WORLD CONFERENCE ON TIMBER ENGINEERING 2025
BRISBANE, AUSTRALIA

Advancing Timber for the Future Built Environment

EFFICIENT CONNECTIONS FOR MODULAR PREFABRICATED TIMBER BUILDINGS TO HELP RECONSTRUCTION IN UKRAINE

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ABSTRACT: The project presented in the paper aims at the development of a new solution for an universal connector in Cross-laminated timber structures, which offers the possibility of quick and easy installation and assembly, as well as easy disassembly and reuse. This solution shall contribute to the necessary reconstruction of the damages in Ukraine and facilitate the quick restoration of housing as well as providing a long-lasting sustainable and circular connection solutions. The developed connector is a unit in the form of a steel plate on glued-in rods, that are embedded in the CLT panels. This allows to connect CLT panels in various arrangements together or to other building parts such as foundations or concrete cores. Connections with glued-in rods are widely used in Eastern European countries, especially in long-span timber structures for buildings of various types.

KEYWORDS: glued-in rods (GiR), bonded-in rods, universal joint, CLT panels, connector, disassembly.

1 – INTRODUCTION

1.1 – BACKGROUND

The construction sector is responsible for a significant share of Green House Gases emissions (ca. 30-40%) and raw material consumption (ca. 50%) globally. Building with timber and the shift of the construction sector towards a circular economy are key elements to success in order to achieve a more sustainable built environment and a more sustainable society. In their development it as to be put emphasis on long-lasting sustainable and circular solutions instead of unsustainable single use solutions of buildings. Adaptable buildings that can be extended over time are suitable to provide quick shelter for many and allows the further extension when recourses are available. Modular prefabrication of elements allows the fast production, construction, and even reaction to local demands.

One of the barriers for the greater utilisation of timber in construction is that engineers, architects, contractors, and authorities have often little experience with the construction material timber and its utilisation in high-performance structures compared to other conventional building materials such as concrete and steel. Often the experience, skills, and workmanship regarding timber on the construction site are limited. Besides training also simple connection and detailing solutions need to be developed, that can be easily and safely applied by unskilled personnel. Prefabricated connections with bonded-in rods or bolted connections are examples of such solutions.

1.2 – THE PROJECT RECONNECT

In the project *ReConnect - Efficient connections for modular prefabricated timber buildings to help reconstruction in Ukraine*, that is funded by SI – Sveriges Institutet, the partners from O.M.Beketov National University of Urban Economy in Kharkiv (Ukraine), Chalmers University of Technology, Gothenburg (Sweden), Tallinn University of Technology, (Estonia), and National University of Water and Environmental Engineering in Rivne (Ukraine) are collaborating.

The project had the objective to develop a novel connection system for timber members that makes it possible to adopt the concepts of reusability, adaptability and circularity of members in timber structures. By optimizing the connection layout, we intend to enhance the performance towards low damage and to avoid brittle failure modes in the timber. The project reduces the complexity of high-performance connections for timber buildings and lower the entrance barrier towards the use of timber in structures.

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https://doi.org/10.52202/080513-0075

In an experimental campaign we experimentally validated the performance, predictability, universality and reusability of the novel connection system in timber members with different loading situations.

1.3 – Connection development and Application area

There are different examples of connections that can be seen as first steps towards the direction of a universal timber connection systems that allow for high performance, prefabrication, easy application, dis-assembly and reuse. Examples are: Bolts, dowels, screws, or bonded-in steel rods. Especially bonded-in rods allow for a direct transfer of tension forces along the grain direction of the timber. By placing rods at different inclination into the timber, brittle failure in the timber in tension perpendicular to the grain can be prevented and the connection can resist a variety of loading directions. By combining the rods with adequate connection elements into one system, it becomes possible to prefabricate, assemble and disassemble timber components. The rods remain in the timber but the connector element can be easily adapted and re-connected. Such a connection system has to be developed towards predictability of behaviour, universality in application, reusability and efficiency.

The prefabrication of the proposed connection in the factory and its uniform spacing along the edges of CLT panels makes it possible to produce entire series of unified building components of different sizes and layout solutions, see Figure 1. The regular spacing allows that the CLT panels can be prefabricated mostly independent of its later application, and they can be assembled and connected in different arrangements between each others or to other structural elements depending on the specific demand in a structure. The connector is installed in the side face of CLT panels in a pre-milled recess for the plate and can be completely hidden in the interior or invisible, which is also good in fire conditions.

1.4 – Proposed connection system

For the first time, this type of connection for CLT panels was proposed in the frame of the EECTC conference in Kharkiv (Ukraine) in 2018 (Bidakov et al. 2018). In these conference proceedings tests of glued-in rods in CLT samples were reported by Bidakov et al. (2018), where pull-pull configuration with different variants for their location in the panel cross section were studied.

The common practice and experience with using glued-in steel rods (GiR) in the CIS countries is very large and in the USSR this connection type was already included in the standard for the design of timber structures SNiP II 25-80 (SNiP 1980). The current draft version of Eurocode-5 (FprEN1995-1-1: 2025) (FprEN 2025) contains recommendations regarding design of bonded-in rods (BiR) and, hence, opens the possibility of a more wide implementation of BiR solutions in practice. The design standard works together with the testing standard for the bondline strength in EN 17334 (EN 2021), which assures the high-performance and high quality of the BiR solutions.

To date, many laboratory tests have already been carried out on glued-in rods in CLT, both single (Andersen & Høier 2016, Azinov et al. 2018, Azinov et al. 2019, Jockwer et al. 2023, Stepinac et al. 2013) and groups of glued-in steel rods (Ayansola et al. 2022). However, this new connection type requires further laboratory testing on the full connection, since the metal plate can redistribute the actions to the different rods. Depending on the loading condition of the CLT panel and subsequently the connector the rods experience various loading conditions, including complex stress states with simultaneous axial loading with pull-out of the rod and lateral loading with the rod acting as a dowel and stressing the timber perpendicular to the grain. Another possible complex combination of stresses is pullout and torsion.

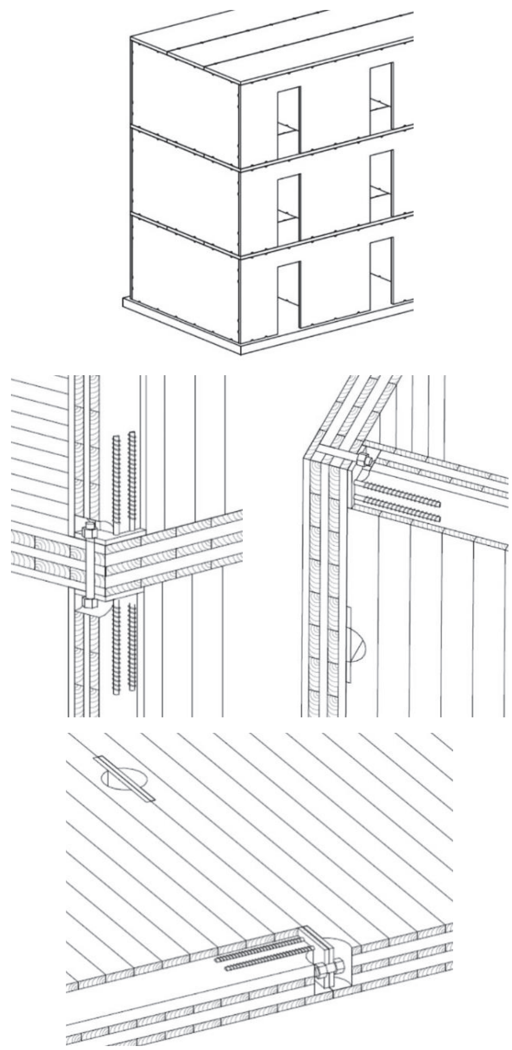

***Figure 1**: Options for using a unit in a building made of CLT panels and examples of interstorey, corner wall, and floor connection details in CLT buildings.*

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2 – MATERIALS AND METHODS

2.2 – CONNECTOR GEOMETRY

The proposed type of connection as shown in Figure 2 consists of a 12 mm thick steel plate (steel grade S355) to which steel bars RiBa A500C diameter 10 mm are welded. The length of the reinforcing bars is 150 mm. The bars are glued into pre-drilled holes using a two-component epoxy adhesive system, see Figure 3. To distribute the high shearing or pulling forces across the thickness of the CLT panel with its orthotropic and heterogeneous boards, it was decided to use 8 glued-in rods for the connection.

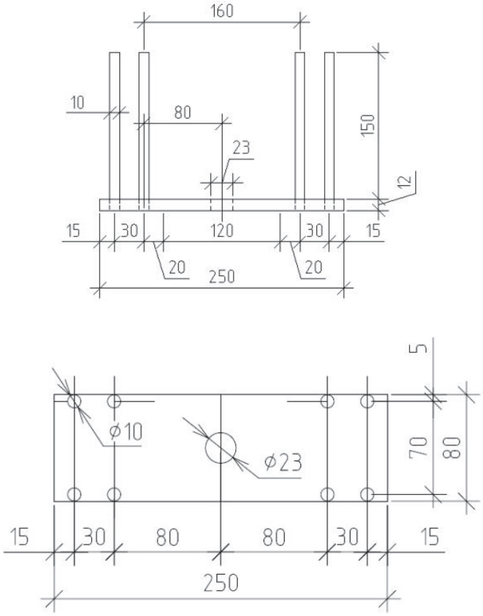
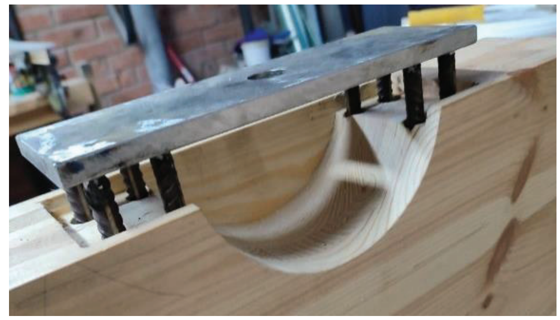


Figure 2: *Geometric parameters of the connector.*

The steel plate has 8 holes for the rods and a centric hole in the middle of the plate for connecting it with a bolt (e.g. M24) to the other unit in another CLT panel (Figure 3 (b)) or to another CLT panel directly (Figure 3 (c)).

The connection between the steel plate and the CLT panel is rigid due to the lack of slip deformation in the timber element, and deformations might only occur in bending of the steel plate. This connector can also be attached to reinforced concrete members or foundations. It is also possible to attach such a connector to steel components and structures or even weld them to them with a discontinuous seam. The connector has a semi-circular milled hole in the CLT panel around at 2/3 of its thickness to allow installation of a bolt or nut (Figure 3 (a)).



(a)

(b) (c)

Figure 3: *General view of the installation of the connection (a) and assembly of two units (b) and of the unit directly to CLT panel (c) Photos by Andrii Bidakov*

The connector is installed in the side face of CLT panels in a pre-milled recess for the plate and can be completely hidden in the interior or invisible, which is also good in fire conditions

This connector unit makes it possible to assemble and connect CLT panels in 6 main cases: a) two floor panels parallel to the span, b) two wall panels in a planar manner, c) two wall panels at the corner of a building (L shape), d) a longitudinal wall panel and a transverse wall or partition wall (T-shape), e) wall panel to the foundation, f) floor to wall joint. It is also possible to attach beams and columns to CLT panels using the proposed unit in combination with glulam beams.

2.3 – POSSIBLE CONFIGURATIONS

The geometric configuration shown in Figure 2 is provided for connecting CLT panels with a thickness of 100-120 mm since the width of the metal plate is 80 mm (see Figure 3) and must be hidden. For CLT panels 120-140 mm, it is proposed to use a connector with a plate width of 100 mm, in order to increase the load-bearing capacity of the connection. From a static point of view it is important to reduce the distance from the edge of the panel to the axis of the glued-in rods, which should, however, not be less than 2.5 d according to EOTA TR 070 (EOTA 2019) or FprEN1995-1-1:2025 (FprEN 2025) in order to avoid splitting. Increasing the distance from the edge of the CLT panel to the axis of the rods improves furthermore its fire resistance. Hence, the position of the rods in the panel must be carefully chosen to achieve high efficiency and still keep the rods in the longitudinal layers of the panel.

https://doi.org/10.52202/080513-0075

The option of attaching the plate to the CLT panel with full-threaded screws is also possible as one of the variations of this type of connector. Particularly efficient and low compliance of the connection can be ensured by inclined screws in different directions. Inclined screws have low slip deformations and can be quickly installed in production without quality control of the connection, unlike glued-in steel rods. A connection with screws can be a second equivalent version of the developed system for connecting building frame panels, which is based on the same pitch of standardized connections along the edges of the CLT panel, DLT panels or GLT elements.

2.3 – EXPERIMENTS

The current draft version of Eurocode-5 (prEN1995-1-1: 2023,[16]) (prEN 2023) contains recommendations regarding design of bonded-in rods (BiR) and, hence, opens the possibility of a more wide implementation of BiR solutions in practice. However, these rules relate primarily to uniaxially loaded rods unders pure axial or lateral loading. To consider the variety of loading states acting on the connector, different tests have to be performed. An overview of the possible tests carried out in this project are shown in Figure 4.

More information on the tension tests in pull-pull are reported in (Bidakov et al. 2024).

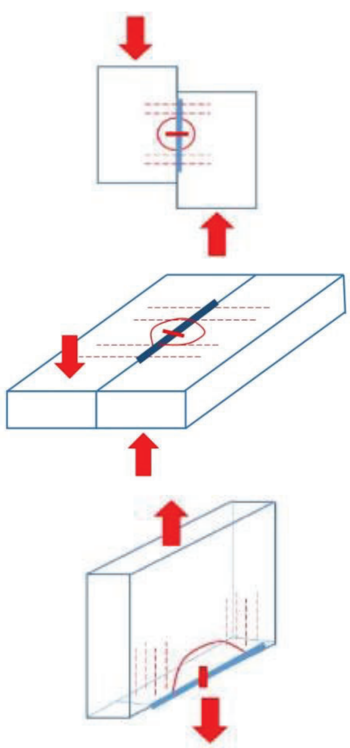


Figure 4: *Test configurations for the connector: shear in-plane (top)- shear out-of-plane (middle), pull-pull (bottom)*

In-plane shear tests

Five test specimens were tested for serie K-2. The tested connection was between two CLT panel parts with dimensions 280x700 mm and a thickness of the panel of 140 mm with board layers 40/20/20/20/40 mm, see Figure 5. The specimens had tapered edges at the supports to ensure an inclined load introduction of about 14° and the load along the vertical axis passing through the centre of the tested connection.

The test specimens were loaded with a universal 500 kN hydraulick jack. During the test, both the applied force and the relative displacement between the two members of the connection were recorded. Measurement devices were attached on the sides of the connection near the joint line for relative displacement measurements on the front of the test specimens. The test procedure and the evaluation were based on EN 26891 [6]. Both the ultimate load F_{max} and the stiffness k_s per connector were determined. The stiffness was determined in the range between 10% and 40% of the maximum load in the linear-elastic range.

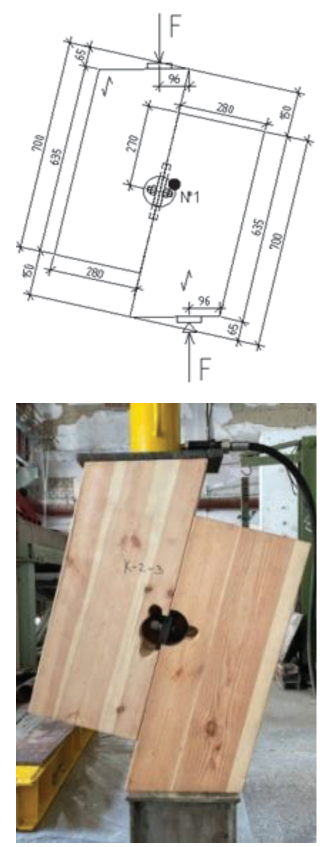


Figure 5: *Specimen geometry and example of test setup of the in-plane shear tests*

The connection components of the test specimens had a precise geometry as specified and the connection of the two parts of the connection was established by one M20

https://doi.org/10.52202/080513-0075

bolt with firm tightening by hand. The level of tension of the bolt was not controlled. In the first tests the M20 bolts failed before the damaging of the wood around the glued-in steel rods began, which was intended to be investigated. Hence, the bolt diameter was increased to a diameter of M22 and M24. The hole in the CLT panels for the tightening of the bolts had initially a rather small diameter (Figure 5) and was increased to make it possible to install these larger bolts.

The hole in the middle of the plate was taken to be 23 mm for installing the M20 bolt, and was increased to a diameter of 26-28 mm for installing the M24 bolts.

Out-of-plane shear tests

The tested connection in CLT panels loaded out-of-plane had dimensions 750 x 2000 mm with thickness of the panel of 100 mm with layers 20/20/20/20/20 mm, see also Figure 6. The specimen was positioned horizontally and located on two supports in such a way that one support point was in the form of a metal plate fixed to the connector with a bolt. The support of this end of the panel with the connector was through the edge of the fixed plate, which had a width greater than 40 mm, which made it possible to develop deformation of the connector when loading the panel along a line at a distance of 500 mm from the connector (Figure 6). The panel support was hinged. Measurement devices were attached near the connection on the top of the CLT panel for relative displacement measurement of the test specimens. The total number of tested specimens of series P-1 was 5.

The test specimens were loaded with a universal 500 kN hydraulic jack (see also Figure 7). During the test, both the applied load and the relative displacement between support and outer layers of CLT panel were measured. The ultimate load $F_{V,test}$ and the stiffness k_s per connector were determined. The stiffness was determined in the range between 10% and 40% of the ultimate load in the linear-elastic range.

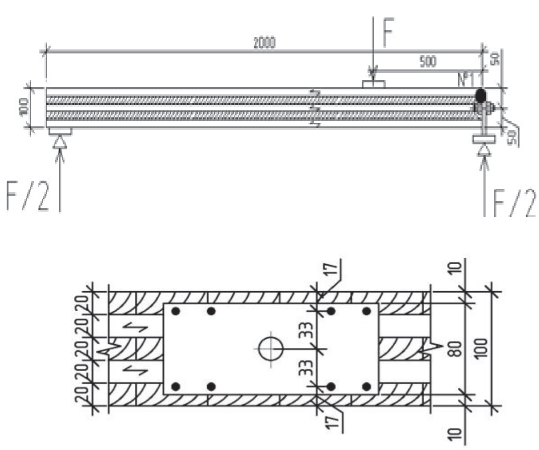


Figure 6: *Test setup and connection geometry of the out-of-plane shear tests*

Figure 7: *Test setup of the out-of-plane shear tests*

3 – Results and discussion

3.1 – RESULTS

The conducted primary tests of the connector made it possible to evaluate the parameters of strength and deformability relative to the data obtained during calculations using existing methods of glued-in rods as dowels when loading them perpendicularly relative to the axis of the glued-in rod. A statistical analysis of the obtained experimental data was conducted, the characteristic values of the connector strength and the magnitude of the slip module were determined as the main necessary parameters for using this joint in CLT building.

In-plane shear tests

Load-displacement plots for series K-2 or shear in-plane are shown in Figure 8. The mean value of the slip modulus in the in-plane shear tests of the connector in the CLT plane of the panel is $k_{s,mean,con,in}$ = 31.3 kN/mm.

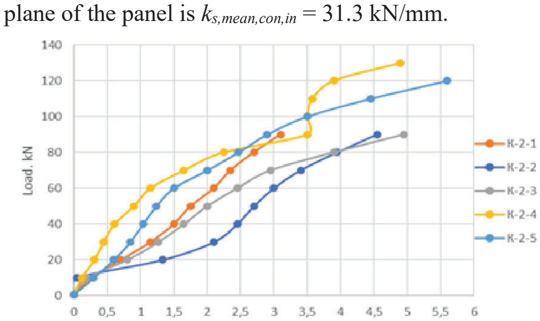


Figure 8: *Load-displacement plots for test series K-2*

The typical failure mode of the tested specimens of the serie K-2 shown in Figure 9 occurred due to displacement of the connected parts of the connection along the joint line from the front side. When disassembling the unit, the shift of the plates in the milled recesses was about 5 mm and, respectively, the timber was compressed on the other side of the plate.

Figure 9: *Failure mode of the tested specimens in serie K-2 with M20 bolt failure (top) and wood failure with larger M24 bolts (bottom). Foto source: Andrii Bidakov*

After testing the deformation of steel rods welded to the metal plate had a characteristic classic bending shape as in single shear dowel type steel-timber connections with thick steel plates. According to EOTA TR070:2019-10 and FprEN 1995-1-1:2025 laterally loaded bonded-in steel rods should be considered similar to dowels. The bending intensity of one group of rods (4 rods) is typically greater than that of the other group when testing the connections in the plane of the CLT panel's, which is explained by the existing heterogeneity of the panel structure and the uneven distribution of forces in the metal plate itself.

Out-of-plane shear tests

Load-displacement plots for series P-1 or shear out-of-plane are shown on Figure 10. The mean value of the slip modulus in the out-of-plane tests is $k_{s,mean,con,out}$ = 32,5 kN/mm.

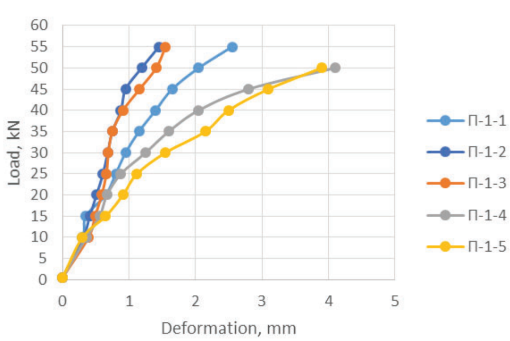


Figure 10: *Load-displacement plots for test series P-1*

The typical failure mode of the tested specimens of the series P-1 shown in Figure 11 occurred due to displacement of the connected parts along the edge side of the panel. When disassembling the unit, the shift of the plates in the milled recesses was about 5 mm and, respectively, the timber was compressed on the top side of the plate with fracture perpendicular to the grain extending along the layer direction.

The calculated value of the characteristic load carrying capacity of the connection with 8 BIR was with $F_{V,calc,k}$ = 61,7 kN higher than the characteristic value results obtained during testing $F_{V,Test,k}$ = 55,2 kN.

One of the reasons for this difference is that lateral rod failure was considered according to the calculation whereas in the experiments the connection failed with splitting. This can be related ot the small distance from the axis of the BIR to the side edge of the panel was only 17 mm or 1,7 d, while the required distance as the minimal distance for laterally loaded dowel-type fasteners in the narrow side of cross laminated timber should be no less than $a_{4,t} = 6d$ = 60 mm according to FprEN 1995-1-1:2025.

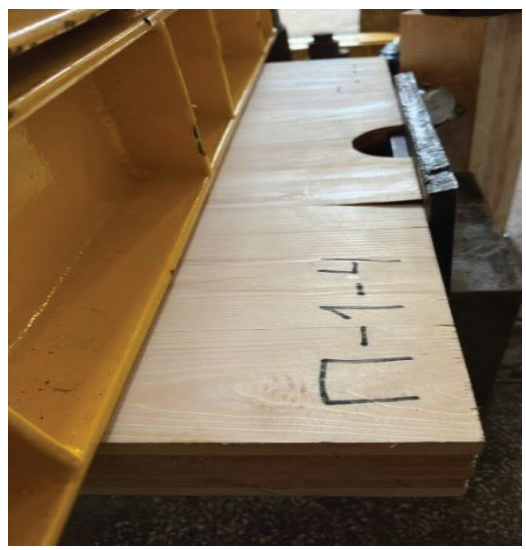


Figure 11: *Example of the failure mode of a specimen of series P-1: (specimen P-1-4). Foto source: Andrii Bidakov*

3.2 – DISCUSSION

The performance of the proposed connection was tested in pull-out at the Laboratory of Structural Engineering of Taltech University in Estonia. At the structural laboratory in Kharkiv, Ukraine, in-plane and out-of-plane shear tests were carried out. The test results presented in this paper show the load-carrying capacity, deformability and failure modes in shear in-plane and out-of-plane of CLT panels with the newly developed solution of a universal connector for CLT timber structures, which offers the possibility of quick and easy installation and assembly, as well as easy disassembly and reuse.

https://doi.org/10.52202/080513-0075

Non-linear dependence of loads to deformations was observed on the all stages of connection loading. Characteristic value of the carrying capacity of connector by shear in-plane of the CLT panel equal 74,96 kN according to test results and out-of-plane 55,2 kN. The calculated strength is higher than the test results in shear out-of-plane because the distance should not be less than 6*d* but in testing specimens this value was 1,7*d* which explains the low level of carrying capacity.

For an initial assessment of the load-bearing capacity of the connection with the steel plate and glued-in rods in a CLT panel and for the evaluation of the prospects for its serial use, analytical calculations and modelling of a 3-story building were carried out. The preliminary calculations on a FE-model of the 3-storey case-study building with the proposed connector with glued-in rods show that the resulting forces in the connections do not exceed the estimated theoretical values of load-carrying capacity derived from the standards in pull-out and shear loading (see also Jockwer et al. 2024).

The proposed geometry is suitable without modification for the case-study building with 3-5 floors, where the forces do not exceed the analytical and experimental resistances. For tall buildings in platform construction, when the load between the walls exceeds the crushing strength of the timber perpendicular to the grain of the floor panels, it is necessary to insert steel tubes between the connector plates that transfer the loads through the floor panel. This solution has been used already in many cases for the transfer of loads through floors between columns.

4 – CONCLUSIONS

In the project RECONNECT, a new type of connection system with a steel plate and glued-in rods for CLT panels was investigated both analytically and experimentally. The proposed new type of connection system is universal, easy to implement in production and can be used (with minor modifications) in buildings of 5 floors and above. The glued-in rods can be replaced with screws if necessary. However, it should be considered that the costs of connections with glued-in rods is much cheaper in Ukraine than connections using fully threaded self-tapping screws.

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In this paper, the strength and slip moduli of connectors with glued-in steel rods located in edge side of CLT panels subjected to shear loading in-plane and out-of-plane of the CLT panel were investigated. 10 static tests were conducted till failure of each specimen.

The tests of connection in CLT panels with a connector loaded by shear in-plane and out-of-plane of the panel revealed a fairly reliable character of their failure in the area of placement of a metal embedded part with steel glued-in rods that work as dowels. The character of the failure is ductile by shear in-plane and is accompanied by crushing of the wood around the glued-in rods in the places of their attachment to the metal plate. By tests out-of-plane occurred brittle failure mode due to the cracking of the boards at the final stage of loading the sample.

Connections with glued-in rods in CLT panels have already been studied by several researchers. Most of the research has be done on uniaxially loaded rods. However, the application of rods in practical applications requires also the evaluation of rods under complex loading situations with interaction of axial and lateral loads.

ACKNOWLEDGEMENT

The work presented in the paper has been conducted in the project "Efficient connections for modular prefabricated timber buildings to help reconstruction in Ukraine" within the programme for Academic Collaboration in the Baltic Sea Region, which is funded by The Swedish Institute (SI). We would like to thank SI for their financial support for this research project!

This contribution is based on (Bidakov et al. 2024 and Бідаков et al. 2024).

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