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HARDWOOD PLATE-TYPE CONNECTORS ANALYSIS FOR MULTIPANEL CLT SHEAR WALLS

Andrii BIDAKOV[1]; Oksana PUSTOVOITOVA[2]; Viacheslav KOSMACHEVSKYI[3]; Yurii KUZUB[4]

[1,2,3,4]O.M.Beketov National University of Urban Economy
Chornoglazivska St., Kharkiv, Ukraine, 6100217
[1]bidakov@kname.edu.ua, https://orcid.org/0000-0001-6394-2247
[2]oksana.pustovoitova@kname.edu.ua, https://orcid.org/0009-0003-4774-6686
[3]Viacheslav.Kosmachevskyi@kname.edu.ua, https://orcid.org/0009-0006-8281-3946
[4]Yurii.Kuzub@kname.edu.ua, https://orcid.org/0009-0000-7529-2069

Andrii BIDAKOV
Assistant Professor, Department of construction design,
Dr.Sc

Oksana PUSTOVOITOVA
Assistant Professor,
Department of construction design,
PhD (Tech. Sci.)

Viacheslav KOSMACHEVSKYI
student

Yurii KUZUB
student

Abstract. Developing multi-storey timber construction requires control and minimized deformations of both the building frame elements and their connections. This is especially important for buildings made of CLT panels, where optimizing the building frame and minimizing material consumption comes down to constructing parts of the wall panel above the window and door openings of separate elements. Also, dividing CLT panels into smaller fragments is often attempted to simplify logistics or reduce scraps when cutting a large slab in production. Such frame detailing requires monolithic connection of CLT panel elements, achieved with a large number of screws, which is extremely expensive, especially for Eastern European countries. Timber structure joints deformability is minimal in adhesive joints and joints on glued-in rods. The analysis of the rigidity and strength of CLT panels connections provided with plate elements and the test results discussed in this publication prove the efficiency and prospects of this connection type, especially manufactured with modern methods ensuring high dimensional accuracy in cutting frame parts through the application of various milling techniques.

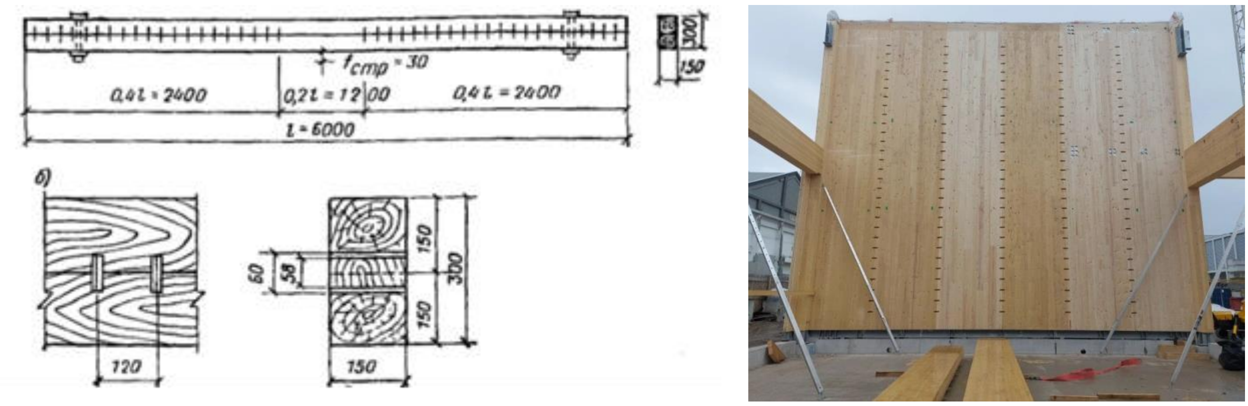
The publication presents the results of tests conducted with oak shear-key connectors of CLT panels and compares them with the results of similar studies using aluminum shear-key and connections with a big number of screws in spline joints. Analysis of the deformation behavior of connections in multi-story building frames made of CLT panels requires special attention and the search for new solutions for connections and their components. Currently, shear-key connectors from different manufacturers offer various geometric variations that simplify their installation during building frame assembly and sometimes even allow for tightening of the connected components using wedge-shaped surfaces.

Keywords: cross-laminated timber (CLT); multi-panel walls; plate-type timber connector; shear-key connector.

INTRODUCTION BACKGROUND

Intensive use of CLT panels in modern construction makes the issue of connecting frame panels to each other crucial. CLT panels are most commonly connected with screws. Minimizing the number of screws connecting CLT panels significantly reduces the cost of the building frame, which is important for promoting timber structures in Eastern European countries, including Ukraine. Timber plates made of hardwood (oak, beech or birch) were used to join logs or beams lengthwise to achieve a solid cross-section and full joint work well before the advent of timber gluing technology. As described in numerous previous references, many bridges and long-span wall designs were enabled with such connections. The old SNIP 2-25-80 standards [5], adopted in 1982, provide data for designing such connections, while the standards manual (1986) features examples of calculating such beams.

The largest number of hardwood shear-key connectors in simply supported beams is installed near the support where the maximum shear occurs.



a *b*

Fig. 1 Built-up beams with timber plate-type hardwood shear-key connectors (a) according to SNiP [5] and alumimium slot connector (b) manufactured by Rothoblaas [8]

Рис. 1 Балки складеного перерізу з пластинчастими шпонками (а) згідно до СНіП [5] та алюмінієва шпонка Slot (b) виробництва компанії Rothoblaas [8]

STATE OF THE ART

Such a timber-plate connection made of beech LVL and softwood LVL has already been widely studied by Prof. H. J. Blass and T. Schmidt (2018) for CLT panels connections, as described in their works [3, 10-13]. A similar solution, based on connecting keys, has been adapted and offered in the form of an aluminium key Slot by the Rothoblaas company [8]. This key-connection solution is widely used in engineering practice and described in the works by D. Cassagrande et al. [1, 2, 14] for multi-panel CLT shear walls, Fig. 2. The deformability is insignificant and such an easily manufacturable connection is crucial for modern construction to connect CLT wall panels [4, 15-19] and floor panels to each other along the edge, as well as to provide corner joints of CLT panels and to connect panels along the face. In this publication, the obtained testing results for oak plates deformability are compared with similar testing results for the aluminium SLOT and LVL-timber plates for a comparative analysis of deformability, as well as an analysis of changing rigidity in such joints depending on the deformations.

The plates in the wall panels' joints are placed in the upper and lower parts of the joint along the length of the vertical joint. This type of connection is both rational and effective for connecting floor slabs made of glued laminated timber independently, without fixing them to the concrete layer for timber-concrete floors.

Ductility and behaviour assessment of connections in CLT panels is very important for buildings located in seismically active regions [20-24]. Cyclic testing of CLT-panels' joints on the mechanical fasteners is conducted according to standard EN 12512:2001 [25], which lists the corresponding methods

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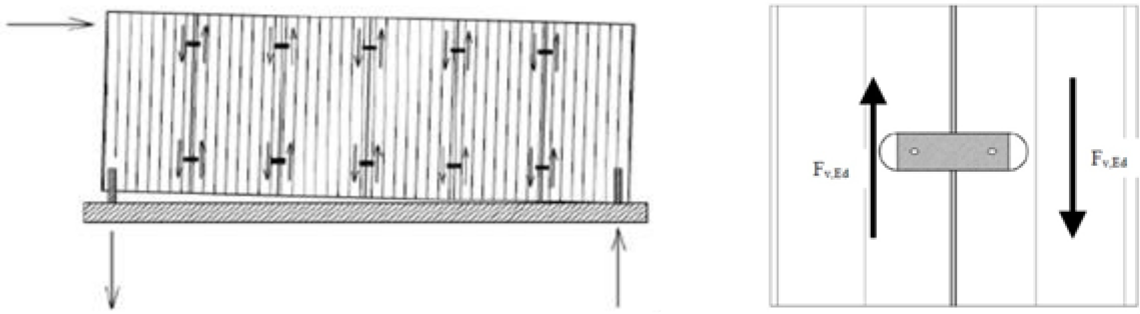


Fig. 2 Multi-panel shear wall with shear-key or plate type stiff connector (D. Cassagrande at al. [1]).
Рис. 2 Багатоскладна стінова панель зі шпонками у стиках або жорсткими конекторами до дії зсуву (D. Cassagrande and all [1]).

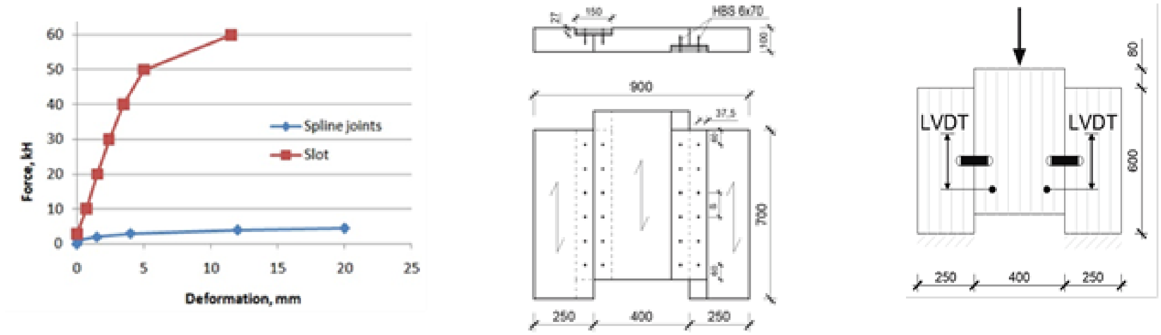
The "X-fix C" key developed by the Haaslacher company (ETA-18/0245 [6]) is formed by two plates with inclined planes. When driven into a pre-milled groove, the connected parts of the CLT panels are pulled together to minimize or eliminate the gap in the joint. This key also has widenings from the centre to the edges to retain tensile forces in such a connection. The general views of the Slot, X-fix C key and oak keys in the tested samples are shown in Fig. 3.

Joints deformations in timber structures is often a key criterion, since the horizontal displacement in wall panels cannot exceed more than h/100, where h is the height of the wall panel. The efficiency of shear-key joints in comparison with connections effected with screws installed in a row along the joint is significantly higher. Figure 4 shows a graph of the deformation of connections tested samples with an aluminium shear-key Slot and screws installed in a row (spline joint) in the same samples, obtained from the publication by D. Cassagrande [1].

The load values and deformations are reported per couple of screws. Initial slip of around .3 to .5 mm was observed as a gap between the SLOT connector and the CLT panel, but there was no initial slip in screwed joints. The number of screws was calculated to match the SLOT connector's strength and stiffness.

a *b* *c*

Fig. 3 General view: Slot key (a), X-fix key (b), and oak keys in the tested samples (c)
Рис. 3 Загальний вид алюмінієвої шпонки Slot (a), X-fix шпонка із шпонкового брусу ЛВЛ (b) та дубова шпонка яка використовувалась у дослідженні (c)



a *b* *c*

Fig. 4 Force-deformation diagram (a) for aluminium Slot shear-key connection (c) and spline joint with screws (b) based on data [1].

Рис. 4 Криві навантаження-деформація (a) для з’єднань з алюмінієвою шпонкою Slot (c) та для з’єднань з накладками та гвинтами (b) на основі експериментальних даних [1].

DESIGN APPROACH TO CALCULATING SHEAR-KEY CONNECTORS

The characteristic values of load-bearing capacities for the SLOT connector calculated according to equation (2.1) are proposed in ETA-19/0167 [8], where t_e is penetration depth which equal 60 mm -.5*t_{gap} (t_{gap}≤5mm) and b_{ef} is the effective connector depth. b_{ef} = b = 89 mm for LVL and glulam, b_{ef} = Σd0 + .1* (b-Σd0) for CLT, where Σd0 is accumulated layer thickness of CLT elements within width b parallel to shear force $F_{v,Ed}$.

$$F_{v,Rk} = k_{al} \cdot b_{ef} \cdot f_{c,0,k} \cdot \left(\sqrt{t_{gap}^2 + 2\cdot(t_e - 5mm)^2 + 2\cdot(t_e - 5mm)^2} - 2\cdot(t_e - 5mm) \right) \quad (1)$$

$$k_{al} = \begin{cases} 1 & for\ a_1 \geq 480mm\ and\ a_{3,t} \geq 480mm \\ 1-0{,}001\cdot\left(480-\min\{a_1; a_{3,t}\}\right) & for\ a_1 480 < mm\ and\ a_{3,t} < 480mm \end{cases} \quad (2)$$

Slip module per Rothoblaas Slot connector according to ETA 19/0167 [8]:

$$K_{ser} = \frac{\rho_k}{20} kN/mm \qquad \text{CLT or softwood LVL} \quad (3)$$

$$K_{ser} = \frac{\rho_k}{15} kN/mm \qquad \text{hardwood LVL or GLT} \quad (4)$$

According to the USSR norms [4, 5], reference bearing capacity in kN is calculated as follows:

$$F_{v,Rk} = 0{,}625\cdot\delta\cdot b \quad (5)$$

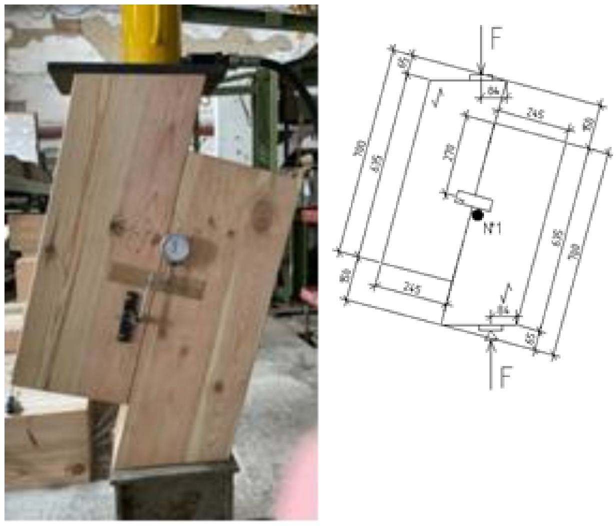
where:

δ is plate thickness with the recommended value of 12 mm and b is the connector width.

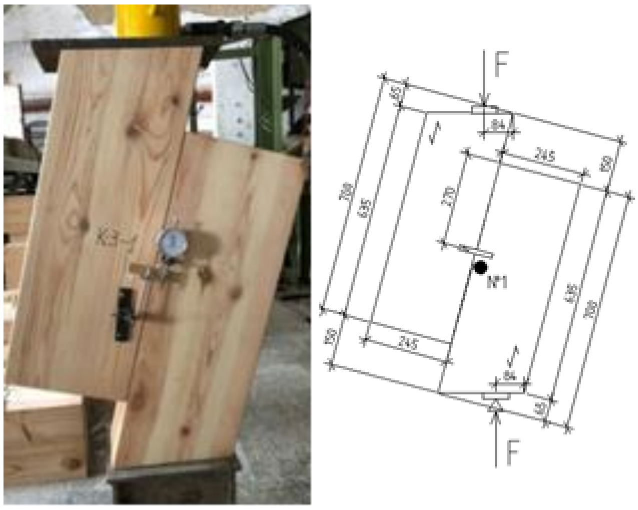
The recommended hardwood shear plates width is 4.5–5*δ, which corresponds to t_e value of 2.25–2.5 and which is very similar to the conclusions published by T. Schmidt and H.J. Blass [3, 10], who tested a group of specimen series with different depth penetration te. When te exceeds 2δ, the bearing capacity does not increase.

EXPERIMENTAL PROGRAMME. SPECIMEN GEOMETRIES AND TEST SETUPS

The shear tests were carried out to evaluate the shear resistance of CLT-to-CLT oak timber plates connections or shear-key connectors, analogous to aluminium Slot shear-key connector manufactured by Rothoblaas. The connection between two adjacent parallel panels follows the configurations in Fig. 5.



a



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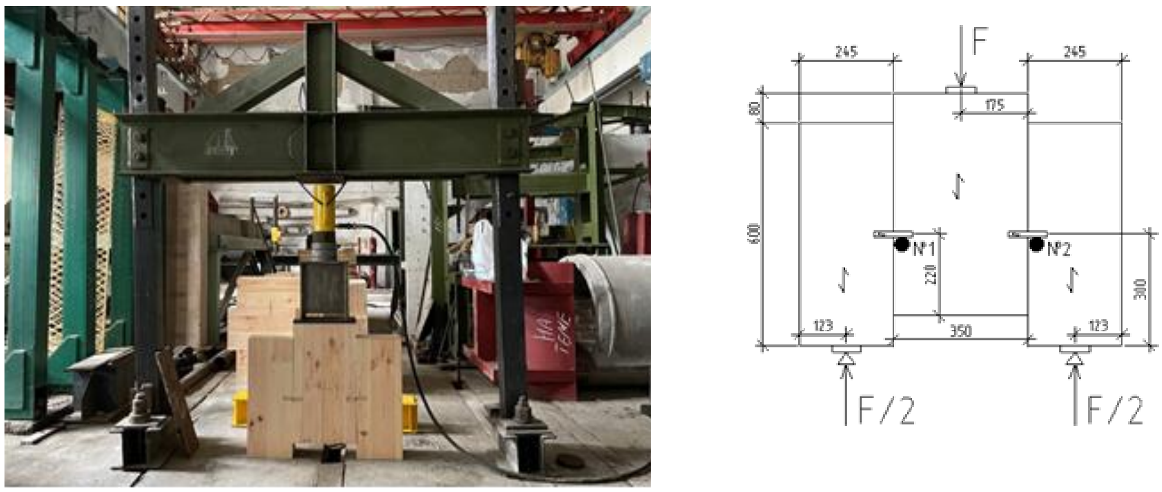

c

Fig. 5 Testing diagrams and geometry of the tested specimens with the shear-key oak connector: *a* - specimen series K-1; *b* - specimen series K-3; *c* - specimen series K-4; Photo by A.Bidakov

Рис. 5 Схема випробувань та геометричні параметри зразків з дубовими шпонками *а* – зразки серії K-1; *b* - зразки серії K-3; *c* - зразки серії K-4; Автор фото А.Бідаков

This solution avoids the cuts needed for lap or spline joints, which are easily manufacturable on the factory production line, but challenging to obtain on-site. The experimental configuration consists of two parts, 245mm×700mm in size, joined with a shear-key connector, as shown in Fig. 5 (a, b) as the single-shear configuration. Also, the considered three-partite double-shear K-4 configuration grants a symmetrical application of the vertical load, see Fig. 5 (c). The authors tested three different configurations, or series, each one within five iterations. Therefore, the total number of conducted tests was 3×5=15. The configurations differ by the size of shear-key oak connector and the number of shear lines in the specimen series. Tested CLT panel layouts provided the accepted thicknesses of 140 mm (40 + 20 + 20 + 20 + 40). Table 1 shows the details of the tested specimen series.

Table 1 Tested configurations details
Табл. 1 Параметри випробуваних зразків

Label	CLT thickness, mm	CLT layouts, mm	Timber plate geometry, mm	Number of shear surfaces	Number of specimens
K-1	140	40-20-20-20-40	40*120*200	1	5
K-3	140	40-20-20-20-40	20*120*100	1	5
K-4	140	40-20-20-20-40	20*120*100	2	5

The tested 140 mm thick CLT elements were produced by the Ukrainian company Rezult, ETA-21/0914 [7]. The oak shear-key connectors had a planed, smooth surface, without any visual defects such as cracks, splits or cavities. The shear-key connectors were installed in milled grooves to a depth of 120 mm, without tolerance for the dowel thickness.

The K-1 and K-3 series of samples had undercut support elements so that the sample incline was approximately 14˚. In this case, the support centres coincided with the vertical axis passing through the shear-key centre in the samples. The oak shear-keys were located in the middle along the vertical axis of the sample, see Fig. 5 (a, b). The K-4 series of samples had the shear-keys in the middle of the vertical section of the joint. All the samples were loaded until the shear-keys began to fail

The load was applied with a constant load rate of .1 mm/s and according to EN26891 [9] the failure occurred within 300 seconds. The relative slip between the two CLT parts near the shear-key location was measured by a 250 kN load cell. A dial gauge was used to register deformations.

RESULTS & DISCUSSION

The results obtained from testing SLOT connector joints and the screwed connections are presented in Table 2. The load-deformation diagrams for tested single-shear specimen series K-1-1…K-1-5 (thick shear-key) and tests series K-3-1…K-3-5 (thin shear-key) are shown on Fig. 6. Similar diagrams are shown on Fig. 7 for tested double-shear specimen series K-4-1…K-4-5 with two thin oak shear-key connectors.

The curves of the tested oak connectors show an initial slip around .2–.4 mm due to the imperfections and a small gap between the connector and the grooves surfaces of CLT panels' parts. Observations confirmed the oak shear-key elastic behavior and, additionally, wooden laminations failure parallel to the load direction, which was also observed for LVL connectors in tests performed by Schmidt and Blass [3, 10] and in the tests with aluminum SLOT shear-key performed by D. Casagrande [1, 2].

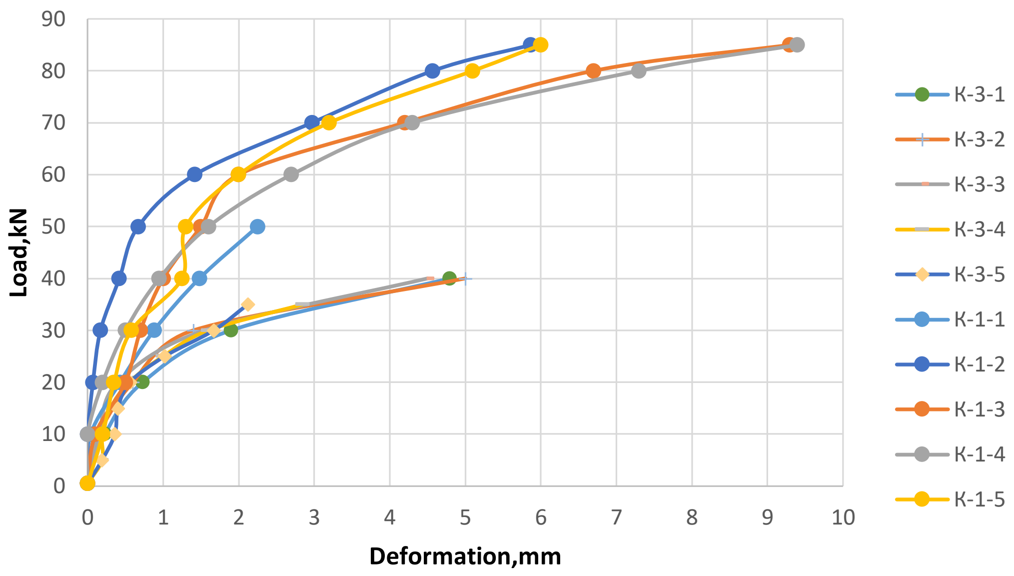

Fig. 6 Load-deformation curves of tested series K-1 and K-3 single-shear specimens

Рис. 6 Криві навантаження-деформація випробуваних зразків з одним стиком та однією шпонкою серій К-1 та К-3

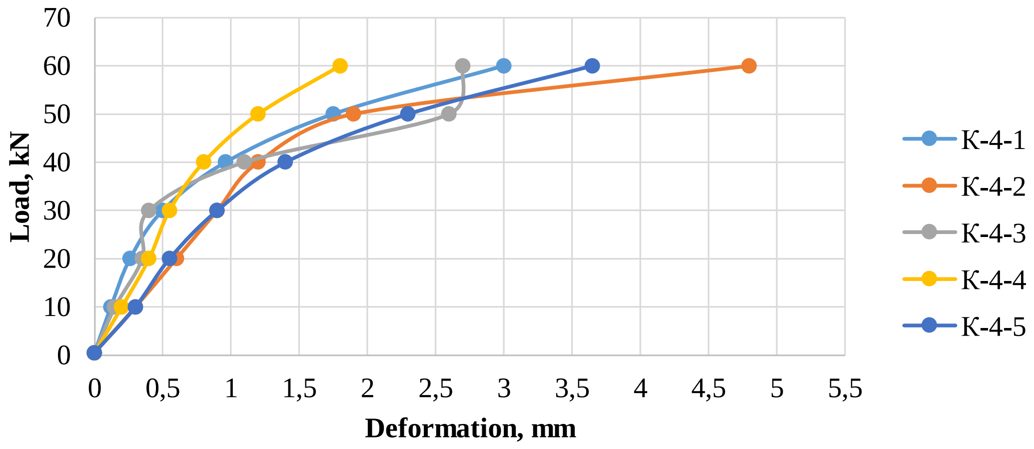

Fig. 7 Load-deformation curves of tested series K-4 double-shear specimens

Рис. 7 Криві навантаження-деформація випробуваних зразків з двома стиками та двома шпонками серії К-4

Table 2 Test results of series K-1, K-3, and K-4 joints

Таблиця 2 Результати випробувань з'єднань серій зразків К-1, К-3 та К-4

Label	Average value, F_{max}, kN	Average value, max. deformation, mm	SD of F_{max}	COV of F_{max}, %
K-1	87	6,81	4,29	4,93
K-3	45,22	3,85	5,41	11,96
K-4	68,8	4,11	0,46	0,7

Fig. 8. Failure mode in tested specimens:
a-deformation types for thick oak shear-key connector (series K-1);
b-deformation types for thin oak shear-key connector (series K-3);
c-deformations of thin oak shear-key connector (series K-4) in double-shear conditions
Photo by A.Bidakov

Рис. 8. Види руйнувань випробуваних з’єднань зі шпонками:
а - типи деформацій для масивної (товстої) дубової шпонки (серія К-1);
б - типи деформацій для тонкої дубової шпонки (серія К-3);
в - деформації тонкої дубової шпонки (серія К-4) в умовах подвійного зсуву.
Автор фото А.Бідаков

The failure modes for the joints with oak shearkey connectors are shown in Fig. 8, with the observed typical failure of timber near the shear-line (Fig. 6a), i. e. compressed along the grain direction timber and bent oak shear-key. In both failure modes, a rigid body rotation with no residual plastic deformations of the connector was observed.

The test procedure and the evaluation were based on DIN EN26891 [9]. Both the ultimate load $F_{V,test}$ and the stiffness k_s per connector were determined. The stiffness was determined in the 10% to 40% range of the ultimate load in the linear-elastic range.

$$k_s = K_{ser} = \frac{0,4 \cdot F\max - 0,1 \cdot F\max}{\upsilon_{04} - \upsilon_{01}} \qquad (6)$$

The low deformation of shear-key connections proves their significant advantage compared to screws, nails, pins, and bolts. Intensified deformation was observed along the line two connected CLT panels due to compression in the grain direction of the CLT panel and perpendicular to the grain of the hardwood in the shear-key itself, see Table 3 for each series of the tested specimen.

Comparative analysis diagram of CLT-panel shear-key connector slip module in shear in-plane tests with marked min/max values and mean value is presented in Fig. 9.

The load-bearing capacity of the tested K-1 series shear-keys is greater than that of the Slot aluminium key due to their greater width and length, but the character of the deformation is the same, as shown in Fig. 10.

According to equation (1), the characteristic strength $F_{v,Rk}$ equals 40.57 kN for the aluminium Slot connector in the 90 mm (24-42-24) CLT panel and 122.96kN for the 200*120*40mm oak shear-key connector in the 140 mm (40-20-20-20-40) CLT panel. Shear-key joints are versatile and they can minimize ductility and deformation of both the connections between CLT panels and between CLT and beams or columns made of glued laminated timber that need to be included in the joint work.

Table 3 Slip module $k_{s,connector}$ for joint with dowel-type fasteners per shear plane in in-plane tests of the series K-1, K-3, and K-4 specimens

Табл. 3 Модуль ковзання $k_{s,connector}$ для нагельних з’єднань на один стик зсуву при випробуваннях у площині панелі для зразків серій K-1, K-3 and K-4

Number of specimen	K-1- k_s, kN/mm	K-3- k_s, kN/mm	K-4- k_s, kN/mm
1	24.6	24.5	57.72
2	99.12	13.7	33.4
3	34.37	11.23	73.22
4	40.16	45.3	54.97
5	34.57	43.05	34.06

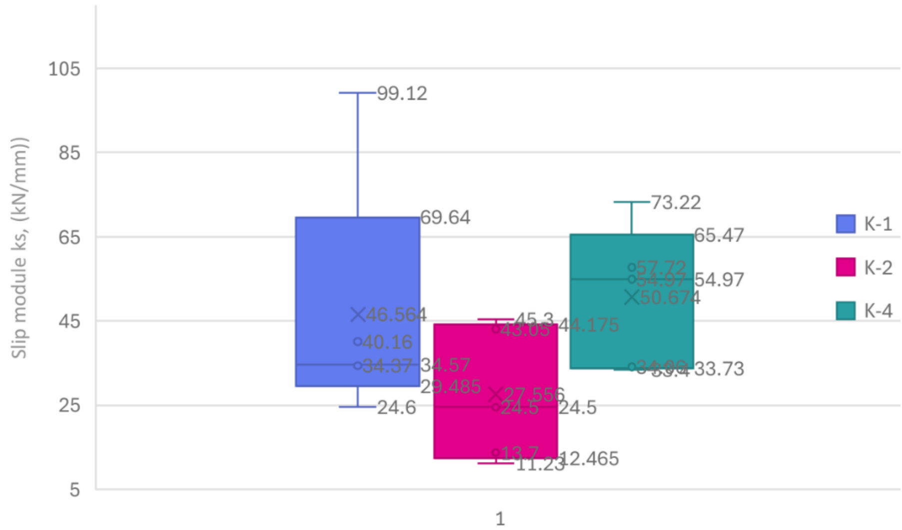

Fig. 9 Slip module values analysis of specimens subjected to shear testing.

Рис. 9 Аналіз величин модуля ковзання випробуваних серій зразків з дубовими шпонками при випробуваннях на зсув

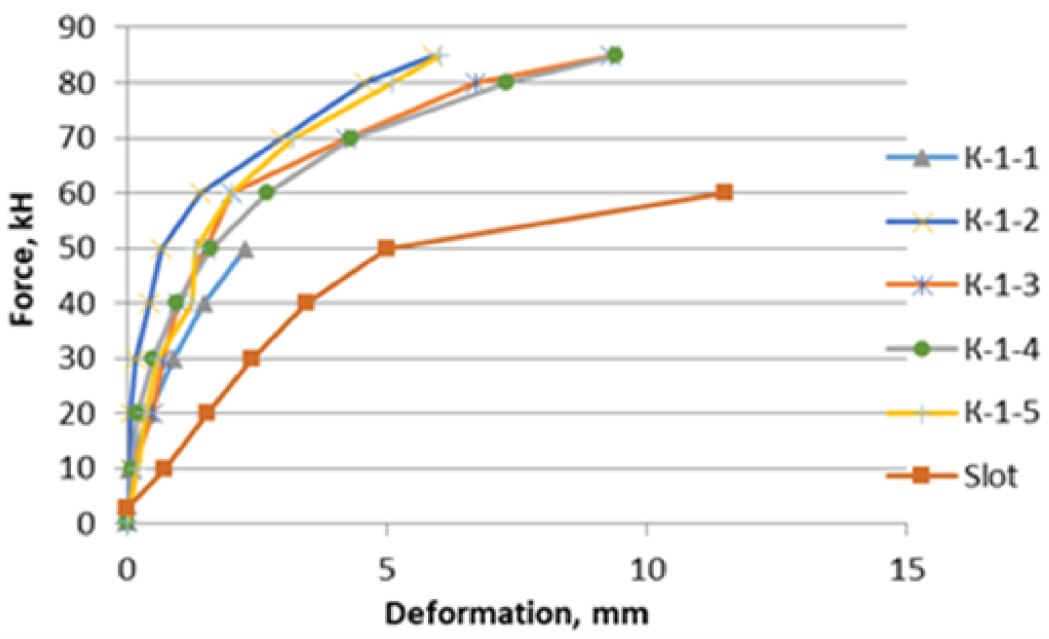

Fig. 10 Load-deformation curves of tested single-shear specimens, series K-1 and Slot (by Casagrande et. al. [1])

Рис. 10 Криві навантаження-деформація випробуваних зразків з одним стиком та однією шпонкою серій К-1 та Slot (by Casagrande at. all [1])

CONCLUSIONS

This paper analyses mechanical behaviour of two types of stiff shear-key connectors made from oak and used in CLT structure joints. Static tests were carried out on 3 specimen series with one and two shear lines and yielded values of stiffness and strength, which were additionally compared with similar data for the aluminium SLOT connectors and screw spline joints, described in other publications.

The test results of oak shear-key connectors in CLT panels' shear joints showed that their strength and deformability values belong to the same range as the values for the SLOT aluminium shear-key manufactured by Rothoblaas. The the shear-key connectors at all the loading stages are characterized by a close-to-linear dependence of the force F/Fmax to deformation d/dmax ratios. The efficiency of shear-key connector joints is evident and extremely promising in comparison with screw joints, since one SLOT aluminium shear-key is equivalent to 28 screws (HBS8*100) in a half-joint joint and to 114 screws (HBS6*70) in a joint with an overlay [1]. The work of the aluminium shear-key and the thick oak shear-key is almost identical, with the oak key being twice cheaper, which is crucial for the Ukrainian market. K-1 series shear-key connectors are wider and longer, which accordingly increases their load-bearing capacity and reduces the connection flexibility in comparison with the one-size aluminium shear-key connectors.

Today, the prospects of shear-key connections application and demand for them are evident in the construction of CLT panel houses, especially in terms of the building frames' rigidity, calculated as 1/1000 of the building height for horizontal displacements. Easy installation of shear-keys in pre-milled or made in-situ grooves make this solution widely applicable. This research is continued to combine the work of glued laminated timber columns and beams with CLT diaphragm walls in the building frame.

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АНАЛІЗ РОБОТИ НА ЗСУВ З'ЄДНАНЬ ЗІ ШПОНКАМИ З ДЕРЕВЕНИ ТВЕРДИХ ПОРІД У СТИКАХ СТІН З ПКД ПАНЕЛЕЙ

Андрій БІДАКОВ;
Оксана ПУСТОВОЙТОВА;
Вячеслав КОСМАЧЕВСЬКИЙ;
Юрій КУЗУБ

Анотація. Розробка багатоповерхового дерев'яного будівництва вимагає контролю та мінімізації деформацій як елементів каркаса будівлі, так і їх з'єднань. Це особливо важливо для будівель з CLT-панелей або ПКД панелей, коли оптимізація каркаса будівлі та мінімізація витрат матеріалів зводиться до будівництва частин стінової панелі над віконними та дверними отворами у вигляді окремих деталей. Також поділ ПКД панелей на дрібні фрагменти або деталі каркасу часто проводиться для спрощення логістики чи зменшення залишків матеріалу при розкрої великої плити у виробництві. Така деталізація каркасу вимагає досягнення монолітного з'єднання відправних марок ПКД панелей, що вимагає великої кількості гвинтів, що є надзвичайно дорогим, особливо для країн Східної Європи. Деформативність з'єднань дерев'яних конструкцій мінімальна в клейових з'єднаннях та з'єднаннях на вклеєних стрижнях. Аналіз жорсткості та міцності з'єднань між ПКД панелями на пластинчастих конекторах чи шпонках з деревини твердих листвяних порід і результати випробувань, розглянуті в цій публікації, доводять ефективність та перспективність цього типу з'єднання. Це особливо сьогодні актуально при використанні сучасних методів різання деталей каркаса з високою розмірною точністю на автоматизованих лініях різання, яке відбувається у відповідності до завантаженої моделі каркасу будівлі. Також шпонкові з'єднання можуть використовуватись у стиках колон чи балок з ПКД панелями для забезпечення сумісної роботи те економії великої кількості нагельних з'єднувальних елементів. Проведені експериментальні дослідження виконувались з урахуваннях аналогічних досліджень в інших постановках європейських дослідників і порівнювались з отримані результати (Україна).

У публікації представлені результати випробувань, проведених з дубовими шпонко-вими у стиках CLT-панелей, та порівнюються з результатами аналогічних досліджень з використанням алюмінієвих шпонкових з'єднань та з'єднань з великою кількістю гвинтів у з'єднаннях з накладками. Аналіз деформаційної поведінки з'єднань у каркасах багатоповерхових будівель з CLT-панелей вимагає особливої уваги та пошуку нових рішень для з'єднань та їх компонентів. Наразі шпонкові з'єднання різних виробників пропонуються з різними геометричними варіаціями, що спрощують їх монтаж під час складання каркаса будівлі, а іноді навіть дозволяють затягувати з'єднувані компоненти за допомогою клиноподібних поверхонь.

Ключові слова: стінові панелі; поперечно-клеєна деревина; шпонкові з'єднання; зсув з'єднань; жорсткість стиків.

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