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Development of Prefabricated Timber-Concrete Composite Floors

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Abstract: Timber-concrete composite structures are coming to be very important in housing sector. They have many advantages compared to traditional timber floors and are widely used as an effective method for refurbishment of existing timber floors. Current research at CTU (Czech Technical University) is focused on industrial production of prefabricated timber-concrete panels and their easy and quick assembly, in order to reduce the total cost of production, transport and assembly. A new shear connector was developed for those purposes. It is a punched metal plate fastener with double-sided teeth and omitted area nearby contact of timber and concrete. Direct shear tests were performed on four series of punched metal plate fasteners with different geometrical properties. Results of these tests and determination of slip modules K_{ser} and K_u is presented in this paper.

Key words: Timber-concrete, composite structures, tests.

1. Introduction

Timber-concrete composite structures are becoming very important in the housing sector. They have many advantages compared to traditional timber floors and are widely used as an effective method for refurbishment of existing timber floors. Due to the many benefits they are now being used more in new multi-story timber framed houses.

Timber-concrete floors have higher stiffness and load bearing capacity in comparison with traditional systems. The performance as regards vibrations, noise transmission is also better. Concrete slab is an efficient barrier against fire propagation. It brings the benefit of thermal mass, which can be used to help regulate the internal temperature in the building [1].

The fire resistance of timber-concrete composite floors is mainly influenced by the timber and the connectors [2]. The temperature inside the timber members depends particularly on the cross-sectional dimensions, density and moisture content of wood and on the fire load and temperature development during the fire. The temperature development in the place of the shear connection can be governed by the cross-sectional dimensions, particularly by the width [3]. When using those types of shear connectors such nail plates or special types, their position in relation to fire exposure is very important too.

In the Czech Republic, it is possible to see an increased interest in the construction of timber buildings in recent years. Constantly debated topic of sustainable development is very helpful, but also the gradual removing of prejudices and the desire to return to these once-traditional materials is important too. Increased productivity is evident particularly in implementation of family houses, where the number of implementations during last year is doubled in comparison with the situation five years ago. Continued growth is expected. A little bit worse situation is in implementation of multi-storey residential buildings and amenities. To some extent, this may not only be caused by the strict fire safety regulations, but also not so good timber properties in terms of serviceability limit states and acoustics, which is crucial for multi-story building design. There is a big interest to enhance this kind of

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structures in our country. One of the possibilities to solve above-mentioned constraints is the usage of timber-concrete composites primarily for floor structures. Using these types of structure is rare in The Czech Republic. They primarily are used for refurbishment and strengthening of floor structures in historical buildings. Dowel type fasteners for shear connection and “wet” process of casting concrete slabs are mostly used.

The ongoing research at CTU (Czech Technical University) deals in a complex way with the problems of timber-concrete composite floor structures. The aim of this research is to determine design models for timber-concrete composite beams that are applicable for computer simulations as well as for hand calculations. The biggest interest in research is focused on the development of prefabricated composite floor element thanks to advantages of prefabrication. An important part of the research was to design a new mechanical shear connector on the basis of punched metal plate fasteners.

2. Technical Solution Development

Increasing competitiveness of timber structure producers in our region is major reason for developing of a new timber-concrete element. Even for multi-story buildings (higher than 3 stories) dry assembly is very important for successful application on the market. Thus, prefabricated variation with elimination of wet processes has been developed. For higher buildings, new and more strict requirements appear such a fire resistance of structures, higher stiffness and rigidity of floor structures and acoustic performance of separating structures. All abovementioned factors should take into account economical and thus fast production, transport and assembling.

For these reasons, the emphasis is focused on usage of commonly available materials and products in our region or products which can be easily and inexpensively manufactured. Concrete improves fire resistance, stiffness and rigidity of load-bearing structures and its application in timber-concrete composite sections can help in negotiating with the authorities granting building permits. Timber and concrete are commonly used materials in our region and thus development has focused on shear connection between timber and concrete and technology used for shear connector assembly. To ensure low cost on production, neither gluing processes nor adjustments of timber beams like notches, dimples or holes have been willed.

Development of a new type of prefabricated composite timber-concrete elements (primarily for floor slabs) has been focused on improving of common punched metal plates placed between a pair of timber beams in whole length at once.

Two technology procedures can be used for achievement of composite structure, pouring fresh concrete mixture in a factory over semi-prefabricated timber beams with installed shear connectors or concreting shear connectors into a slab and after hardening of concrete assembling of timber beams. In first case, caution with water cement ratio and removable formwork are needed. In second case, a special assembling machine has to be used.

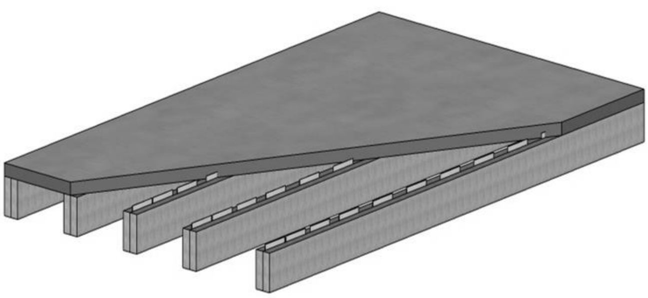


Fig. 1 Prototype of prefabricated timber-concrete panel—visualization and photo of real structure.

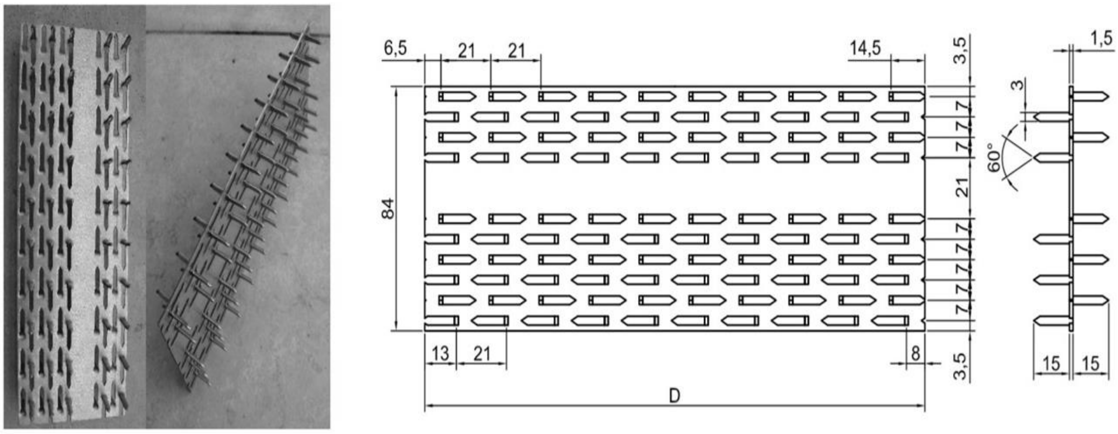


Fig. 2 Prototype of double-sided nail plate and manufacturing drawing with dimensions.

2.1 Shear Connector

For connecting timber and concrete to a composite structure, a modification of common punched metal plate fastener was chosen. Extensive research was performed at University of Delft [4], Karlsruhe [5] and Stuttgart [6] where both different modifications and positions of punched metal plates were investigated. Results of all these researches and developments were considered for improving a common nail plate and thanks to collaboration with a Czech manufacturer of metal fasteners for timber structures BOVA s.r.o., an innovative punched metal plate fastener has been developed.

A first prototype for first two series of direct shear tests was manufactured. It is a double-sided punched metal plate fastener made of hot-dip galvanized 1.5 mm thin steel sheet with zinc coat S280GD+Z275. Dimensions of the plate are 84 $\times D$ mm, where D is a length parameter and can be produced in multiple of 105 mm. Teeth are punched in four rows—two rows on each side, followed by a continuous surface formed by omitting three rows of teeth, followed by another six rows of teeth—three rows on each side. The axial distance of edge row is 3.5 mm and 7.0 mm between rows. Teeth are 3 mm wide, 15 mm long and ended with 60° spikes. The mass of steel plate between two consecutive teeth in one row is about 9 mm. Innovative shear connector is protected by an application of utility model. Manufacturing drawing and a photo of double sided nail plate is shown in Fig. 2.

3. Experimental Program

3.1 Test Specimens

First two series “A” and “B” of timber-concrete samples using double-sided punched metal plate fastener were experimentally tested for describing mechanical behavior of shear connectors and determining slip moduli for simplified design methods given in Eurocode 5.

Two KVH profiles 60 × 240 mm, 400 mm long are made of timber strength class C24 according to EN338, visually graded according to EN1611-1. As their surfaces are planned and edges are trimmed, the quality corresponds with standard used elements in traditional timber structures based on light timber frames.

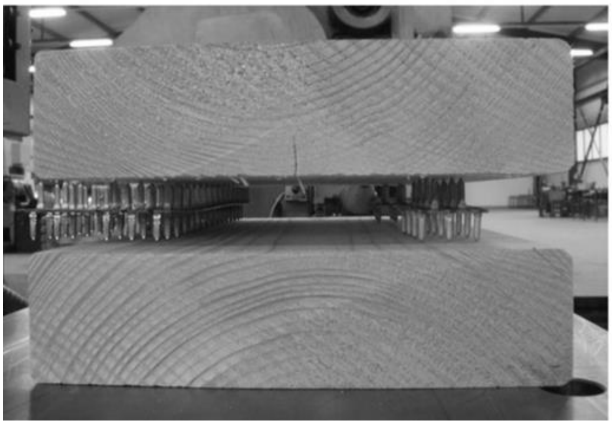
Timber density and moisture content were measured before shear tests and average values were about 425 kg/m^3 with 11% moisture content. Summary of measured properties is shown in Table 1.

Two timber elements are jointed together with innovative shear connector on the upper edge (where the timber-concrete contact is) and one small standard double-sided punched metal plate 35 × 84 mm inserted nearby the bottom edge. This small plate is inserted for securing timber beams position during pressing together. Concrete desk is made of handmade concrete mixture and reinforced with steel welded mesh with 6

Table 1 Timber and concrete measured properties.

Test series		Timber properties				Concrete properties		
		Density (kg/m^2)	Moisture content (%)	Strength class*	Age (days)	Density (kg/m^2)	$f_{c,cube,exp}$ (MPa)	$f_{c,cube,k}$** (MPa)
A	Range	399 522	9.2 12.5			1,996 2,118	21.8 27.4	
	Average	436	10.8	C24	64	2,047	24.6	19.31
	σ	35	1.1			43	2.4	
B	Range	390 447	10.4 11.6			1,955 2,049	21.9 25.4	
	Average	419	11.1	C24	48	20.14	24.3	21.25
	σ	15	0.6			33	1.3	

* according to EN 338; * according to EN 14358.



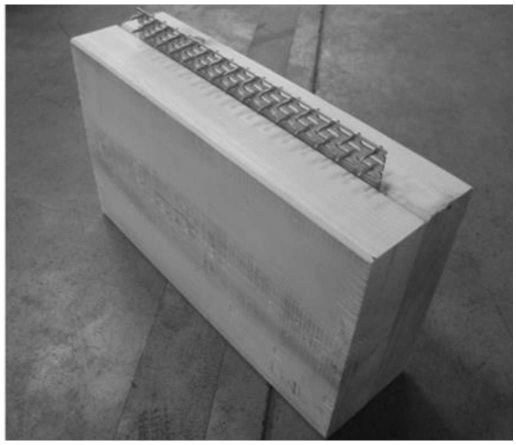


Fig. 3 Punching nail plates between a pair of timber beams, preparing of test specimens.

mm rods and 150 mm distance of mesh. Concrete mixture was made from a dry concrete mix with the addition of appropriate amounts of water.

Then the mixture was poured into handmade formworks and let to harden. Thickness of desk is 80 mm and dimensions are 600 × 400 mm. This unusual solution was chosen to ensure protection of an intellectual property in the beginning of research and will not be realized anymore. Due to significant human factor, corresponding to concrete making, cube compressive strength was checked at five small cubes of each series according to EN 12390-3. Expected cube compressive strength was about 25 MPa and, as shown in Table 1, average reached value was about 24.5 MPa. But characteristic value calculated according to EN 14358 was just about 20 MPa. For further calculation and numerical modeling, strength class C16/20 will be taken into account.

The difference between both series is just in length of nail plate. It was 210 mm long for “A” series and 315 mm for “B” series (it means one and a half times longer). Different length was chosen for experimental investigation of relationship between geometrical properties and failure mode in variable load levels and gaining reference data for refining numerical 3D FEM model. Also practical aspects of pressing double-sided punched metal plate fasteners of different length were verified. The longer plate is more difficult to punch between timber beams due to the need of higher pressing force and also is more complicated to secure the correct beams position.

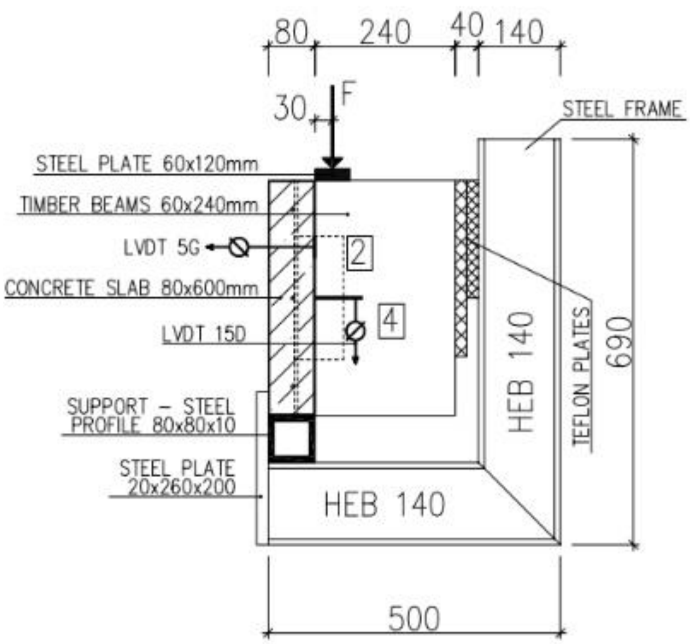
As we verified during pressing the metal plates to timber beams, it is better to use one small double-sided punched metal plate nearby the bottom edge of the beams. This plate helps to secure optimal position of timber beams during pressing and avoiding splitting of timber beams. An illustrative photo of pressing is shown in Fig. 3.

3.2 Experiments

Because the pressing of punched metal plates on both sides to an optimal position would be very complicated, direct shear tests using an asymmetrical specimen were performed. This type of set-up was selected for the reason that the specimens are much easier to construct than the standard push-out tests specimens, where the concrete slab is on both sides. These specimens are also lighter, cheaper and faster assembled for experimental testing. Consideration of a disadvantage of an asymmetrical shear test set-up is important. Due to eccentricity of the shear force, an overturning moment will lead into a compressive force at the interface between timber and concrete, which increases the friction and thus improves mechanical behavior of the shear connectors [4, 7]. Geometrical and material properties of tested samples are given in previous chapter.

Shear test set-up is presented in Fig. 4. An asymmetrical specimen is placed on a special self-made anchoring steel frame inspired by testing device used for large experimental testing in Sweden [7]. Stability of specimen is secured by a sliding support at the top of the timber elements. The support is made of two Teflon plates; one is screwed to the steel frame, the second one to the timber. To ensure ideal sliding and to minimize friction, the Teflon plates were oiled.

The shear tests were carried out according to EN 26891, where also provisions for the determination of the connector slip moduli are given. The first sample of series "A" was loaded with parameters corresponding to estimated failure F_{est} = 50 kN. The real maximal reached shear force was about 36 kN and thus the loading scheme was modified to F_{est} = 40 kN. The tests were carried out within 15 min until the failure load was reached. Slip between concrete and timber was measured in the middle of the timber beams and on both sides using LVDT (linear voltage displacement transducers), type 15D. Timber-concrete layer opening was measured on both sides 100 mm from the upper edge of timber beams with LVDT 5G. All transducers were glued to timber surface. The tests were performed under a controlled force increment on hydraulic press with key points at $0.1\times F_{est}$, $0.4\times F_{est}$ and $0.7\times F_{est}$ and data retrieved with a frequency of 2 Hz. Load range of hydraulic press is 0-200 kN with an accuracy of 1%-2%.



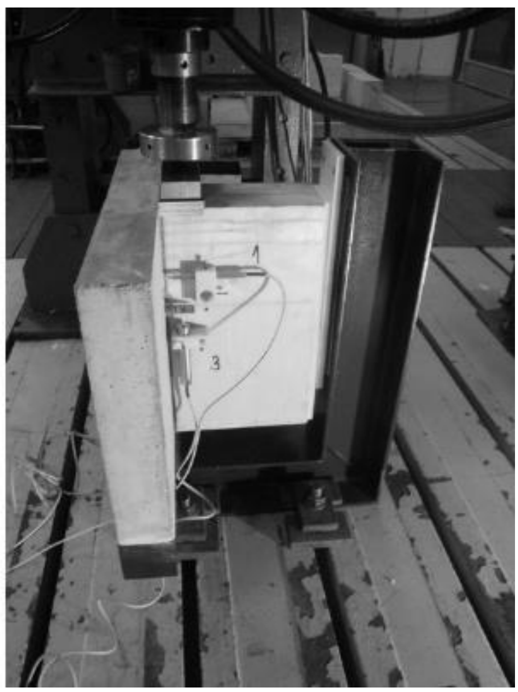


Fig. 4 Direct shear tests set-up.

Probable failure model of the samples could not be reliably deduced. One of the following failures was predicted: a shear failure of the timber beams; a shear failure of metal plate between holes of the first “timber” teeth row; plastic deformation of teeth in combination of embedment of timber holes; cutting of concrete slab and combinations of previous. Currently two series of five samples each were experimentally tested. As the results, dominant failure model observed was shear failure of punched metal plate in the plane intersecting the middle part of the first row of holes in timber beams area.

Twisting of first row of teeth punched into the timber with combination of plastic deformation of the area of first two rows of teeth and holes can be observed too. Small shear cracks occurred in some of the timber beams with lower density. As evident, just two rows of teeth and holes in timber area are deformed. No visible deformation or cracks at concrete slab and no significant deformations of concrete part of the steel plate were observed. This observation will help with rearrangement of teeth and their geometrical properties.

3.3 Results

As the shear connection is usually characterized by non-linear force-slip behavior, two different slip moduli are considered for simplified design purposes [4, 7]: K_{ser} for serviceability limit state and K_u for ultimate limit state design. The slip modulus K_{ser} corresponds to the secant value at 40% of the load-carrying capacity of the connection and is presented by K_{04} value. For the slip modulus K_u, the use of the secant modulus at 60% presented by K_{06} value is recommended. All calculated values are based on provisions according to EN 14358 and correspond to 5-percentile characteristic values.

Whereas steel failure is dominant, very similar behavior described by load-slip diagram can be observed in series “A”, except the sample “A3” and “B4”, where stiffer behavior was reached since some teeth in first row punched in timber were twisted of. As evident, there is a very low scatter of load-slip curves in series “A”, for longer plate in series “B” is higher scatter of load-slip curves in the range above $0.5F_{max}$. An average slip is about 5.5 mm in both series and failure force about 35 kN and 54 kN respectively. Average values of slip moduli and maximal force of both series are presented in Table 2. Although the metal plate in series “B” is one and a half times longer, only maximal shear force was reached with the ratio of 1.5.

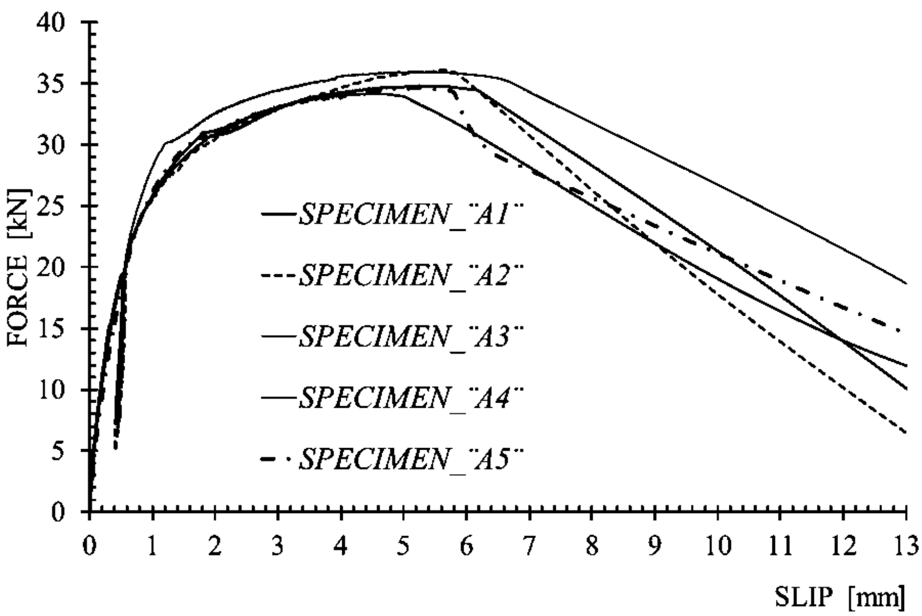


Fig. 5 Direct shear test results for “A” series.

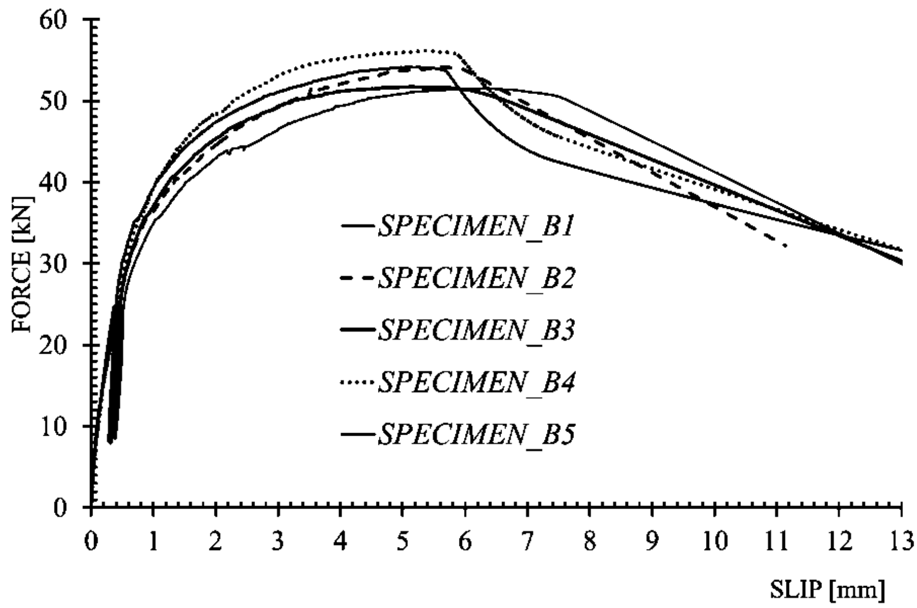


Fig. 6 Direct shear test results for "B" series.

Table 2 Slip moduli characteristic values.

	Test series	Slip modulus (kN/mm)				F_{max} (kN)	
		K_{04}		K_{06}			
A	Range	34.0	38.4	27.3	33.1	34.2	36.1
	Average	36.7		29.5		35.1	
	σ	1.5		2.0		0.8	
B	Range	43.1	56.7	37.0	56.0	51.6	56.2
	Average	51.0		48.1		53.6	
	σ	4.9		7.2		1.7	

Table 3 Slip moduli ratios.

		Slip moduli ratios: characteristic values*					
		Series "A"			Series "B"		
		K_{04}	K_{06}	K_{08}	K_{04}	K_{06}	K_{08}
Series "A"	K_{04}	1.00	1.32	3.79	0.83	1.02	2.38
	K_{06}	0.76	1.00	2.87	0.63	0.77	1.80
	K_{08}	0.26	0.35	1.00	0.22	0.27	0.63
Series "B"	K_{04}	1.20	1.59	4.56	1.00	1.22	2.86
	K_{06}	1.30	1.30	3.73	0.82	1.00	2.34
	K_{08}	1.59	0.56	1.59	0.35	0.43	1.00

* according to EN 14358.

As shown in Table 3, where all slip moduli ratios are calculated, no significant influence of longer metal plate was observed. Although the length of metal plate in series "B" is one and half times higher, the ratio of characteristic values K_{04} and K_{06} calculated according to EN 14358 is just 1.2 multiple and 1.3 multiple respectively. In comparison with material consumption, economic cost for manufacturing and difficulties related to pressing longer nail plate into timber beams, the nail plate of 210 mm length seems to be sufficient.

Therefore this nail plate will be used for further research and for comparison with 3D FEM model.

3.4 Preliminary Numerical Model

Preliminary numerical 3D FEM model of direct shear test has been created in ANSYS® WORKBENCH 13 software for comparison of FEM model solution and experimental behavior of innovative shear connector in timber-concrete composite structure. Orthotropic elasticity was used to design timber with material properties presented by Astley [8]. Concrete was designed as an isotropic material adequate to concrete strength class C16/20 and shear connector was modeled as non-linear steel with bilinear isotropic hardening. Contact regions were added on all concrete-steel and timber-steel surfaces. Friction was considered with the coefficients gained in Engineers Handbook. Model was loaded with force F = 20 kN that corresponds to $0.5F_{est}$ and behavior is comparable, but still overestimated due to timber elasticity.

Although the FEM model is just tentative and inaccurate, deformation of metal plate and zones of potential material failures are adequate. Refining of the model is a scope of future research. A revision of contact regions and friction coefficients is required as well as defining plasticity of timber and mesh optimization.

4. Future Research and Conclusion

Future research will be focused on precising the 3D FEM model and follow up the parametrical study. Results of this study will help to determine optimal geometrical and material properties of a final double-sided punched metal plate shear connector. Machinery for manufacturing of nail plates and assembling them into the composite elements will be developed in parallel.

Standard bending tests of large-scale elements are planned for verification of composite timber-concrete elements behavior. Analytical model of shear connection and simplified method for structure design as well as software utility should be done. All ongoing results and progresses obtained will be continuously presented in future papers and conferences.

Current research results of prefabricated timber-concrete composite floors are given in this paper. An innovative engineering solution and developed shear connector are also presented. Experimental program on two modifications of the shear connector was performed. Currently obtained results of direct shear tests are presented in load-slip diagrams and 5-percentile slip moduli characteristic values were calculated.

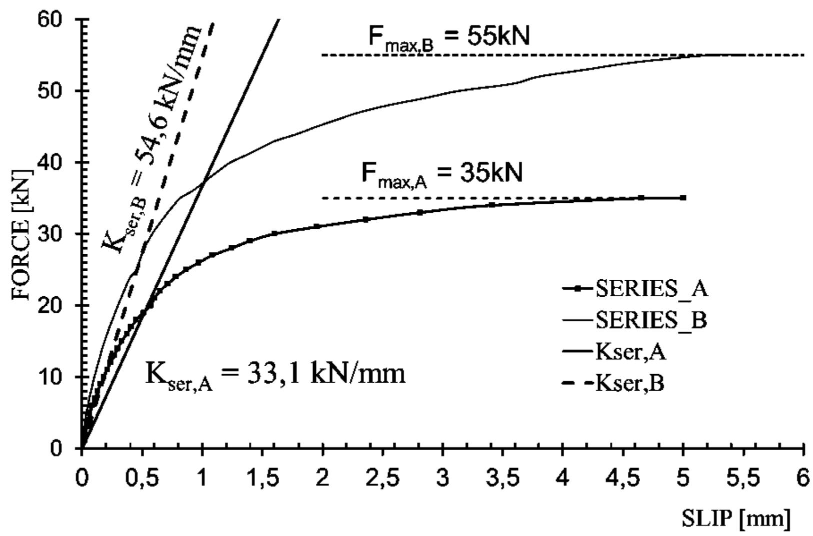


Fig. 7 Load-slip diagrams for both tested series and slip moduli characteristic values.

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