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ANALYSIS OF STUDIES ON INCREASING THE EXPLOSION RESISTANCE OF CONNECTIONS IN WOODEN STRUCTURES

Gilodo A.Y., PhD., Assistant Professor,
gil@soborka.net, ORCID: 0000-0001-5387-5538
Kolomiychuk G.P., PhD., Assistant Professor,
gp11klm@gmail.com, ORCID: 0000-0003-4484-7791
Kolomiichuk V.G., postgraduate student
slavikkolomy@gmail.com
Arsiriy A.M., PhD Assistant Professor,
arsiriy@ukr.net, ORCID: 0000-0003-3262-1488
Odessa State Academy of Civil Engineering and Architecture

Annotation. Mitigation of the effects of the explosion is in the spotlight due to the unstable geopolitical situation. Existing wooden structures are not designed to withstand an explosive load, and in areas of a possible attack, their sensitive elements require anti-explosive modernization. The search for rational constructive solutions for connections that can plastically deform and dissipate the energy of an explosion, while preserving the supporting frame from destruction, is an urgent problem. The number of studies on the characteristics of connections of wooden structures under explosive loading is very limited and requires a holistic and systematic approach. Dynamic tests of connections of wooden structures using the Shock Tube installation, which is capable of creating high strain rates similar to those observed during explosions in the far zone, are presented. A load transfer device (LTD) with two third-span load transfer beams was used to convert the reflected shock tube pressure into two concentrated forces applied directly to the specimens. While the structural member is subjected to a uniformly distributed load in a real explosion, the use of LTD generates similar strain rates and general dynamic responses in the timber member and connections. The LTD consists of rigid steel panels covering the entire opening of the end frame. Thanks to the slotted hinges, the LTD can move up to 200 mm, which allows the transfer of pressure without changing the rigidity of the tested specimens. A technique for the development of energy-absorbing connections (EAC) in assemblies of glued laminated timber and cross-laminated timber (CLT) for protection against the impact of a blast wave is considered. Explosive overloads were modeled with the introduction of the Shock Tube installation. Experimental test results have shown that, when properly designed, EACs allow assemblies to withstand more blast energy than conventional glulam and CLT connections. The behavior of an EAC wood bar element under explosive loading can be divided into three stages. The initial loading stage is the region where both the EAC and the wood element behave resiliently by the time the EAC yields. The second stage is characterized by a yield plateau where EAC exhibits almost perfect ductility and the load acting on the wood element is constant. The last stage consists of a compaction stage accompanied by an increase in stiffness and strength, which exceeds the strength of the wooden element. Awareness of the need to protect wooden structures from significant dynamic effects (explosion, tornado) is an insufficiently solved problem. The analysis of literary sources made it possible to identify the advantages and disadvantages of different types of connections of wooden rod structures under the action of significant dynamic loads. Their advantages and disadvantages are determined, as well as the ways for their further improvement and application.

Keywords: energy-absorbing connections, explosion mitigation, constructive solution, explosion resistance, wooden rod elements.

Introduction. The need for innovative knowledge of modern structural connections of wooden structures, and their behavior under the action of a dynamic load in a complex stress-strain state, makes the task of studying, systematizing and developing solutions for practical application relevant [1, 2]. Mitigation of the effects of the explosion is in the spotlight due to the unstable geopolitical situation. Existing wooden structures are not designed to withstand an explosive load, and in areas of a possible attack, their sensitive elements require anti-explosion modernization [3].

Analysis of recent research and publications. Most experimental studies of wood elements subjected to explosive loads have been carried out to establish material properties and their behavior at high strain rates with idealized limiting conditions. Testing of glued laminated timber with bolted connections [17] showed that connections with high ductility, designed to experience significant flow, performed better than connections that were designed with excessive strength according to the Canadian Explosion Design Standard.

The importance of energy dissipation through boundary junctions has been explored in research outside of timber structures. In [4], energy-absorbing connections (EAC) were developed for precast concrete panels, which reduce the transfer of dynamic load to the frame elements. Used deformable and collapsible steel connectors under explosive load. Limit connections dissipate energy, absorbing the load on the supporting frame of the building. Cylindrical mild steel dampers are proposed in [5]. The tests were carried out at impact velocities ranging from 3 to 5 m/s using a fixed mass falling on the specimens under the action of gravity. Their crushing behavior and energy absorption capacity were analyzed experimentally and modeled numerically using LS-DYNA. Oswald [6] developed and tested precast concrete panels with steel EACs with and without aluminum honeycomb inserts similar to those proposed by Whitney [4]. It has been found that EACs limit the peak dynamic reactive load transferred to the support structure and reduce damage to the supporting element compared to traditional rigid supports. Lavarnway and Pollino [7, 8] explored the feasibility of using simple, effective blast-resistant ductile connectors (BRDC) implemented between the building envelope and the lateral force-resistance system (LFRS). For a wide range of explosion scenarios, the BRDC was able to completely dissipate the energy of the explosion, leaving the load-bearing structures unscathed. Reference [9] presents an EAC made of a curved aluminum foam plate to be inserted between a blast-resistant facade and the supporting structure of a building. The influence of aluminum foam, the thickness and the radius of the curved plate on the energy absorption characteristics of the connector was experimentally investigated, which showed that the energy absorption capacity of the connector can be improved by increasing the thickness of the curved plate. EAC tests of variously shaped corrugated plates filled with polyurethane foam have proven that polyurethane foam filler can improve the energy absorption performance of the connector [10].

Targets and goals. The purpose of this study is to search for rational design solutions for connections that can plastically deform and dissipate the energy of an explosion, preserving the supporting frame from destruction and further application of the accumulated factual information in connections of wooden rod elements.

Materials and research methods. Modern connections of rod wooden elements are an integral part of unique buildings and structures tuned to the perception of explosive loads. The latest experimental and theoretical studies of their behavior under the action of an explosion are considered. Due to the small number of similar design solutions for connections, only those that are in the range of this study were selected for analysis, and are promising for further improvement and development.

Research results. The environmental benefits of using wood as a construction medium are well known. Architects and developers are increasingly attracted to the concept of wood specification for construction, thanks to the use of structural wood composites such as laminated veneer timber; glued veneer; parallel chipboard; laminated timber.

The spans and load-bearing capacity of timber structural elements have increased to an economically competitive level with other materials traditionally associated with modern long-span structures. Prefabricated connection systems have several potential advantages over traditional ones, both in appearance and strength. Hidden factory connectors have the potential for close quality control in production.

The wood has a high strength-to-weight ratio, which is favorable for dynamic loads.

To meet modern design requirements that take into account the action of significant dynamic loads, wooden structures must demonstrate plastic and dissipative behavior. A well-designed plastic wood structure can withstand extreme impacts such as tornadoes or explosions [14]. It is important to design fasteners that are weaker than the wooden elements so that they can deform and dissipate a large amount of energy. The way to ensure both proper ductility and sufficient load-bearing capacity are to use a large number of weak fasteners. The use of energy dissipation techniques allows you to protect the structure and people from an explosion, make repairs promptly and reuse the building. In [10], wall panels were developed that perform explosion-proof functions. They are connected to the supporting structure using assemblies of energy dissipating elements along the edge of the panel. When subjected to an explosive load, the panels transmit the pressure of the shock wave through the assemblies, thereby reducing the forces transmitted to the supporting structure. Subsequently, panels and blocks of energy-dissipating components can be quickly and easily replaced, allowing the building to be reused within a short time after an explosion.

Dynamic testing is undoubtedly the best choice for detecting the behavior of timber structures under explosion, seismic or wind loads. Also, given the fact that failure modes can be very different in static and dynamic conditions, it is necessary to have an idea about the plasticity of wooden connections.

A large amount of factual materials, as well as experimental and theoretical studies on the impact of tornadoes, makes it possible to qualitatively study the consequences of the behavior of wooden elements and their connections [12].

Tornadoes cause extreme localized wind pressure and uplift forces greater than the action of straight wind. When a structure is located in the center of a tornado's path, it experiences the most damage, making economical lightweight timber construction impossible for the most intense tornadoes. However, as it stretches outwards perpendicular to the tornado's path, the intensity of the tornado decreases. The standardized method for estimating wind speed during a tornado is the Enhanced Fujita (EF) scale, based on damage observations since direct measurement of wind speed during a tornado is generally not possible. The extreme localized wind pressure and wind debris in a tornado make it difficult to streamline the design process.

The collapse of the timber frame roof of an apartment building is one of the most common and costly types of damage caused by tornadoes. The work to mitigate damage to wood-framed residential roofs is important, and this is possible through improved design approaches and innovative solutions.

Connections in modern wooden buildings are metal devices that ensure the transfer of forces between structural elements. Their design is the most strategic part of the structural design of a wooden structure since the characteristics of the connections (type, mechanical properties, geometry, distance, assembly technique) strongly depend on the rigidity, strength, plasticity and dissipation energy of the entire structure.

A wide range of formations of hidden moment connections of wooden structures can be divided into five general types (Fig. 1): hidden rods, hidden glued plates, adhesive connections of surface contact connections, wooden lap connections and dowel connections [13]. Concealed connections provide not only aesthetic benefits but also resistance to environmental degradation, fire and significant dynamic impacts.

Recently, high-rise wooden houses have been built using a structural system in which massive diagonal members are connected by multiple slotted and tongue-and-groove steel plates to ensure structural strength. However, this application system limits large openings.

Moment Resistant Timber Framing (MRTF) with semi-rigid beam-to-column connections allows buildings to be erected without stiffeners or shear bracing, allowing openings to be enlarged, and redistributing internal forces through the connection with sufficient ductility is critical to ensuring the strength of the structure [15].

The significance of plasticity in a structural system lies in the fact that dissipative zones are located in connects, while the wooden elements themselves behave elastically. Dissipative structures can dissipate energy through plastic hysteresis behavior, and in wooden structural members connected by bolts or rods, energy is dissipated by plastic deformation of both wood and metal connectors under reciprocating cyclic loading.

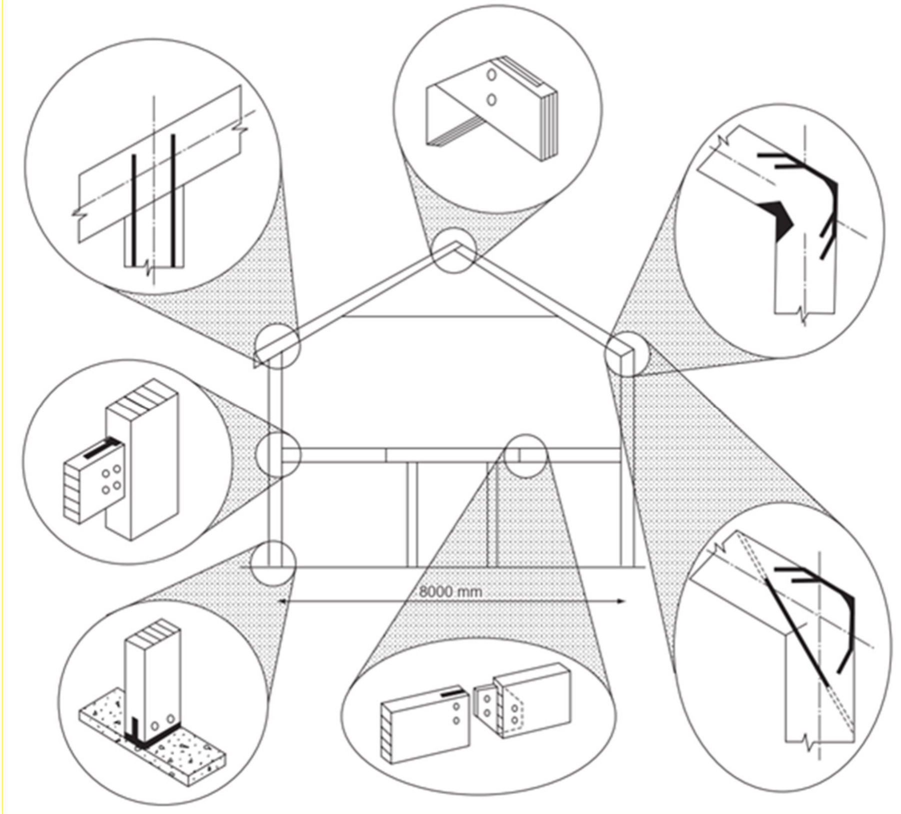


Fig. 1. Hidden moment connections of wooden structures

Plasticity is understood as the ability of a structure to undergo cyclic deformations of large amplitude in the inelastic range without a significant decrease in strength. Plasticity is measured by the ratio between boundary strain and yield strain.

The process of quantifying plasticity coefficients depends on the onset of yield strain, defined as the load at which the assembly begins to plastically deform. Theoretically, this deformation can be detected during monotonous load tests; however, most timber connections present a non-linear load-displacement relationship and an unclear transition between elastic and plastic behavior. Therefore, in practice, there are several different definitions of yield strength, leading to different results.

A proposed classification system for the ductility of timber connections, whereby connections and members can be classified into four categories (Table 1) associated with a particular failure mode.

Table 1

Classification of the plasticity of a wooden connection according to the failure mode

Wood connection failure mode	Average coefficient of plasticity
Fragile	$\mu \leq 2$
Low plasticity	$2 < \mu < 4$
Moderate plasticity	$4 < \mu \leq 6$
High plasticity	$\mu > 6$

In experiments [16], the characteristics of moment-resistant bolted connections of wood with self-tapping screws acting as reinforcement perpendicular to the fibers were evaluated. Due to the non-reinforced beam-to-column connection with slotted steel plates as the baseline, a power increase of 1.7 times was observed when the connections were reinforced with self-tapping screws under reversed cyclic loading. This increased further by 22.5% when the bolt diameter in the reinforced connection was increased from 19.0 to 25.4 mm. Reducing the edge distances between the bolts in the reinforced connection provided an additional increase in the bearing capacity by 35.3% to the total increase in the bearing capacity and by 2.9 times compared to non-reinforced connection in maintaining high plasticity. However, experimental results in cyclic testing have shown that a larger bolt diameter can increase the maximum moment and elastic stiffness, but will reduce the rotational capacity by almost 50%. This resulted in brittle fracture (Fig. 2) with a low ductility coefficient.

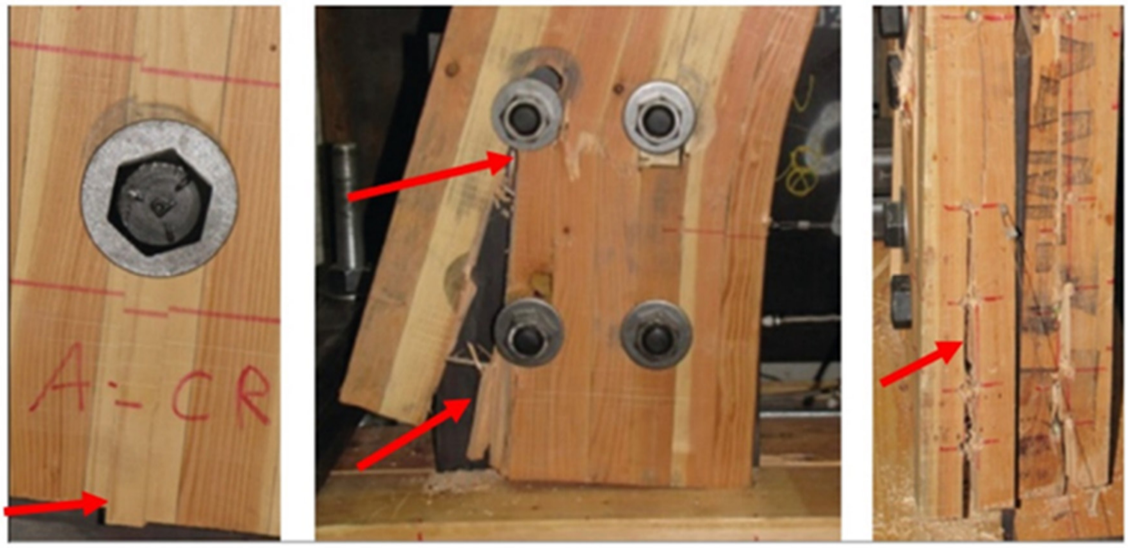
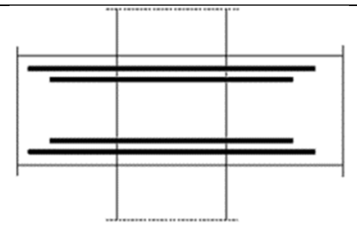
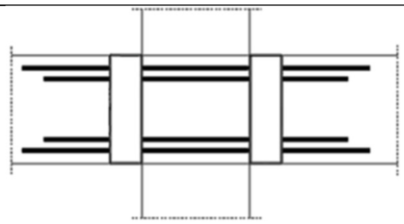
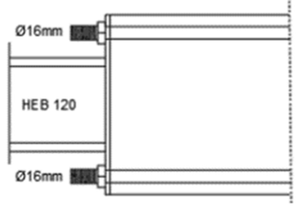
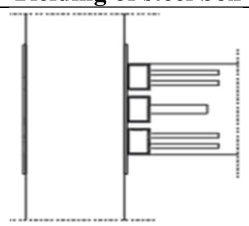
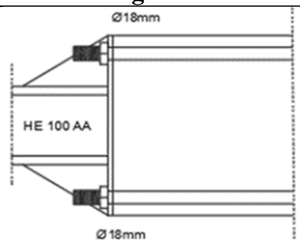


Fig. 2. Brittle fracture of a bolted connection

Studies of glued bars used in beam-to-column connections with several horizontal bars parallel to the beam fiber showed brittle failure with diagonal shear cracks in the middle of the connection (Table 2, type Ia) [15]. The best plastic performance of this type of connection was achieved due to the geometric configuration (Table 2, type Ib), where one rod was inserted inside the connection. It has reached several loading cycles and plasticity coefficient μ=6.

Table 2

Schemes of wooden connections with glued rods and failure modes

Type I **Glued-in steel rods in timber**	**Type II** **Glued-in steel rods with steel box**	**Type III** **Glued-in steel rods with steel link**
 a	 a	 a
Diagonal shear cracks	**Yielding of steel box**	**Yielding of T-stub**
 b	 b	 b
Horizontal cracks at bottom of the beam	**Yielding of steel box**	**Yielding of T-stub**

Based on studies involving glued bars bonded to steel boxes and pipes (type II of Table 2), plastic behavior was observed in monotonic and cyclic tests, with failure occurring on the steel side and not on the wood element. The use of three boxes and self-tapping screws (STS) for reinforcement is beneficial, as it improved the resistance to the moment of connection and reduced the likelihood of cracks and splits at the supports. On the other hand, when the wall thickness of the steel box is very thin, the connection bends diagonally between the stiffeners and cannot achieve high plasticity.

Type III compounds (Table 2) showed the highest degree of plasticity due to their high rotational ability. The preferred failure mode in this steel connection geometry was plastic deformation of the T-bar. It was possible to find out that with an increase in the thickness of the end plate, there is greater resistance to the moment of connection and lower rotational ability. In most studies, the specimen with a thick end plate demonstrated the failure of a brittle rod. Therefore, as the thickness of the end plate increases, the connection becomes less plastic, moving from a connection classified as a high plasticity connection to a low plasticity connection according to the proposed classification. In general, works in which steel plates were inserted showed a decrease in the maximum torque limit, indicating a decrease in plasticity.

The use of steel side plates with nails or bolted connections of slotted steel plates without reinforcement does not provide plasticity. These connections show brittle failure with low rotational capacity and a low limiting moment even when changing the geometric cross-sectional configuration or applying modifications to bolt and nail diameters.

The number of studies of the characteristics of connections of wooden structures under explosive loading is very limited and requires a holistic and systematic approach [17].

In [18], dynamic tests were carried out using a Shock Tube setup, which is capable of creating high strain rates, similar to those observed in explosions in the far zone. The shock tube uses compressed air, which can generate reflected pressure and impulses up to 100 kPa and 2200 kPa-ms, respectively. The reflected pressure is controlled by the driver pressure, while the reflected pulse is controlled by changing the length of the driver. Evenly distributed shock wave fronts are generated through the use of a double diaphragm inflammation system. The shock tube end frame measures 2032 mm by 2032 mm (80 in. x 80 in.), allowing both large and full-sized specimens to be tested. A load transfer device (LTD) with two load-transfer beams located in the third span was used to convert the reflected shock tube pressure into two concentrated loads applied directly to the specimens. While the structural member is subjected to a uniformly distributed load in a real explosion, the use of LTD generates similar strain rates and general dynamic responses in the timber member and connections. The LTD consists of rigid steel panels covering the entire opening of the end frame. Thanks to the slotted hinges, the LTD can move up to 200 mm, which allows the transfer of pressure without changing the rigidity of the tested specimens.

An experimental program has been developed that investigates the behavior of stacks of glued laminated timber with various bolted connections subjected to simulated explosive loading [18]. 14 full-scale tests of glued elements with a cross-sectional size of 137 × 267 mm were performed with idealized and realistic limiting conditions using a shock-tube apparatus capable of simulating the effects of explosions in the far zone. Full-size glulam samples with bolted connections designed for flexibility in bolt bending performed better than those designed with a margin of safety. It has been found that proper detailing of the bolt group geometry is sufficient to achieve the desired failure sequence. Reinforcement with self-tapping screws changed the splitting failure mode to a combination of bolt deformation and wood failure and provided additional plasticity of the connection. Reinforcement with screws changed the failure mode from splitting to bolt deformation and wood crushing and provided additional plasticity in the assembly.

The article [19] presents a technique for the development of energy-absorbing connections (EAC) in assemblies of glued laminated timber and cross-laminated timber (CLT) for protection against the effects of a blast wave. Explosive overloads were modeled with the introduction of the Shock Tube installation. In total, 23 dynamic tests of full-scale wooden assemblies were carried out with different limiting conditions. The CLT samples consisted of 445 x 175 mm class E1 panels with five layers of 35 mm thick laminate. The beams of glued beams consisted of spruce-pine-fir layers with a cross-sectional size of 137 × 267 mm.

Based on observations of damage to connections and wooden elements, the behavior of nodes was established and failure modes were characterized. The behavior of the nodes has been established and the failure modes have been characterized based on observations of damage occurring in connections and timber elements. Experimental test results have shown that, when properly designed, EACs allow assemblies to withstand more blast energy than conventional glulam and CLT connections. At failure, average reflected impulses of 534 kPa-ms and 646.8 kPa-ms were observed for simply-supported glulam beams and CLT panels, respectively.

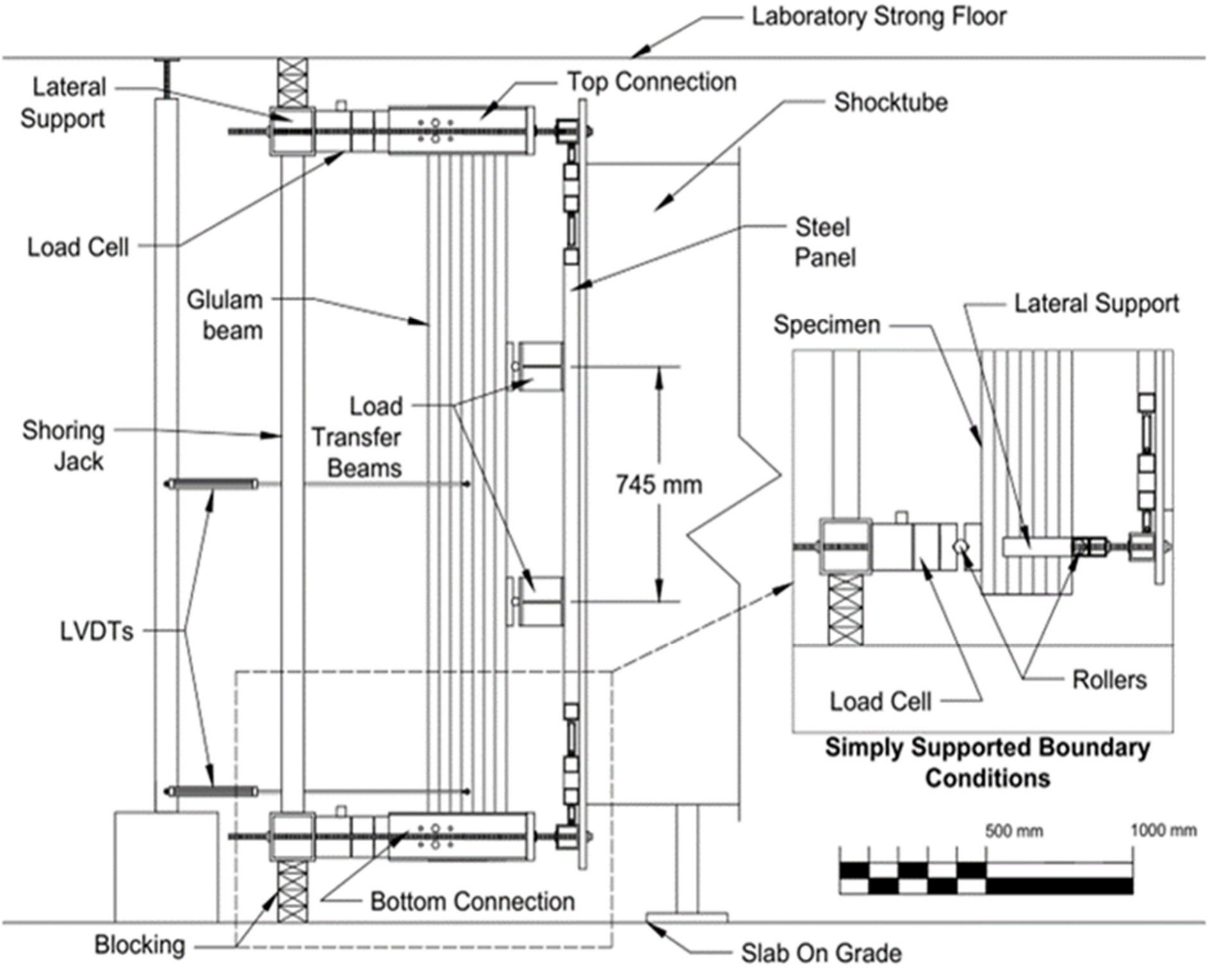
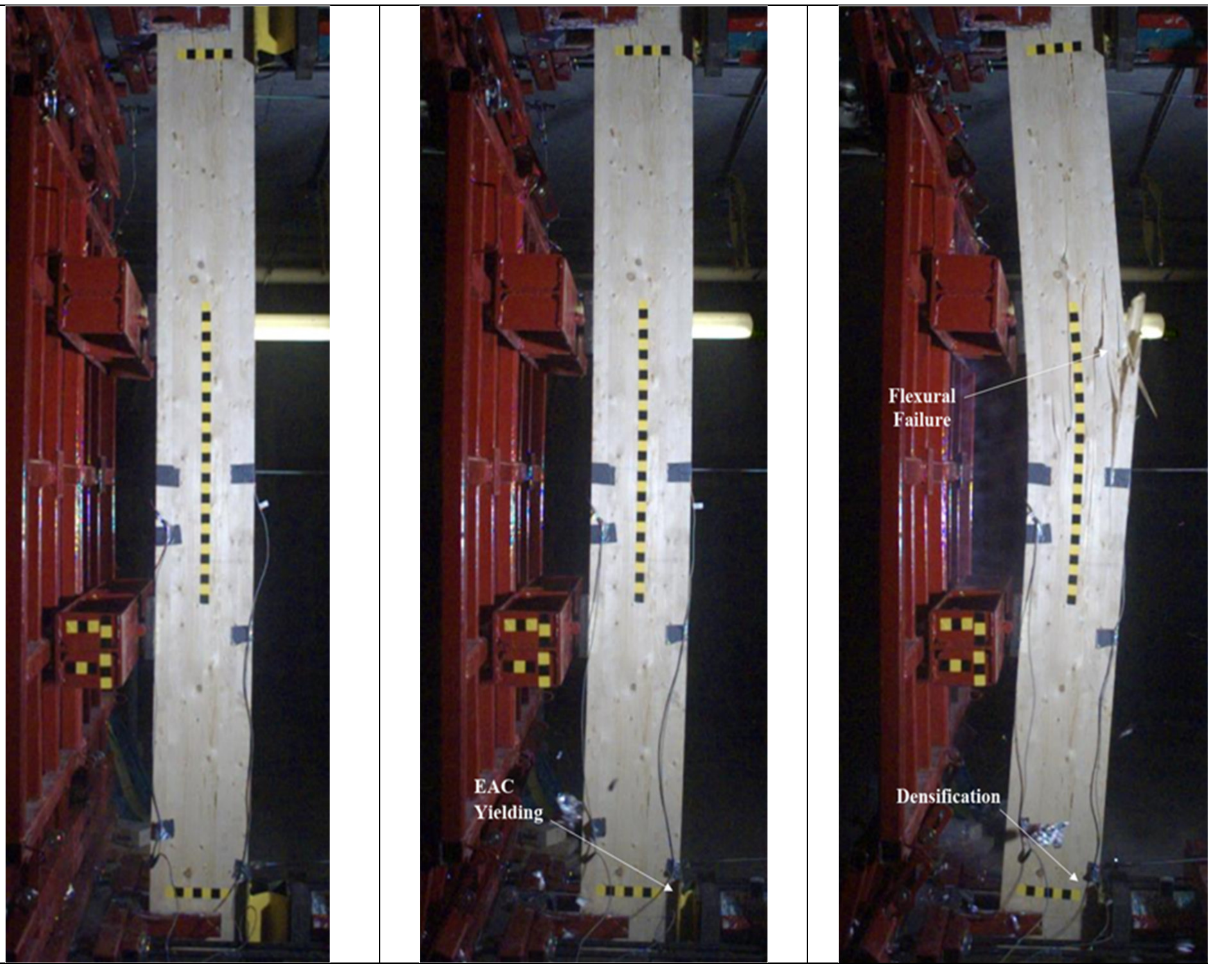


Fig. 3. Installation of Shock Tube for dynamic testing of wooden elements

On fig. 4 shows photographs of testing a wooden rod element with energy-absorbing compounds (EAC) under the action of an explosive load for different periods. The behavior of the sample can be divided into three stages. The initial loading stage is the region where both the EAC and the wood element behave resiliently by the time the EAC yields. This is characterized by a bending of the wood element with a slight misalignment at the ends caused by EAC deformation (Fig. 4a). The second stage is characterized by a yield plateau where EAC exhibits almost perfect ductility and the load acting on the wood element is constant (Fig. 4b). Finally, the third and final stage consists of a densification stage accompanied by an increase in stiffness and strength that exceeds the strength of the wood element. This causes the wooden element to reach its maximum resistance and not be subjected to bending, as shown in fig. 4c.

The impact of a high strain rate on the yield strength and stiffness of thin bolted connections of wooden rod elements is given in [20, 21]. Single-bolt connections were tested during static and simulated explosive loading. The connection was studied both parallel and perpendicular to the fibers. The results showed that links loaded in parallel with fibers exhibited a different failure mode under dynamic loading compared to static loading. The reinforcements that have been used to prevent split failure improve the bearing capacity of the connection.



a	b	c

Fig. 4. The behavior of a wooden rod element under the action of an explosive load

Conclusions. To achieve the goal, a review was made of modern structural connections of wooden elements, their behavior under the action of a dynamic load in a complex stress-strain state, and trends in the development of innovative solutions.

A system for classifying the plasticity of wooden connections under the action of a dynamic load is given, which is associated with a specific failure mode. Experimental results are considered and comparisons are made.

Awareness of the need to protect wooden structures from significant dynamic impacts (explosion, tornado) has not sufficiently solved the problem. The analysis of literary sources made it possible to identify the advantages and disadvantages of different types of connections of wooden rod structures under the action of significant dynamic loads. Their advantages and disadvantages are determined, as well as the ways for their further improvement and application.

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