0.1	m
Speed before impact	v_{imp}	1.401	m/s

The study provides for a comparison of the dynamic responses of the studied structural elements (beams) made of massive, glulam, and cross-laminated timber.

5. Results of experimental analysis of the response of timber beams to impulse loading (impact)

5. 1. Experimental data of beam tests under impact loading

Table 3 gives mean values for the oscillation peaks (positive and negative) according to the three results of the study of a massive timber beam.

The resulting oscillograms of free vibrations of a massive timber beam are shown in Fig. 2.

Data analysis (Table 3, Fig. 2) reveals that the process occurs relatively fast, vibrations excited by impact almost completely decay within 0.18 s.

Table 4 gives mean values for the peaks of vibrations (positive and negative) according to three results of the study of a glued-laminated timber beam.

Oscillograms of vibrations of a glued-laminated timber beam are constructed based on experimental data are shown in Fig. 3.

Experimental study on a glulam beam (Table 4, Fig. 3) demonstrates a slower damping of natural vibrations compared to a beam made of massive timber.

Table 5 gives average values for the peaks of vibrations (positive and negative) for three results of the study of a cross-laminated timber beam.

Based on the experimental data, oscillograms of the natural vibrations of cross-laminated timber beam were constructed (Fig. 4).

Table 3

Results of research on massive timber beams

No.	Time, s	Displacement, mm
	t_{mean}	δ_{mean}
0	0	0
1	0.003	1.17
2	0.010	–1.11
3	0.017	0.88
4	0.024	–0.84
5	0.030	0.81
6	0.038	–0.74
7	0.044	0.67
8	0.052	–0.57
9	0.058	0.50
10	0.065	–0.45
11	0.072	0.44
12	0.079	–0.41
13	0.086	0.36
14	0.093	–0.30
15	0.100	0.28
16	0.106	–0.25
17	0.113	0.25
18	0.120	–0.21
19	0.127	0.17
20	0.134	–0.14
21	0.141	0.12
22	0.148	–0.09
23	0.155	0.12
24	0.162	–0.09
25	0.170	0.09
26	0.177	–0.07

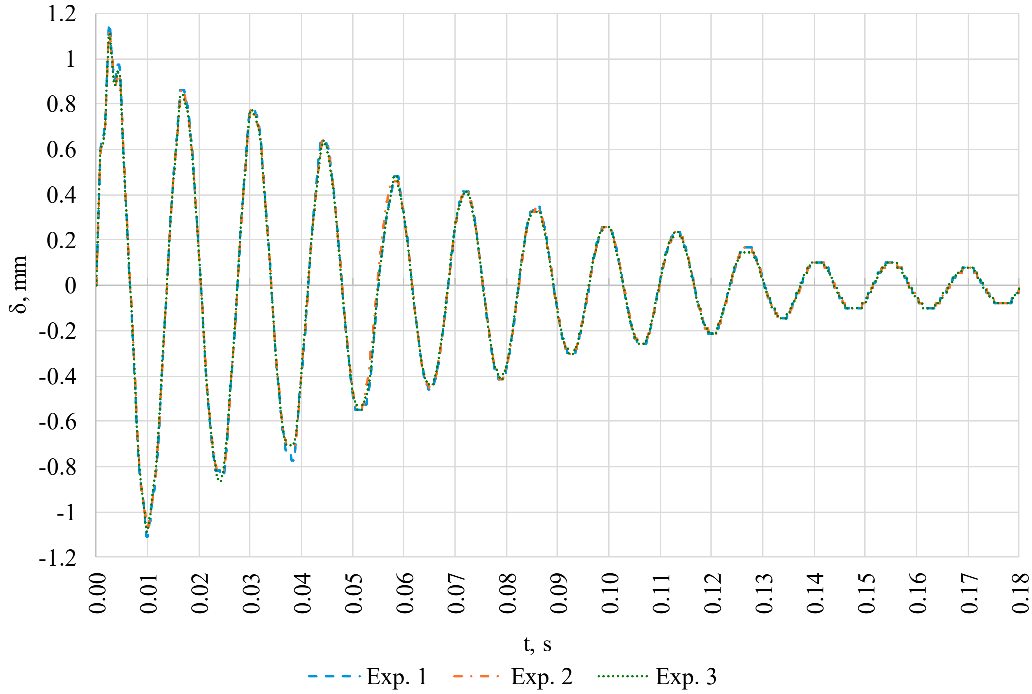


Fig. 2. Oscillogram of free vibrations of a massive timber beam

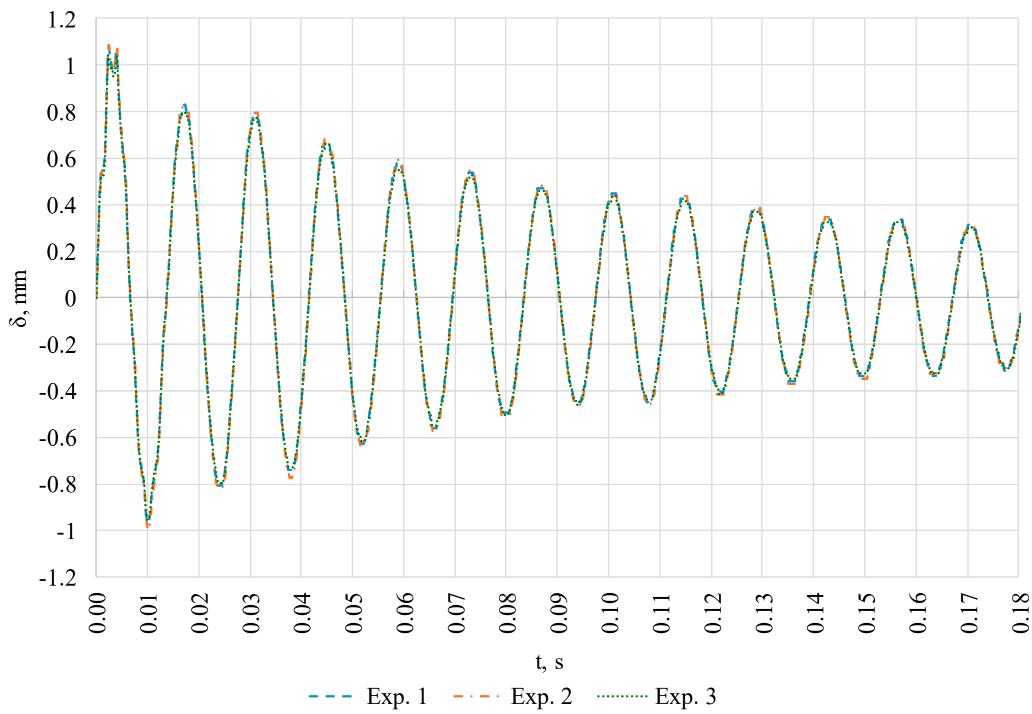


Fig. 3. Oscillogram of free vibrations of a glulam timber beam

Table 4

Results of research on glued-laminated timber beams

No.	Time, s	Displacement, mm
	t_{mean}	δ_{mean}
1	2	3
0	0	0
1	0.002	1.10
2	0.010	–0.99
3	0.017	0.84
4	0.024	–0.82

Continuation of Table 1

1	2	3
5	0.031	0.81
6	0.038	–0.76
7	0.045	0.70
8	0.052	–0.64
9	0.059	0.60
10	0.066	–0.57
11	0.073	0.56
12	0.080	–0.51
13	0.087	0.49
14	0.094	–0.46
15	0.101	0.46
16	0.108	–0.45
17	0.115	0.44
18	0.122	–0.41
19	0.129	0.40
20	0.136	–0.36
21	0.143	0.35
22	0.150	–0.34
23	0.157	0.35
24	0.164	–0.33
25	0.171	0.32
26	0.178	–0.31

Table 5

Results of research on cross-laminated timber beams

No.	Time, s	Displacement, mm
	t_{mean}	δ_{mean}
0	0	0
1	0.003	1.25
2	0.012	–1.00
3	0.019	0.89
4	0.027	–0.85
5	0.035	0.76
6	0.043	–0.78
7	0.050	0.73
8	0.058	–0.67
9	0.065	0.66
10	0.073	–0.60
11	0.081	0.60
12	0.089	–0.56
13	0.096	0.58
14	0.104	–0.52
15	0.112	0.53
16	0.119	–0.47
17	0.127	0.49
18	0.135	–0.44
19	0.142	0.45
20	0.150	–0.42
21	0.158	0.43
22	0.166	–0.39
23	0.173	0.40
24	0.181	–0.38
25	0.189	0.39
26	0.196	–0.35

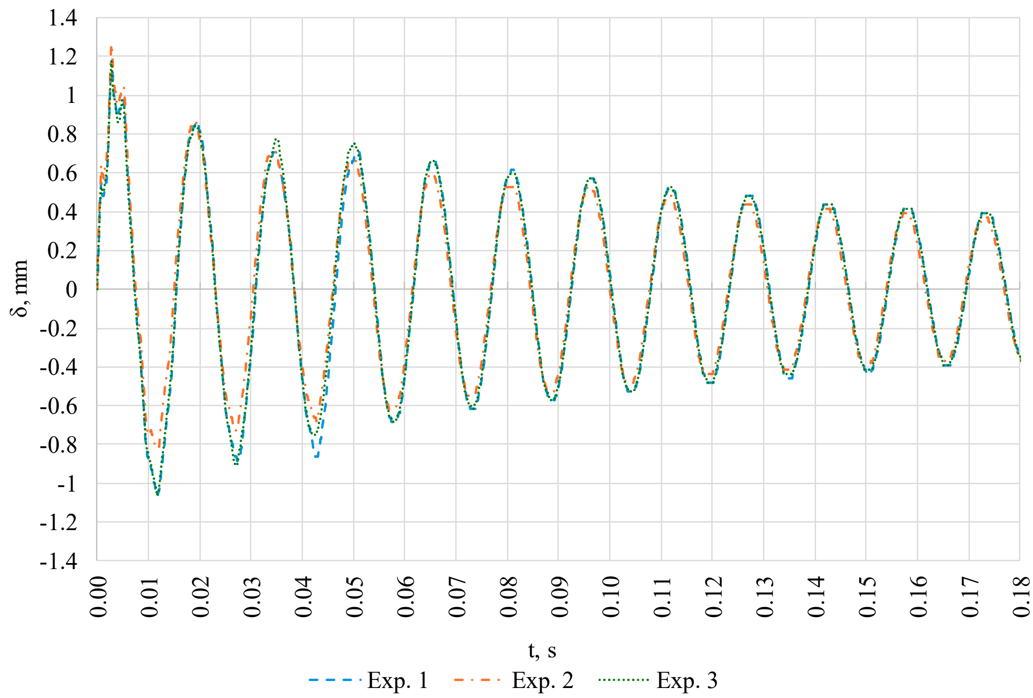


Fig. 4. Oscillogram of free vibrations of a cross-laminated timber beam

Based on the experimental data (Table 5, Fig. 4), it was determined that the cross-laminated timber beam has an even slower vibration decay. Additionally, it was noted that under dynamic loading, an increase in deformations persists, which was also observed during static tests.

5. 2. Analysis of the experimental data: vibration frequencies of beams, damping decrement

To determine the vibration frequencies of the studied beams, spectral analysis was performed using the discrete Fourier transform method, implemented using the fast Fourier transform (FFT) algorithm.

The fundamental vibration frequency of a massive timber beam is 75 Hz (Fig. 5). Conducting Spectral analysis allowed us to detect the presence of an additional frequency of similar magnitude.

The diagram of the spectral analysis of a glued-laminated timber beam shows the fundamental frequency at 73 Hz (Fig. 6) without including additional frequencies, unlike massive timber.

Analysis of the natural frequency spectrum of a cross-laminated timber beam reveals one fundamental frequency of 67 Hz (Fig. 7) without additional inclusions, same as for a glulam beam.

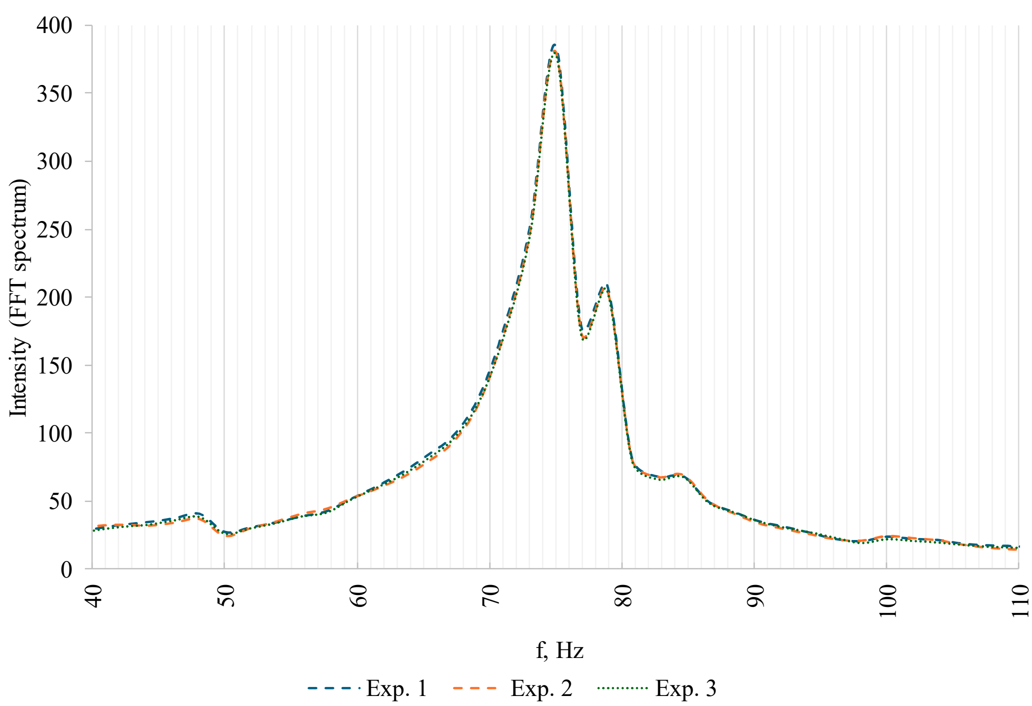


Fig. 5. Spectral analysis for a massive ~~solid~~ timber beam

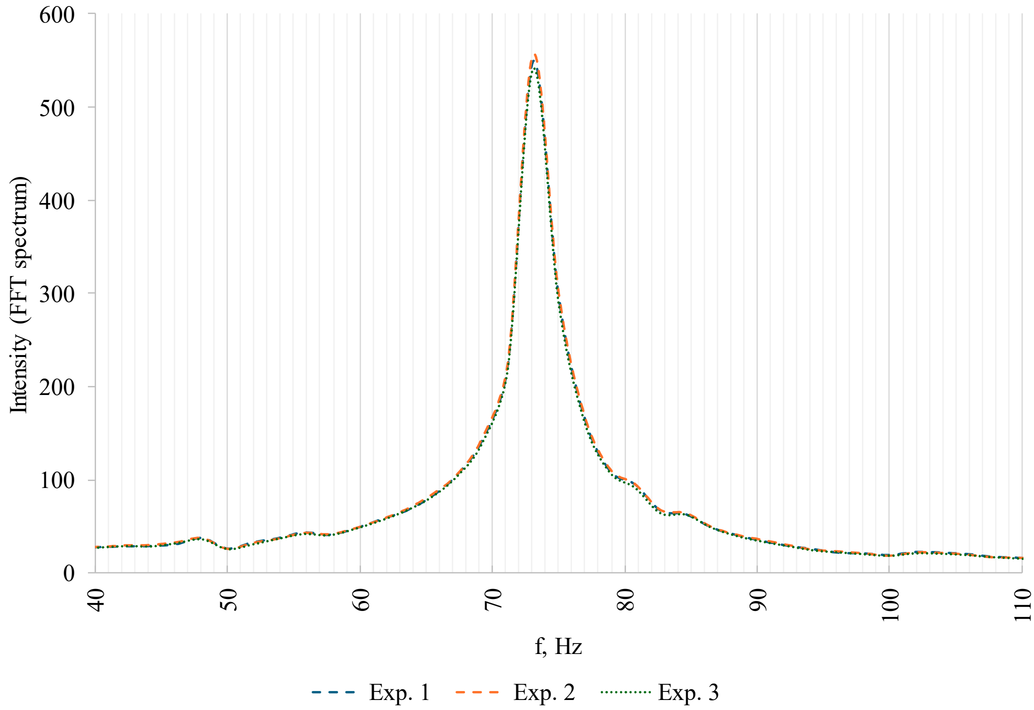


Fig. 6. Spectral analysis for a glued-laminated timber beam

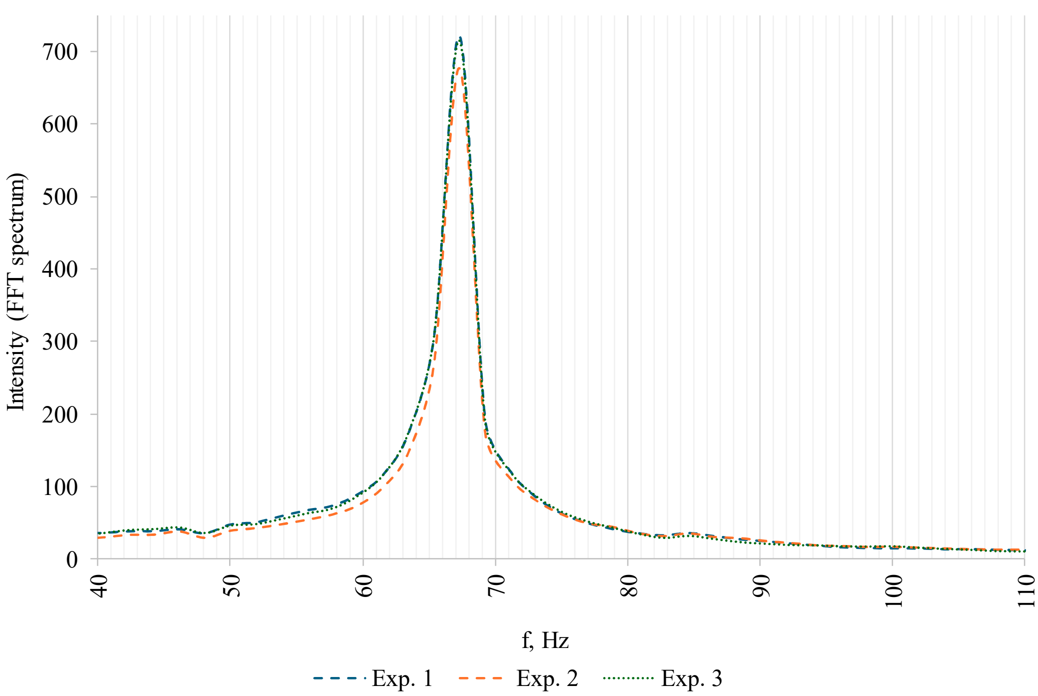


Fig. 7. Spectral analysis for a cross-laminated timber beam

A comparison of the experimentally obtained data with the theoretically calculated ones was performed. The comparison was conducted by the natural frequency. The natural frequency of the beam f_i can be obtained from angular frequency [20]

$$f_i = \frac{\omega_i}{2\pi}, \tag{5}$$

where ω_i –angular frequency of free vibrations.

The angular frequency of free vibrations ω_i of a hinged beam taking into account the shear modulus [21] is

$$\omega_i = \frac{i^2\pi^2}{l_{ef}^2}\sqrt{\frac{EIg}{A\rho}}\left\{1-\frac{1}{2}\cdot\frac{i^2\pi^2}{l_{ef}^2}\cdot\frac{I}{A}\left(1+\frac{E}{\kappa G}\right)\right\}, \tag{6}$$

where i –number of the oscillation form; l_{ef} – design span; E – elasticity modulus of the material; I – moment of inertia of the section; g – gravitational acceleration; A – cross-sectional area; ρ –-density of the material; κ – coefficient of correction of shear stiffness (depends on the shape of the cross-section, $\varkappa = 5/6$ for beams of rectangular cross-section); G – shear modulus.

Oscillation period T_i – the time of one complete oscillation – is the inverse characteristic of the linear frequency [20]

$$T_i = \frac{1}{f_i}. \tag{7}$$

To estimate the energy loss in an oscillatory system, the logarithmic damping decrement is used, which indicates the rate of decrease in the amplitude of oscillations over time.

Logarithmic damping decrement of neighboring oscillations β_j [22] is

$$\beta_j = \ln \frac{A_j}{A_{j+1}}, \tag{8}$$

where j – oscillation number; A_j – amplitude of the j-th oscillation.

The decrease in the oscillation amplitude over time is described by an exponential law. The exponential envelope of damped vibrations is described by the following function [23]

$$A(j) = A_0 e^{-\beta j}. \tag{9}$$

Table 6 gives the vibration frequency (experimental and theoretical), period, and logarithmic damping decrement for the studied beam types. The damping decrement was determined based on the averaged experimental data (Tables 3–5) as the arithmetic mean of the decrements of all positive and negative vibration peaks.

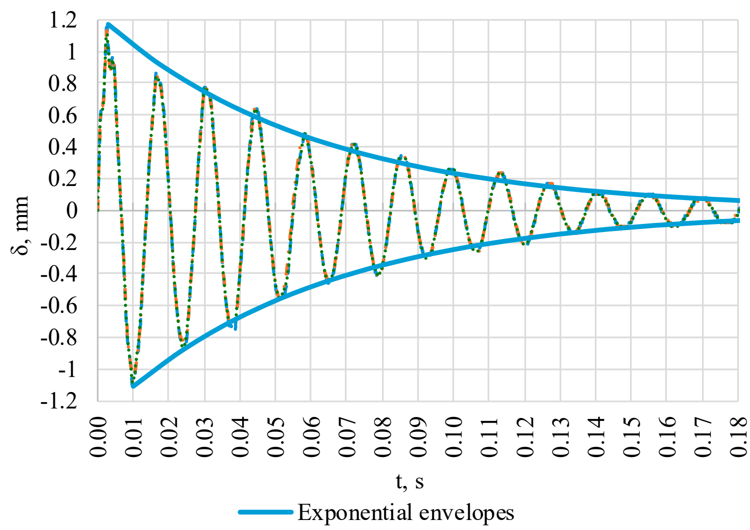
Table 6

Vibration frequency, period, and logarithmic damping decrement for massive, glulam, and cross-laminated timber beams

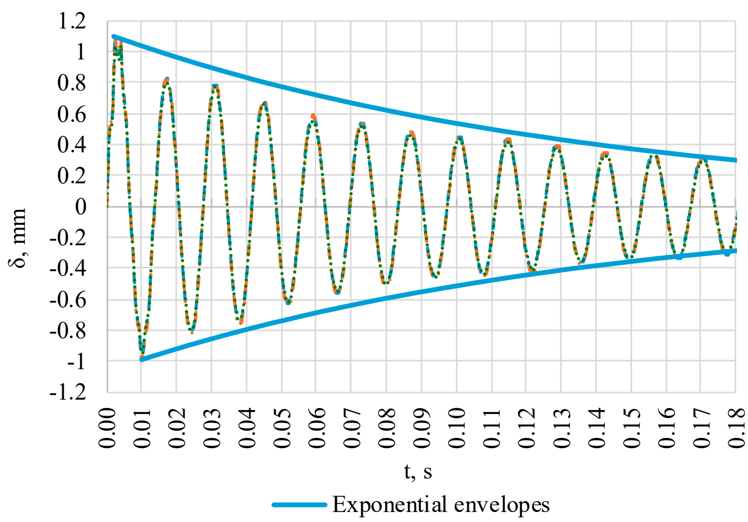
Beam type	f_{exp}, Hz	T_{exp}, s	f_{calc}, Hz	β_{mean}
MT	75	0.0133	74	0.222
GLT	73	0.0137	70	0.100
CLT	67	0.0149	64	0.092

For illustration, Fig. 8 presents the exponential envelopes of the vibrations providing mathematical representation of the amplitude decay behavior.

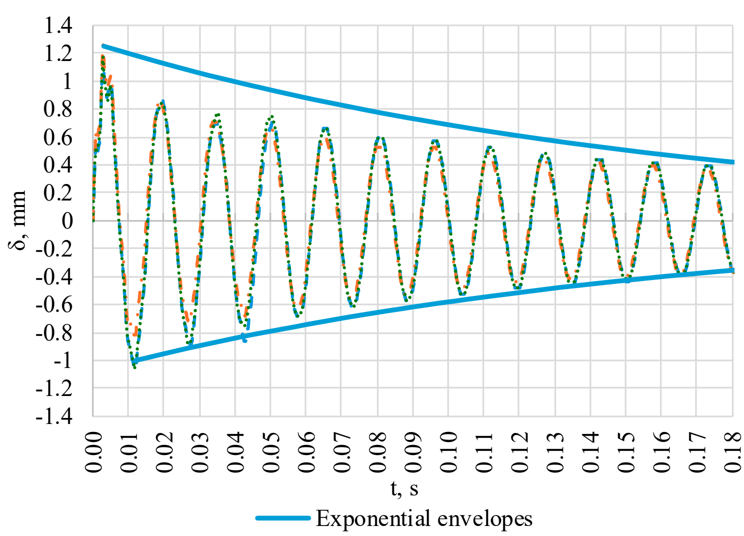
In order to compare theoretical calculations, the resulting exponential curves were superimposed directly on the experimental oscillograms. The combined representation of calculated and experimental data allows us to evaluate the applicability of using the logarithmic damping decrement model for the studied types of beams and the correspondence to the actual physical process.



a



b



c

Fig. 8. Calculated exponential envelopes of damped vibrations for beams made of: *a* – massive timber; *b* – glulam timber; *c* – cross-laminated timber

6. Discussion of results based on investigating the response of timber beams to impulse loading (impact)

Based on the analysis of the response of massive (MT), glued-laminated (GLT), and cross-laminated (CLT) timber beams to an impulse loading, several key aspects can be distinguished that explain the physics of the process and have practical significance for design.

For the sample of the studied massive timber beam, a significantly higher damping decrement $\beta_{MT,mean} = 0.222$ (Fig. 8, *a*) can be noted, which is twice as high as the indicators for the other two types of materials. This result can be explained by the inhomogeneity of the structure of the solid wood and, in any case, by less control and a greater presence of micro- and macrostructural defects (cracks, resin canals, knots, etc.). Under dynamic loading, such elements can dissipate energy. In contrast to the results from [17], in which CFRP-tape-reinforced glulam timber beams were studied, this comparison allows us to state that it is the natural inhomogeneity of the solid wood (cracks, knots) that acts as an effective dissipator of impact energy.

Relatively low damping decrements for samples made of glulam (GLT) $\beta_{GLT,mean} = 0.100$ (Fig. 8, *b*), and cross-laminated (CLT) timber $\beta_{CLT,mean} = 0.092$ (Fig. 8, *c*) may indicate that the process of industrial gluing under pressure makes the material more homogeneous; control over material imperfections also increases. As a result, the element effectively accumulates energy and returns it in the form of free vibrations.

For the purpose of engineering interpretation of our results, it is advisable to compare them with the standard values of damping given in [15]. In the above-mentioned Eurocode for timber bridges, a logarithmic decrement of structural damping within the range of 0.06–0.12 is recommended. Thus, the results for GLT $\beta_{GLT,mean} = 0.100$ and CLT $\beta_{CLT,mean} = 0.092$ are in good agreement with the standard recommendations for structural damping of timber systems. This may indicate that for engineering assessments of the dynamic performance of glulam and cross-laminated timber beams, it is permissible to use the standard values as indicative. At the same time, a significantly higher level of energy dissipation was recorded for massive timber.

It should be noted that the standard values in [15] are established for long-span engineering structures (bridges); in our study, the work of individual elements, namely beams, is considered. Therefore, exceeding the standard range for massive timber should not be interpreted as a non-compliance.

The largest amplitude of displacements $\delta_{CLT,\max} = 1.25$ mm (Fig. 4) and the lowest natural vibration frequency $f_{CLT,exp} = 67$ Hz for a cross-laminated timber (CLT) beam can be explained by the orientation of part of the layers perpendicular to the span. Accordingly, layers with transverse orientation of the lamellas have a significantly lower modulus of elasticity in the main direction of the study, which increases the overall flexibility of the element. Under dynamic loading, this leads to greater inertial response.

Comparison of experimental vibration frequencyies values with theoretical calculations showed a strong agreement across all types of materials under study, with an error of less than 5%. The correspondence between the experimental and calculated frequencies ($f_{MT,exp} = 75$ Hz, $f_{MT,calc} = 74$ Hz; $f_{GLT,exp} = 73$ Hz, $f_{GLT,calc} = 70$ Hz; $f_{CLT,exp} = 67$ Hz, $f_{CLT,calc} = 64$ Hz) confirms that accurate prediction of the dynamics of timber elements cannot rely on pure bending. Consideration of the shear modulus (G) according to equation (6) is critical. The slight deviation of the experimental data towards an increase in frequency compared to the theory can be explained by the dynamic strengthening of the timber material – an effect in which the elasticity modulus of the material increases under short-term high-speed impulse loadings. This confirms the hypothesis put forward in [11] regarding the dynamic strengthening of timber. However, whereas in [11] this was observed when the speed of the static load changed, in our study the effect was recorded precisely under high-speed load, concentrated impact.

Unlike composite beams (GLT, CLT), the spectrum of massive timber (Fig. 5) contains additional frequency spike near the fundamental vibration frequency. This phenomenon can be explained by possible natural imperfections, which, under dynamic loading, trigger more complex vibration patterns. Glued materials, due to control over the selection of lamellas and the rejection of defects, demonstrate "cleaner" vibration response.

The obtained results have direct practical significance. The high accuracy of the mathematical model for determining the vibration frequencies of beams and the possibility of its application for calculations of elements made of glued-laminated and cross-laminated timber are confirmed. The calculated logarithmic damping decrements could also be used for engineering calculations.

It is worth noting that this study has certain limitations. The tests were carried out on samples with a relatively small span ($l_{ef} = 1854$ mm). A hinged support scheme was adopted. The study was limited to a single pendulum impact (concentrated impulse). The behavior of beams under the action of long-term vibration and cyclic loads can reveal additional features of the operation of timber beams. For composite materials, only one configuration of lamellas and their sizes were studied.

In addition to the above limitations, a number of shortcomings can be identified in the work. Measurements were carried out only in the middle of the span (at the impact point). The small discreteness of the measurement points does not allow for a full assessment of the wave propagation of the impulse along the beam. This drawback can be eliminated in the future by installing a network of sensors along the length of the beam.

In a full-scale experiment, it is difficult to achieve ideal boundary conditions (supports). Micro-displacements of the beam on the supports under the impact loading can dissipate part of the energy, which can artificially inflate the indicators of the damping decrement. By eliminating it, it is possible to consider the possibility of increasing the rigidity of the support nodes and preliminary measuring their vibration characteristics for the purpose of further filtering and exclusion from the results.

Further research may involve determining and comparing the influence on the results of different beam support types, the number of layers of lamellas for glulam and cross-laminated timber, as well as studying other wood species. It will also be advisable to investigate the influence of wood imperfections (knots, cracks, etc.) on the behavior of elements under dynamic impact.

It is planned to conduct own research in the direction of verifying the modeling of beams response to dynamic impact in software packages based on calculations using a finite element method (FEM) and determining dynamic load factors.

7. Conclusions

1. Experimental studies on the free vibrations of massive, glued-laminated, and cross-laminated timber beams showed significant differences in the nature of the damping of the vibration process under the action of a concentrated impulse loading (impact). For a massive timber beam, the fastest decay was recorded – the vibrations nearly vanishing within 0.18 s, which indicates greater energy losses in the system. The glulam beam demonstrates a slower amplitude decay, which indicates a lower level of internal damping compared to massive timber. The slowest decay was observed for the cross-laminated timber beam, for which also maintained higher deformations under dynamic loading ($\delta_{MT,\max} = 1.17$ mm, $\delta_{GLT,\max} = 1.10$ mm, $\delta_{CLT,\max} = 1.25$ mm), which is consistent with the results of static tests.

2. Spectral analysis allowed us to determine the main natural frequencies of the beams: 75 Hz for massive, 73 Hz for glulam, and 67 Hz for cross-laminated timber. Comparison with theoretically calculated values (74, 70, and 64 Hz, respectively) showed satisfactory convergence of the results, which confirms the applicability of the mathematical model taking into account shear deformations to predict the dynamic behavior of the studied types of timber beams. It was established that a massive timber beam has the highest level of damping ($\beta_{MT,mean} = 0.222$), while for glulam ($\beta_{GLT,mean} = 0.100$) and cross-laminated ($\beta_{CLT,mean} = 0.092$) beams showed slower vibration decay.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

Authors' contributions

Dmytro Bitiukov: Methodology, Investigation, Validation, Writing – original draft; **Serhiy Bilyk:** Conceptualization, Supervision, Writing – review & editing.

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