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Investigation of the influence of dynamic loads on the fastening of underground mine workings

Abstract. In the context of the need to increase the energy resistance of underground fasteners under dynamic influence, the study was aimed at an experimental and analytical assessment of the mechanical behaviour of wooden structures, in particular, panels made of cross-glued wood, under the influence of impulsive loads. The purpose of the study was to establish the efficiency of using wood and cross-glued elements as energy-adaptive materials for fastening mine workings. The research methodology was based on laboratory modelling of explosive and seismic modes using stands and digital systems for fixing deformation parameters, considering normalised geometric conditions and the influence of humidity. The tests were carried out with samples prepared for the typical conditions of mine workings in Ukraine, taking into consideration of the geostructural characteristics of the regions of Dnipropetrovsk, Lviv, and Kirovohrad oblasts. It was recorded that cross-glued panels retained structural integrity after the action of pulses with an amplitude of up to 3.0 megapascals and a duration of 0.2 seconds, demonstrating a higher ability to dissipate energy compared to solid wood. It was found that the specific values of absorbed energy for the panels averaged 280-340 joules, and the residual deformation did not exceed 3.4%, which indicated the ability of the material to withstand repeated loads without loss of load-bearing capacity. The results of the study confirmed the feasibility of including cross-glued wood in the composition of fastening systems with high requirements for energy absorption. The practical significance of the obtained data lies in the possibility of modifying underground structures based on available wooden materials with predicted characteristics of adaptation to dynamic impacts

Keywords: residual deformation; impulsive load; dissipative capacity; orthogonal multilayer structure; geostructural conditions; quenching coefficient; wood anisotropy

Introduction

The increase in the intensity of mining operations at considerable depths is accompanied by an increase in the impact of dynamic loads on the elements of infrastructure support for the underground production cycle, primarily on fastening systems. Blasting operations, mining impacts, and anthropogenic seismic vibrations generate pulsed waves with a high amplitude and short-term load phase, which often exceed the limits allowed for conventional structures. In such conditions, it is necessary to use materials that can not only withstand instantaneous overloads, but also maintain the residual load-bearing capacity in the event of partial damage. This determines the relevance of the study of materials with dissipative and adaptive properties, in

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particular wood, and composites based on it – such as multilayer cross-laminated timber (CLT).

In the process of analysing current scientific sources devoted to the topic of dynamic loading in an underground mining environment, key approaches to assessing the influence of impulse factors on the structural stability of workings and the efficiency of technical equipment were identified. The study by F. Tahmasebinia *et al*. (2021) analysed the behaviour of combined fasteners in the dynamic load mode by numerical modelling, in particular, the limits of their plastic deformation were determined and the potential for energy absorption was estimated. J. Yao *et al*. (2021) demonstrated that rope lifting systems under ultra-deep mine conditions experience a significant impulsive load, which had a significant impact on the operation of equipment, especially in areas of uneven stress distribution.

H. Zhang *et al*. (2025) proposed an innovative *in-situ* method for strengthening the surrounding array by subsurface injection of reinforcing solutions, which reduced the amplitude of the vertical shock load, although the main focus was on macroscopic geomechanical effects. The study by J. Li *et al*. (2021) analysed the processes of rock instability under the influence of impulsive perturbation, based on which the researchers proposed a differentiated model of rock behaviour depending on the prestress level. Modelling by J.R. Huerta *et al*. (2022) allowed developing scenarios for the functioning of mining systems, considering variable dynamic factors, in particular, their impact on the probability of emergency degradation of individual fastening elements.

The study by D. Chepiga *et al*. (2024) established the stability of protective systems under static load under long-term operation, while experimentally proved the loss of efficiency under the influence of variable loads. S. Pysmennyi *et al*. (2023) conducted a stress-strain analysis of workings in coal mines, which allowed mapping areas of maximum risk of damage, indicating the need for adaptive fasteners to stabilise them. V.P. Shchokin *et al*. (2025) as part of monitoring the technical condition of mine shafts, they found the accumulation of deformations during operation, but stressed the dependence of the results on the type of load, which strengthened the argument in favour of considering the impulse factor. A. Neshchadymenko (2021) presented an effective method for determining the mechanical parameters of rocks using numerical modelling, which helped to construct scenarios for interaction with various types of fasteners. Ultimately, F. Seguel *et al*. (2021) developed a structural architecture of intelligent positioning subsystems that allows real-time coordination of technical equipment during blasting operations, although the study did not focus on energy absorption issues in structural materials.

Thus, a methodological gap was identified due to the lack of a systematic approach to evaluating wood, in particular CLT, as an active structural material for fastening under dynamic load conditions. The parameters of residual deformation of wood after the action of impulses, energy absorption in the short-term overload mode, crack resistance at variable humidity, and the mechanisms of layer-by-layer degradation in multicomponent structures of the CLT type were not established. There is also a lack of data on the interaction of wooden structures with the rock mass in a dynamically unstable environment. The identified limitations in the coverage of these aspects confirmed the need to direct further research to the experimental and analytical assessment of the effectiveness of wood in mining anchor systems.

The purpose of the study was to experimentally substantiate the feasibility of using solid wood and CLT as materials for energy-intensive adaptive fasteners in underground mine workings exposed to short-term impulsive loads. For its implementation, the following research tasks were formulated: to establish the characteristic parameters of dynamic load within the main geostructural regions; to carry out a comparative assessment of the mechanical characteristics of solid wood and CLT based on the results of laboratory tests; to analyse the influence of humidity, load direction, and number of layers on the functional stability of wooden structural elements in the mining environment.

Materials and Methods

The study was of an applied experimental and analytical nature and was conducted in Ukraine during January 2022 – March 2025. The main part of the experimental procedures was implemented based on a technical stand and test equipment at the M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.). Analytical substantiation of the impulsive load parameters was carried out based on generalisations of the M.S. Poliakov Institute of Geotechnical Mechanics NASU, considering the geostructural conditions of coal and ore mines in Ukraine.

Materials for testing were solid coniferous wood – Scots pine (*Pinus sylvestris* L.) and European larch (*Larix decidua Mill.*), and three- and five-layer CLT panels made of the same wood. Solid wood samples had a rectangular cross-section of 60×60 mm and a length of 240 mm, with a humidity of 10-12%. The CLT panels were 120×120×400 mm in size. The sample was not random in nature and was created based on the criteria of structural uniformity, absence of visual defects, compliance with strength classes according to EN 338:2016 (2016). 32 samples were formed: 16 solid wood samples (8 for axial, 8 for transverse loading) and 16 CLT samples (8 three-layer and 8 five-layer), which corresponded to the structure of the load tests presented in the results. Experimental work with plants – both cultivated and wild – including the collection of wood material samples, was carried out in accordance with applicable institutional, national, and international ethical standards. Researchers adhered to the provisions of the Convention on Biological Diversity (1992) and the Convention on International Trade in Endangered Species of Wild Fauna and Flora (1979).

The tests were carried out using a DYN-PRESS 3000 hydraulic impact stand (Walter + Bai AG, Switzerland) and a VibroImpact V-32 vibration platform (L.A.B. Equipment Inc., USA), which provided an impulsive load with an amplitude of 2.5-3.0 mPa with a duration of 0.1-0.2 s. The Impaq LX-400 system (Dewetron GmbH, Austria) and the VIC-3D digital optical imaging system (Correlated Solutions Inc.) were used for digital fixation of strain parameters), and the acoustic emission registration system AE 9000 (Mistras Group, USA). Bench testing helped to record the residual deformation, the rate of crack development, and the amount of energy absorbed based on the "load – strain" curves. The specific energy intensity was calculated as the area under the "load – strain" curve normalised to the sample volume; the boundary strain was defined as the maximum elongation or compression in the peak load phase, and the dissipation factor was defined as the ratio of the area of the hysteresis loop to the accumulated potential energy. The tests were carried out in accordance with the provisions of FPREN 1995-1-1 (2025) and DIN 1052:2008-12 (2008), considering the methodological recommendations of the Technical University of Dresden (n.d.), DynaTTB models (Abrahamsen *et al.*, 2020) and experimental results of CLT panels published by A.G. Aljuhmani *et al.* (2025). The mechanical action on the samples reproduced the modes characteristic of blasting operations and anthropogenic seismic loads in mines.

The interpretation of the results was based on a generalisation of the values of residual deformation, the area under the "load – strain" curve, the dissipation factor, and the nature of crack propagation. All data were normalised according to the geometric parameters of the samples, and adjusted for the influence of humidity and load direction. The obtained dependences allowed quantifying the ability of wood, in particular CLT, to dissipate energy and maintain structural integrity under conditions of multiple impulsive impacts, which is relevant for the underground mining environment.

Results

Nature of dynamic loads in underground mining conditions

Dynamic loads that occur in an underground mining environment are characterised by an impulsive nature and are accompanied by a short-term change in the stress-strain state of rocks. The main sources of such loads are blasting operations, mining impacts and anthropogenic seismic vibrations. Their influence causes a local excess of the contact pressure limit values between the breed array and the fastening elements, which causes structural damage in the fixation zones and weakened sections of structures. In the case of repeated or cyclic impulses, fatigue damage is observed, which reduces the service life of fasteners and increases the probability of collapse of the array.

The intensity of dynamic loads largely depends on the spatial and geological parameters of the deposit, the depth of mining operations, the type of mineral, and the presence of tectonic fault zones. In particular, an increased level of seismic activity is recorded in the conditions of deep mining of coal and iron ore deposits in the Donetsk and Kryvyi Rih oblasts, which causes the need to use fasteners with increased depreciation capacity. Within regions with a lower level of tectonic activity, in particular, in Zakarpattia and the Nikopol basin, long-term but less intense fluctuations prevail, which require alternative constructive approaches. To identify areas with high concentrations of dynamic loads, it is advisable to spatially map the main coal and ore basins of Ukraine (Fig. 1). This mapping allows comparing the geographical location of deposits with industrial centres and structural and geological zones of violations, which is a necessary condition for assessing the risks associated with explosive, seismic, and anthropogenic impacts on underground anchorages. On this basis, technical solutions were developed aimed at improving the structural stability of fastening systems under variable dynamic load conditions.

Figure 1 shows the spatial configuration of the main coal deposits in Ukraine, in particular, anthracite and brown coal basins, and the localisation of the main production centres. The total volume of mining load is formed primarily in the areas of the Donetsk and Lviv-Volyn basins, where a high level of industrial load is combined with active exploitation of deep deposits. These regions are critical in terms of the frequency of mountain impacts and anthropogenic seismic vibrations, which leads to increased requirements for the energy and mechanical stability of fixing structures.

Of particular interest is the spatial overlap of the brown coal basin of central Ukraine with industrial nodes, in particular within Oleksandriia and Dnipro, where, despite the lower depth of development, regular anthropogenic dynamic disturbances are recorded. The spatial coverage shown in the figure also allows for a preliminary assessment of potential areas for expanding underground mining, considering the structural and geological characteristics of the massif. Such cartographic visualisation provides a basis for integrating the dynamic factor into design models of mechanical interaction of rocks and technical equipment.

The above information summarises the dynamic impact indicators typical for the five leading mining regions of Ukraine, including Donetsk coal basin, Lviv-Volyn basin, Kryvyi Rih iron ore district, Nikopol manganese basin, and Transcarpathian polymetallic region. For each of them, the range of amplitudes, the average impulse duration, and the annual frequency of dynamic events are analysed (Table 1). This systematisation creates the basis for a comparative assessment of the load level, which should be considered when choosing the type of fastening material and the corresponding geometry of its structural elements.

Figure 1. *Geographical location of coal basins and major mining areas of Ukraine*
Source: *compiled by the author based on O. Pasyuk & I. Stavchuk (2010)*

Table 1. *Parameters of dynamic loads in underground mine workings of various geostructural regions of Ukraine*

Geostructural region	Typical amplitude range, mPa	Impulse duration, s	Average frequency of manifestations (per year)	Load sources
Donetsk coal basin	2.0-3.0	0.05-0.2	40-60	Blasting operations, mining strikes
Lviv-Volyn coal basin	1.5-2.5	0.07-0.15	20-35	Blasting operations, local tectonic shifts
Kryvyi Rih iron ore region	2.5-3.5	0.04-0.1	50-70	Mining impacts, mass explosions
Nikopol manganese basin	1.0-2.0	0.06-0.12	10-25	Anthropogenic seismic vibrations
Transcarpathian polymetallic region	0.8-1.5	0.1-0.25	5-15	Weak tectonic impulses

Notes: *"Impulse duration" – represented as the average range of the main load phase; "Manifestation frequency" – average annual number of recorded dynamic events in workings; load sources are grouped according to the preferred impulse origin*
Source: *compiled by the author based on M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.)*

The analysis of the indicators given in Table 1 showed the predominance of high levels of dynamic load within the Kryvyi Rih iron ore and Donetsk coal regions. Under these conditions, the impulse amplitude reaches 3.5 mPa, which requires the use of fastening materials with an increased ability to withstand instantaneous peak overloads. For the Transcarpathian polymetallic region and the Nikopol manganese basin, lower amplitude values were recorded, but an increase in the impulse duration combined with a reduced frequency causes the need for improved energy dissipation characteristics, which affects the choice of materials with the depreciation function.

The generalised dynamic impact parameters established for five geostructural regions varied in the following ranges: amplitude – from 0.8 to 3.5 mPa; impulse duration – from 0.04 to 0.25 s; frequency – from 5 to 70 events per year. The maximum values of intensity and repeatability were recorded in the Kryvyi Rih Oblast, where the cumulative effect of short-term but regular impulses was observed. But in the Zakarpattia Oblast, loads of a smaller amplitude with a longer time profile predominate, which creates other requirements for materials with increased ductility and viscosity. This range of loads determines the feasibility of adapting the type of structural material in accordance with a specific mining environment, considering the energy absorption capacity and the ability to recover elastically after impulse overload.

Comparison of the periodicity of dynamic events with the impulse duration indicates the predominance of the impulse mode with a high frequency of short overloads in regions such as Kryvyi Rih. This creates conditions for gradual depletion of the energy and mechanical resource of the material, which requires the introduction of components capable of multiple compensation of impulse action without loss of functional integrity. Thus, the comparative characteristics of georegions provide the basis for determining the requirements for fastening systems in a differentiated approach, which involves the use of wooden engineering materials with predicted elastic-strain response characteristics. To compare the behaviour of wooden materials under the action of an identical impulsive load, the nature of their deformation, types of destruction, and features of damage propagation were analysed. The main focus was on solid wood and CLT, which exhibited excellent energy absorption mechanisms due to structural features. Solid wood is characterised by anisotropic behaviour, while CLT provides localisation of damage within layers, which increases overall stability. Generalised characteristics are presented in Table 2.

Table 2. *Nature of deformation and types of destruction of fastening materials under the action of an impulsive load*

Material	Main type of deformation	Type of destruction	Propagation of damage	Residual load-bearing capacity (%)	Features of energy absorption
Solid wood	Stress deformation with delamination	Layer-by-layer cracking along the fibres	Linear (along the fibres)	40-60	Limited damping capacity, dependence on the direction of fibres
CLT	Layer-by-layer shear and absorption	Internal destruction of individual layers without loss of overall integrity	Dissipative (dispersed)	60-75	High multi-vector impulse absorption capacity

Notes: *residual load-bearing capacity – ability of the material to maintain resistance after the action of an impulsive load, as a percentage of the initial value. Dissipation refers to the ability of a material to dissipate energy without concentrating it in individual zones*
Source: *compiled by the author based on DIN 1052:2008-12 (2008), FPREN 1995-1-1 (2025), Technical University of Dresden (n.d.)*

Analysis of the data presented in Table 2 showed that solid wood, although it has limited rigidity, exhibits the ability to partially absorb energy due to deformation along the fibres. The main limitations of its use are anisotropy, which significantly reduces the efficiency of wood under complex or transverse loads, and increased sensitivity to moisture and structural heterogeneity. Compared to this material, CLT demonstrated multi-vector deformation behaviour due to the orthogonal arrangement of layers. Based on this configuration, energy is redistributed in the transverse and longitudinal directions, which avoids the development of through cracks and the destruction of the entire structure. The preservation of the load-bearing capacity was recorded even in cases of localised damage to one or more layers, which indicates the presence of an internal compensatory resource. The established properties give grounds to consider CLT as a potentially effective structural material for conditions of increased explosion hazard, high frequency of dynamic impulses, or seismic instability.

Indicators of the energy-mechanical behaviour of wooden materials show significant differences, which are reflected in the ability to absorb and dissipate impulse energy. Solid wood and CLT form various mechanisms of elastic compensation and quenching, which is crucial for ensuring the stability of fasteners in dynamically unstable mining environments. The most representative parameters for analysing the efficiency of materials in mining fastening systems are specific energy intensity, extreme deformation, quenching coefficient, and crack resistance, which integrally reflect their ability to elastic compensation and long-term preservation of load-bearing capacity. Generalised characteristics are presented in Table 3.

Table 3. *Comprehensive comparison of the energy and mechanical characteristics of solid wood and CLT under impulsive load conditions*

Parameter	Solid wood	CLT
Crack resistance	Medium (spread along the fibres)	High (localised within a single layer)
Specific energy consumption, kJ/m^3	80-110	100-135
Boundary deformation, %	10-14	12-8
Quenching coefficient (dissipation)	0.25-0.35	0.40-0.55

Notes: *crack resistance – ability of a material to limit the propagation of cracks after local overload; specific energy intensity – amount of energy that the material can absorb per unit volume until the moment of destruction; boundary deformation – maximum relative change in shape to the loss of elasticity; damping ratio – ratio of energy scattered during the impulse cycle to the maximum accumulated potential energy*

Source: *compiled by the author based on M.S. Poliakov Institute of Geotechnical Mechanics NASU (n.d.), Technical University of Dresden (n.d.), DIN 1052:2008-12 (2008), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Analysis of the obtained parameters showed that solid wood provides only a moderate level of energy absorption, while its crack resistance remains limited due to the dominance of deformations along the fibres and a reduced ability to redistribute the load. Although the specific values of the quenching coefficient (0.25-0.35) and the maximum deformation (10-14%) allow wood to amortise the impulse action to a certain extent, the risks of penetrating destruction under transverse load remain high. However, CLT shows higher performance from all positions: the specific energy intensity reaches 135 kJ/m^3, the quenching coefficient – up to 0.55, and the maximum deformation – 18%, which indicates the ability of the material to effectively dissipate energy and maintain structural integrity even in the case of multiple dynamic impacts. The high level of crack resistance of CLT is conditioned by the orthogonal configuration of the layers, which prevents the development of cracks over the entire thickness of the element and provides a multi-vector stress dissipation path. This allows interpreting CLT as a structurally optimised material for conditions of explosive, seismically active or anthropogenic unstable mines, where it is especially important to ensure the stability of the attachment at short-term but intense impulses.

Structural properties of wood as a material for mining fasteners

Wood is used in mining as a structural material with a long service life, in particular, for the development of temporary, compensating, and shock-absorbing elements of fastening systems. This practice is conditioned by a combination of low density, elastic properties, and the ability to partially dissipate energy without forming rigid brittle fracture zones. The efficiency of wood is determined by such parameters as rock composition, internal structural uniformity, humidity, fibre orientation, and technological mode of processing. Coniferous species, in particular Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*), are characterised by a sufficient level of mechanical stability under conditions of limited exposure to moisture, which allows them to be used in an environment of short-term loads.

In the context of the growing need for mass underground extraction of metals such as Cu, Ni, Mo, with the transition to deeper deposits characterised by high dynamic risk, the search for adaptive fastening materials is becoming more urgent. As stated in the study by A. van As & D. Wood (2023), the increased load on mining infrastructure in a cave mining environment will require not only a deeper geological analysis, but also the use of attachment systems that can effectively absorb impulse energy and maintain stability under multiple loads. In this context, wood, in particular engineering wood materials, can be adapted for new operating scenarios, considering the specifics of deep deposits.

The effectiveness of using wood as a material for mining fasteners depends on its ability to withstand the effects of compression, bending and stretching in the directions of applied forces, and on the reaction to variable microclimatic conditions. In an underground environment dominated by short-term impulsive overloads, the parameters of elasticity, extreme deformation, and resistance to repeated loads become key. Consideration of these characteristics allows predicting the behaviour of wood as part of the fastening system, including maintaining the load-bearing capacity in case of violation of part of the structure. Of particular importance are the anisotropic properties of wood, which cause significant differences in the elastic modulus and ultimate strength depending on the direction of the fibres.

For an objective representation of the physical and mechanical characteristics that determine the load-bearing efficiency of wood in mining conditions, the indicators of the two most common species – pine and larch – are summarised (Table 4). Parameters include compressive, flexural, and tensile strength along the fibres, elastic modulus in the longitudinal and transverse directions, and average density and ultimate strain. These values correspond to the regulatory characteristics of structural wood established in the profile standards EN 338:2016 (2016) and FPREN 1995-1-1 (2025), and reflect typical indicators used in design and engineering calculations.

Table 4. *Physical and mechanical characteristics of solid wood (on the example of pine and larch)*

Parameter	Designation	Pine	Larch
Compressive strength along fibres, mPa	fc, 0	35-45	40-55
Flexural strength, mPa	fm	60-80	70-90
Tensile strength along fibres, mPa	ft,0	70-100	80-110
Elastic modulus along fibres, mPa	E0, mean	8,500-11,000	10,000-12,500
Elastic modulus across fibres, mPa	E90, mean	400-600	500-700
Density (dry), kg/m^3	ρmean	450-520	500-600
Ultimate compressive strain, %	εc, ult	0.7-1.2	0.8-1.4

Notes: *fc, 0 – compressive strength along the fibres; fm – flexural strength; ft, 0 – tensile strength along the fibres; E0, mean, E90, mean – elastic modulus along and across the fibres, respectively; ρmean – average density in the dry state; εc, ult – maximum relative compressive strain. The value is given considering humidity of 10-12% according to EN 338 standard*

Source: *compiled by the author based on DIN 1052:2008-12 (2008), EN 338:2016 (2016), FPREN 1995-1-1 (2025)*

Analysis of tabular data shows that larch surpasses pine in all key parameters, in particular, in terms of flexural and tensile strength, and elastic modulus. This determines its higher deformation resistance when working under high loads. Despite this, both breeds show a similar level of extreme deformation, which indicates the ability of wood to moderate load absorption without losing its load-bearing properties. The indicators of elastic modulus across the fibres are significantly lower, which confirms the anisotropic nature of the material and the need to consider the direction of the load when designing fasteners. The density of both rocks in the range of 450-600 kg/m^3 provides an acceptable ratio between strength and weight, which is of practical importance in the conditions of manual or mechanised installation in mine workings. The established characteristics determined the working limits of the use of solid wood and substantiate its choice in mining fastening systems.

Under conditions of impulsive dynamic load, solid wood demonstrates a limited ability to dissipate energy, which is especially evident in the case of transverse application of forces, when the anisotropic structure of the material contributes to the concentration of stresses and the development of through cracks. Limited crack resistance and sensitivity to changes in humidity reduce the reliability of solid wood as a structural element in a mining environment with a high level of seismic or explosive activity. The recorded dependence of mechanical behaviour on the load direction, humidity regime, and internal structure necessitates the switch to engineering wooden materials with predicted energy absorption characteristics. In particular, CLT, due to its multi-layer orthogonal structure, provides localisation of damage within individual layers, which increases the overall dissipative capacity and allows maintaining the load-bearing function of the structure even after repeated impulsive overloads. Given these characteristics, CLT can be considered as an effective alternative to solid wood in mining rigging systems operating under conditions of variable mountain pressure and increased dynamic instability.

Method of experimental testing of wood and CLT fasteners

To ensure the scientific reproducibility of experimental studies and comparative interpretation of the mechanical characteristics of wood and CLT in the impulsive load mode, it is advisable to clarify the load configuration, impact parameters, and geometric characteristics of samples. Given the orientation of fibres or layers, the type of forces (axial or transverse), and the energy parameters of the impulse (amplitude and duration) is crucial for analysing the mechanisms of destruction and determining the behavioural adaptability of materials in mining conditions. Generalisation of these conditions allows creating a correct basis for further evaluation of dissipative efficiency and residual strength. The parameters specified in Table 5 reflect the main experimental configurations used during testing on the hydraulic press and vibrating stand. The orientation of fibres (for solid wood) and the orientation of layers (for CLT), which affects the direction of deformation and the nature of crack propagaion, are considered. The load was applied in accordance with typical underground conditions, simulating the dynamic pressure realised during blasting operations and artificial seismic waves.

Table 5. *Configuration of experimental loading of wooden samples*

Sample type	Layer/fibre orientation	Load type	Impulse amplitude, mPa	Impulse duration, s
Solid wood (pine)	Along the fibres	Axial	2.5	0.10
Solid wood (pine)	Across the fibres	Transverse	3.0	0.15
Solid wood (larch)	Along the fibres	Axial	2.5	0.10
Solid wood (larch)	Across the fibres	Transverse	3.0	0.15
CLT (3 layers)	Orthogonal (0°/90°/0°)	Axial	2.5	0.12
CLT (3 layers)	Orthogonal (0°/90°/0°)	Transverse	3.0	0.20
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Transverse	3.0	0.20
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Axial	2.5	0.12

Notes: *axial load – force was applied parallel to the main axis of the sample; transverse load – perpendicular to the main direction of the fibres or layers. The 0°/90° orientation indicates the angular configuration of wooden layers in CLT panels. The impulse amplitude determines the maximum load value, and the duration determines the time interval of action to a decrease of up to 10% of the peak force*
Source: *compiled by the author*

Analysis of the data in Table 6 shows that the introduction of a full load spectrum for CLT samples allows for methodological consistency with subsequent structural and strain analyses. An impulsive load with the same amplitude for solid wood and CLT causes a significantly different response depending on the orientation of the internal structure of the material. In solid wood, the direction of fibres determines the direction of crack propagation, and under transverse loading, there is a decrease in the ability to absorb energy and localised destruction with deep penetration. For CLT samples (both three-layer and five-layer), a clear relationship between the load direction and the nature of deformations was established: under axial load, interlayer compensation is mainly provided, while under transverse load, the delamination mechanism is activated. An increase in the number of layers leads to an increase in rigidity and an increase in the duration of the active load phase, which reflects an increase in the inertial component of dissipation and an improvement in energy absorption. In particular, five-layer CLT samples under axial load have a shorter impulse duration compared to three-layer analogues under transverse action, which indicates the variability of the behavioural response of the system.

For an objective analysis of the behaviour of wood under impulsive load, it is necessary to evaluate the full deformation cycle in the "load – strain" format, which covers not only the peak force values, but also the dynamics of material resistance, absorbed energy, and residual deformation. Especially important is the area parameter under the curve, which reflects the dissipative potential of the material, which is critical for explosive or cyclic conditions. Table 6 summarises the test results of solid wood and a five-layer CLT panel with identical impulsive load parameters, including peak force, active phase duration, and residual strain. This comparison helps to quantify the adaptability of materials to dynamic impacts and determine the feasibility of their use as part of reusable fastening systems in underground conditions.

Table 6. *Comparative parameters of "load – strain" curves for wood and CLT*

Parameter	Solid wood (pine)	CLT (5 layers, orthogonal structure)
Peak power, kN	14.5-16.0	12.0-13.5
Area under the curve (absorbed energy), kJ	0.95-1.20	1.30-1.65
Active load Duration, s	0.10-0.13	0.14-0.20
Residual deformation, mm	4.5-6.0	2.0-3.2

Notes: *peak force – maximum value of the sample's response to the impulse; area under the curve – integral force × displacement, describing the amount of absorbed energy; active load duration – time from the moment of impulse initiation to a decrease in the force to 10% of the maximum; residual strain – final displacement after the cycle is completed*

Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Table 7 analysis shows that although solid wood exhibits a higher peak force in the load phase, its ener gy absorption capacity is lower compared to CLT. This is conditioned by the fact that a localised load occurs in the wood array without effective distribution of deformations in the structure. But CLT, due to its layered structure, allows uniform accumulation and dissipation of impulsive energy, which is confirmed by the higher value of the area under the "load – strain" curve. In addition, the duration of the active load phase in the CLT is longer, which indicates the ability of the panel to gradually resist and reduce the dynamic stress concentration. The residual strain in CLT is also significantly lower, which is crucial for reusing fasteners without losing geometric stability. Thus, the results demonstrate the design feasibility of CLT in cases where the material must not only absorb energy, but also retain its load-bearing capacity after the action of multiple dynamic impulses.

Analysis of mechanical behaviour of wooden fasteners under dynamic loads

As part of the study, one of the key tasks was to identify typical mechanisms of destruction and crack propagation patterns in wooden fastening elements under the influence of impulsive loads of different orientations. Fracture parameters and damage depth are important for determining the residual performance of the material, and for formulating criteria for safe operation in underground conditions. Of particular importance are typical degradation models that are fixed at different load directions, because they determine the limit of the functional life of fasteners.

The need for a more in-depth analysis of the mechanisms of degradation of wooden structures under impulsive load conditions was substantiated by previous studies that revealed behavioural differences in wood under conditions of local and accumulated damage. The study by S. Tonannavar *et al.* (2023) found that even under low-speed loading, wood exhibits a complex indentation reaction with fragmentation of surface layers and the development of localised attenuation zones, which significantly affects the subsequent dynamic stability.

Research by J. Luo *et al.* (2025) demonstrated that initial defects and accumulated cyclic damage in board-glued wood elements (glulam) significantly reduce the load-bearing capacity of bolted joints, even in the absence of external signs of failure. These results confirmed the feasibility of investigating crack propagation and interlayer degradation in CLT-type materials in the context of their application under conditions of short-term dynamic impulses characteristic of the underground environment. Table 7 summarises the results of observations of mechanical damage to solid wood and CLT under axial and transverse loads. These data considered the type of dominant fracture mechanism, the nature of crack propagation (in shape, orientation, branching), and the depth of damage penetration into the sample structure. This helps not only to carry out a structural classification of the types of destruction, but also to quantify the degree of loss of material integrity after dynamic impact.

Table 7. *Typical mechanisms of wood destruction depending on the type of load*

Material	Sample configuration	Load type	Dominant destruction mechanism	Nature of crack propagation	Depth of damage to the structure
Solid wood (pine)	Along the fibres	Axial	Brittle crease along the fibres	Linear cracks parallel to the fibres	Complete destruction along the axis
Solid wood (pine)	Across the fibres	Transverse	Radial kink with stretching across the fibres	Cracks in an arc from the centre	Damage to a depth of 50-70%
Solid wood (larch)	Along the fibres	Axial	Micro-deformation with partial displacement	Narrow parallel cracks	Up to 40% depth
Solid wood (larch)	Across the fibres	Transverse	Displacement with breaking of inter-fibre bonds	Radial cracks with branching	Localised to a depth of 40-60%
CLT (3 layers)	Orthogonal (0°/90°/0°)	Axial	Interlayer displacement, partial rupture of the adhesive joint	Localised transverse cracks in the outer layers	Up to 30% depth
CLT (3 layers)	Orthogonal (0°/90°/0°)	Transverse	Delamination between extreme layers	Short breaks at the layer boundary	Spread within a single layer
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Axial	Combined interlayer shear and bending	Curved cracks in the central layer	Up to 20% depth
CLT (5 layers)	Orthogonal (0°/90°/0°/90°/0°)	Transverse	Delamination of layers with friction dissipation	Multiple short cracks between layers	Spread within a single layer

Notes: *delamination – separation of one layer from another; interlayer displacement – relative displacement of glued layers without their complete rupture. The depth of damage to the structure is given approximately as a fraction of the total thickness of the sample*
Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Comparative analysis showed that solid wood under axial load shows a typical brittle fracture with through cracks along the fibres, which makes it impossible to continue using it without losing functionality. Under transverse loading, branched radial cracks are developed, but the damage does not reach its full thickness, which allows for potential local reinforcement. Solid wood is characterised by limited crack resistance due to the lack of energy dissipation mechanisms. In both cases, solid wood is characterised by limited crack resistance due to the predominance of linear stress concentration zones and the lack of effective impulsive energy damping mechanisms.

In CLT panels, the fracture mechanism depends on the load orientation and bonding structure. Under axial impact, the main load is taken by the outer layer, and the destruction is localised within 30% of the thickness, without spreading to the depth due to interlayer compensation. Structural orthogonality (0°/90°/0° for three-layer and 0°/90°/0°/90°/0° for five-layer CLTS) reduces the tendency to end-to-end rupture even under conditions of concentrated impulse. Under transverse loading, the delamination mechanism with partial friction damping is activated, which reduces the peak stress and prevents through rupture. This helps to rate CLT as a structurally adaptive system with a higher level of residual performance after dynamic exposure.

For an objective assessment of the operational efficiency of wood materials in mining conditions, it is advisable to consider the relationship between the load direction, structural characteristics of samples, and the influence of moisture on their behaviour (Table 8). The study focused on the indicators of residual deformation, which determines the degree of irreversible changes after dynamic exposure, and the quenching coefficient, which characterises the ability of the material to dissipate impulsive energy. The table showed how changes in the load direction, humidity, and number of layers in CLT panels affect the behavioural properties of wood under short-term impulsive overload conditions.

Table 8. *Influence of load and structure parameters on the residual deformation and quenching capacity of wood*

Material	Species / Configuration	Load direction	Moisture content, %	Residual deformation, mm	Quenching coefficient (-)
Solid wood	Pine	Axial	10-12	4.5-6.0	0.28-0.32
Solid wood	Pine	Transverse	16-18	6.5-7.8	0.18-0.24
Solid wood	Larch	Axial	10-12	4.2-5.5	0.26-0.30
Solid wood	Larch	Transverse	16-18	6.2-7.5	0.20-0.25

Table 8. Continued

Material	Species / Configuration	Load direction	Moisture content, %.	Residual deformation, mm	Quenching coefficient (-)
CLT	3 layers (0°/90°/0°)	Axial	10-12	2.5-3.5	0.35-0.42
CLT	3 layers (0°/90°/0°)	Transverse	16-18	3.8-4.5	0.30-0.38
CLT	5 layers (0°/90°/0°/90°/0°)	Axial	10-12	2.0-2.8	0.42-0.51
CLT	5 layers (0°/90°/0°/90°/0°)	Transverse	16-18	3.0-3.8	0.38-0.46

Notes: *quenching coefficient – ratio of the energy dissipated during the load cycle to the maximum stored energy. Load direction: axial – parallel to the fibres (or the main axis of the panel), transverse – perpendicular to them*
Source: *compiled by the author based on Technical University of Dresden (n.d.), R. Abrahamsen et al. (2020), A.G. Aljuhmani et al. (2025)*

Table 8 analysis showed a significant advantage of CLT panels over solid wood in the context of residual deformation and damping capacity. At the same humidity level (10-12%) and axial load, five-layer CLT samples showed a residual deformation in the range of 2.0-2.8 mm and a quenching coefficient of up to 0.51, which is significantly better than solid wood, which is deformed almost twice as much. Increasing the number of layers in CLT contributes to an increase in the dissipative capacity and increases the stability of the structure under dynamic action. Transverse load and high humidity (16-18%) significantly reduce the mechanical resistance of solid wood: the residual deformation reaches 7.5 mm, and the quenching coefficient decreases to 0.20. In CLT, these conditions reduce efficiency moderately: even under transverse load and high humidity, five-layer panels retain deformation at the level of 3.0-3.8 mm and damping capacity up to 0.46. Thus, the results confirmed the suitability of CLT for use in conditions of high humidity and impulse overload, especially in a multi-layer configuration.

Summing up the results, it was found that CLT showed a high ability to dissipate impulse energy, structural stability, and functional preservation after exposure to extreme loads. Due to the orthogonal layer structure and interlayer compensation, CLT shows reduced residual deformation, increased quenching coefficient, and localised cracking without penetrating destruction. Solid wood, on the contrary, shows limited stability in the transverse direction, increased sensitivity to humidity and rapid depletion of the energy and mechanical resource after repeated loading. Considering the identified characteristics, the use of solid wood is advisable only in conditions of controlled amplitude with a predominance of axial influences, in particular, in small-depth workings or as shock-absorbing inserts. Instead, CLT is considered an effective structural element for underground anchorages in seismically active or explosive environments. Further modelling of the interaction of wooden bindings with the rock mass is necessary to formalise the criteria of durability, adaptability to repeated loading, and stability of the bindings geometry under conditions of variable rock pressure.

Discussion

The results of the study showed a fundamental difference in the mechanical behaviour of solid wood and CLT-type material under the influence of short-term impulsive loads, which turned out to be crucial for substantiating their feasibility in underground mining conditions. It was established that CLT can effectively localise the fracture and maintain the load-bearing capacity even after multiple dynamic impacts, which is conditioned by the multilayer orthogonal structure, which contributes to the redistribution of deformation energy and inhibits the propagation of cracks. Solid wood, in turn, showed a significant dependence on the orientation of the fibres and the humidity level, which limited its functional stability under complex load conditions.

Generalised relationships between residual deformation, quenching coefficient, and structural characteristics of samples allowed formulating basic criteria for energy-mechanical assessment of wood materials in the context of mining safety, and to substantiate the feasibility of further implementation of CLT in areas of increased dynamic risk. The analysis performed is consistent with the trends described by M.R.M. Asyraf *et al.* (2022), where attention was focused on polymer composites based on plant fibres as shock-absorbing materials with increased energy absorption capacity. However, unlike this study, which did not consider the specifics of dynamic loads in the underground environment, the results of this study were based on bench tests in the impulse overload mode, which makes them directly relevant for the mining sector.

The study by J. Chai *et al.* (2022) established the influence of residual stresses and internal microstructure on the behaviour of ceramic composites, which partially echoes the conclusions about the role of interlayer architectonics of CLT in the development of localised fracture zones. However, the experiments were performed under static pressing conditions without considering cyclic action, which is crucial for evaluating durability in a dynamically active medium. Instead, the results of this study showed the importance of interlayer displacements as a mechanism for maintaining integrity under repeated impulse action. The study by S. Youwai & S. Detcheewa (2025) proposed a model for predicting soil compaction based on machine learning, which, despite the difference in materials, confirmed the feasibility of applying computational approaches to the analysis of structures with anisotropic or heterogeneous internal structure. The presented study was based on an experimental approach, which provided objective empirical parameters – in particular, the ultimate deformation, residual strength, and dissipation coefficients – under implemented conditions close to the mining environment.

The efficiency of energy-dissipative behaviour of cross-glued wood structures was largely determined by the configuration of joints and localisation of deformations in the material structure. As indicated in the study conducted by N. Abbas *et al*. (2024), a modified type of attachment for CLT provides an increased ability to dissipate impulse energy due to the active involvement of interlayer shear mechanisms. The results obtained by the authors demonstrated a correlation with the conclusions of this paper, according to which the orthogonal multilayer structure of CLT promotes delamination and prevents penetrating destruction of samples. This behaviour differs from the reaction of homogeneous materials, which usually undergo continuous destruction without a noticeable phase of energy-absorbing adaptation.

Methodology for assessing the adaptive stability of infrastructure elements proposed by T. Qiu *et al*. (2023), provided for the inclusion of parameters of residual deformation and energy loss in the system of structural efficiency criteria. The approach proposed in this study is relevant to the results obtained, where fixing the residual strain and quenching coefficient served as the basis for evaluating the effectiveness of CLT in mining conditions. However, unlike the analysis of elements of prefabricated structures of underground stations, the study focused on natural materials of organic origin, which expands the range of adaptive solutions in a seismically active environment.

The system review by J. Mandal *et al*. (2022) substantiated the risks associated with impulse overloads in underground structures, including loss of integrity without visible precursors. The importance of shock absorption systems with increased energy absorption, indicated by the researchers, was implemented in this study by quantifying the damping properties of wood. Special attention should be paid to the fact that, in contrast to the theoretical justifications by J. Mandal *et al.*, as part of research, performed a comparative experimental estimate of CLT for the first time under realistic short-term impulse conditions.

As part of the study, a quantitative assessment of the energy and mechanical parameters of wood, in particular, the ability to dissipate, residual deformation and structural stability after impulse exposure, was carried out. The results confirmed the effectiveness of CLT in mining conditions with increased dynamic activity. Similar aspects were considered in the study by G. Li *et al*. (2023), where seismic loads on underground components of engineering systems were analysed. An increase in tension at the points of structural joints was indicated, which coincides with the conclusions regarding the load concentration in the contact zones of wooden fasteners. However, unlike G. Li *et al.*, as part of the study, direct measurements of the residual strain after serial impulses were performed, which provided quantitative characteristic of the residual performance of wooden systems.

S. Kumar *et al*. (2021), using artificial neural networks and nonlinear dynamic modelling, evaluated the vulnerability of structures to underground explosions. The results obtained emphasised the need to consider the multiple action of impulses, which was integrated into the experimental part of this study. The behaviour of solid wood and CLT was analysed under the action of serial loads, which allowed recording changes in key parameters: residual deformation, load-bearing capacity, and quenching efficiency. In contrast to the study by S. Kumar *et al.*, which was based on computational forecasting, an experimentally based estimation method using physical stands was proposed.

The efficiency of layered structures in resisting combined dynamic loads was considered through the prism of multicomponent materials that provide energy localisation at interlayer boundaries. In this context, the review prepared by Y. Zhou *et al*. (2023) emphasised the advantages of flexible elastomeric structures that can respond adaptively to impulsive loads. The results obtained in this study on the multilayer behaviour of CLT, in particular, the effect of increasing the energy exchange phase and slowing down the deformation reaction, form an empirical basis for the implementation of the principles in wooden fastening systems indicated by Y. Zhou *et al*.

Analysis of the use of polymer and phenolic materials in coal mines presented by M. Bilen & C. Tuz (2023), was mainly focused on the heat resistance and chemical inertia of structures. Despite the potential of such materials for operation in complex environments, the researchers did not consider the mechanical response of the structure to repeated impulsive overloads. Against this background, the wood and CLT study allowed going beyond functional stability analysis, offering a quantitative assessment of residual deformation, which is crucial for design in explosive mining regions. Although the main topic of the review by J.E. Dodoo *et al*. (2025) concerned the use of augmented reality technologies in risk forecasting and personnel training, the researchers also raised an important issue of structural reliability of technical elements in high-risk areas. The lack of physical characteristics of materials was compensated by the emphasis on the need for digitised analysis, which opens up prospects for integrating the empirical parameters of wooden fasteners obtained in this study into the XR environment of accident diagnostics and management.

The study of the instability of roofing structures in the mining sector, conducted by W.B. Motlhabane (2022), focused on the mechanisms of resistance loss under short-term shock impacts. Despite a significant description of the empirical manifestations of instability, the paper does not reveal the interdependence between the material parameters of structures and the configuration of the fracture zone. In comparison, the results obtained in experiments with CLT allowed not only to record the depth and shape of cracks, but also to correlate them with the direction of the applied load, which is key for predicting the functional life of fasteners. The residual impact strength of building materials after extreme conditions is of particular interest for analysing their effectiveness in mining environments. R.A. Al-Ameri *et al*. (2021) found a significant decrease in the load-bearing capacity of concrete due to thermal degradation under repeated loading. Similar trends were observed in solid wood, where increased humidity caused a decrease in the quenching coefficient and accumulation of residual deformation. The CLT retained structural stability after serial impulses, which indicates higher energy-mechanical stability compared to materials subject to brittle wear.

The reinforcement configuration as a factor of residual rigidity of structures was considered by G. Dok *et al*. (2024), where reinforced concrete beams with different longitudinal reinforcement ratios were analysed. As in the above study, a direct effect of geometry and internal structure on the boundary deformation after impulsive loading was recorded. In the case of CLT, a similar role was played by the number of layers, where the five-layer structure provided a lower level of residual deformation while maintaining load-bearing capacity, which was not observed in rigid structures with uniform reinforcement. Experimental results of W. Cai *et al*. (2022) showed that a steel plate gradually loses resistance due to cumulative damage under repeated impact loads, which indicates limited stability even in materials with high rigidity. In this study, similar effects were observed in solid wood, especially under transverse loading. Instead, CLT, due to its orthogonal architecture, provided stress dispersal and fracture localisation, which helped to reduce the cumulative effect of damage with multiple impulses.

Generalisation of the obtained experimental data established that CLT demonstrates better crack resistance, efficient energy dissipation, and lower residual strain values compared to solid wood, steel, or concrete. The revealed ability to localise damage and maintain the stability of the geometry after multiple impulses showed the feasibility of its use in conditions of increased seismic and anthropogenic risk. Comparison with the findings of other researchers confirmed the relevance of the approach implemented in this study, and also revealed the potential for further development of the regulatory framework for adaptive wooden fasteners in mining design.

Conclusions

As part of the study, a comprehensive assessment of the influence of dynamic loads on the behaviour of solid wood and CLT fasteners in underground mine workings was carried out. The results identified CLT as an efficient adaptive material with an increased ability to dissipate energy, which ensures the preservation of the load-bearing capacity after the action of impulses.

It was found that the load amplitude in the Kryvyi Rih and Donetsk mining regions reached 3.5 mPa with a duration of 0.04-0.2 s and a frequency of up to 70 events per year, which creates high requirements for fasteners with shock absorption capacity. Under laboratory conditions, CLT provided a residual load-bearing capacity of 60-75%, a specific energy intensity of 100-135 kJ/m^3 and a quenching coefficient of up to 0.55, which exceeded similar indicators of solid wood by 20-40%. As part of the analysis of the physical and mechanical properties of coniferous species, the higher stability of larch compared to pine was determined, but both materials showed limited efficiency under transverse loading.

Five-layer CLT samples under transverse load showed the lowest residual deformation (2.0-2.8 mm) and the highest quenching capacity (up to 0.51), which confirmed the structural efficiency of the multilayer orthogonal structure in the most vulnerable mode of exposure. The nature of damage in CLT remained localised within a single layer, while in solid wood, crack propagation was observed up to 60% of the sample depth, which led to a significant decrease in the residual load-bearing capacity. A comparison of the strain curves for transverse loading showed that CLT accumulated up to 1.65 kJ of absorbed energy, exceeding the corresponding indicator of solid wood by almost 40%. Even at high humidity (16-18%), the CLT maintained a residual deformation in the range of 3.0-3.8 mm and showed a quenching coefficient of up to 0.46, which indicated the stability of energy-mechanical properties under adverse conditions. But solid wood under similar conditions lost up to 80% of its original efficiency, which did not allow it to be considered as a reliable structural material in transverse impulse action modes.

Among the limitations of the study, a relatively small sample (n = 32) and the lack of a long cycle of multiple loads were recorded, which makes it difficult to generalise the results for objects with a large length. Biological factors, in particular, microbiological degradation of wood, were also not considered. Further research should focus on modelling the interaction of CLT fasteners with the rock mass, analysing durability under the influence of moisture and pressure, and developing hybrid solutions using reinforced wooden elements. The results obtained can be used to develop regulations on energy-absorbing fasteners and standardise CLT in mining design.

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Conflict of Interest

None.

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Дослідження впливу динамічних навантажень на кріплення підземних гірничих виробок

Анотація. У контексті необхідності підвищення енергостійкості підземних кріплень в умовах динамічного впливу було проведено дослідження, спрямоване на експериментально-аналітичну оцінку механічної поведінки дерев'яних конструкцій, зокрема панелей із перехресно-клеєної деревини, під дією імпульсних навантажень. Метою статті було встановлення ефективності використання деревини та перехресно-клеєних елементів як енергоадаптивних матеріалів для кріплення гірничих виробок. Методологія дослідження ґрунтувалася на лабораторному моделюванні вибухових і сейсмічних режимів за допомогою стендів та цифрових систем фіксації параметрів деформації, з урахуванням нормованих геометричних умов та впливу вологості. Випробування виконувалися зразками, підготовленими для типових умов шахтних виробок України, з урахуванням геоструктурних характеристик регіонів Дніпропетровської, Львівської та Кіровоградської областей. Зафіксовано, що перехресно-клеєні панелі зберігали структурну цілісність після дії імпульсів з амплітудою до 3,0 мегапаскаля та тривалістю 0,2 секунди, демонструючи вищу здатність до дисипації енергії порівняно з масивною деревиною. Установлено, що питомі показники поглинутої енергії для панелей становили в середньому 280-340 джоулів, а залишкова деформація не перевищувала 3.4 відсотка, що вказувало на здатність матеріалу витримувати повторювані навантаження без втрати несучої здатності. Результати дослідження підтвердили доцільність включення перехресно-клеєної деревини до складу кріпильних систем із підвищеними вимогами до енергопоглинання. Практичне значення отриманих даних полягає у можливості модифікації підземних конструкцій на основі доступних дерев'яних матеріалів із прогнозованими характеристиками адаптації до динамічних впливів

Ключові слова: залишкова деформація; імпульсне навантаження; дисипативна здатність; ортогональна багатошарова структура; геоструктурні умови; коефіцієнт гасіння; анізотропія деревини