EXPERIMENTAL ANALYSIS OF COMPOSITE TIMBER-CONCRETE WALL ELEMENT

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Abstract
The authors present an experimental and theoretical study on a composite or hybrid element used in residential and agricultural buildings. The composite wall element consists of timber studs connected to a concrete plate by means of nail plate shear connectors. Experimental results are presented and compared with an analytical model for partial composite action. A good agreement is obtained between the analytical and experimental results. Also, some suggestions to improve the design of the composite element are discussed.

1 Introduction
Composite structures of different materials are frequently used in building and bridge construction, e.g. as floor and wall elements. In this paper, timber-concrete elements composed of thin concrete plates attached to timber studs by means of nail-plates as shear connectors, are discussed. These elements, usually prefabricated, were originally developed to be used in agricultural buildings as wall elements. With the concrete plate turned towards the inside of the building, it provides a durable surface against damage from the animals. The timber studs faced the other way form the basis for the sheathing of the building. These wall elements subjected to wind loads will bend with the concrete plate either in compression or in tension. In this study, only bending action will be considered. The interaction and response of the composite element with respect to axial loadings from the roof is the subject of another study.

These types of elements are also well suited for the use as floor structures in residential multi-storey timber buildings. With the concrete plate on top, the springeness, air- and structure-borne sound, damping and vibration characteristics will be significantly improved.

Due to the nail-plate shear connectors, partial composite action will develop and greatly enhance the bending strength and stiffness of the element. The function of the shear connectors is to prevent longitudinal slip between the sub-components and the transversal separation of them.

The fundamental equations of the theory for one-dimensional, linear elastic, partial composite action in beam and columns are well established. A literature review is given in Girhammar and Pan [1]. With respect to composite timber-concrete structures with different kinds of shear connectors, the following literature background can be given. Branco et al. [2]

performed shear tests on smooth round nails as shear connectors in timber-lightweight concrete specimens with plywood interlayers to determine the shear capacity and slip modulus of the nails. Brunner et al. [3] investigated a composite timber-concrete structure, where the wet concrete was poured onto the wet adhesive (epoxy based) on the timber beams. Bathon and Graf [4] tested the performance of a continuous steel mesh as the shear connection, inserted halfway into the glulam beam and halfway into the concrete slab. Bathon [5] analyzed different variations of the HBV-hybrid-rib-element (concrete-timber), suitable for commercial and residential housing. Deam et al. [6] investigated a semi-prefabricated system consisting of a plywood board acting as permanent formwork for the cast of in situ concrete slab and timber beams. The shear connection was provided by a timber notch-concrete plug system reinforced with lag screws. Deam et al. [7] tested a wide variety of shear connectors for laminated veneer lumber and concrete with and without an interlayer. It was concluded that the SFS screw was not significantly affected by an interlayer. Clouston et al. [8], tested a continuous steel mesh as a shear connection in composite timber-concrete elements. The shear connection showed ductile behaviour. Tajnik et al. [9] investigated the use of steel-fiber-reinforced concrete. As a result, the plate thickness could be reduced and the initial slip modulus of the shear connectors was increased. Girhammar tested nail-plates as shear connectors [10] in composite timber-concrete elements [11]. Further details on other previous work on timber-concrete composite structures, can be found in Yeoh et al. [12].
This work is based on the tests and analyses earlier conducted by Girhammar [13, 14]. Experimental results are compared with an analytical model for the serviceability and ultimate limit states.

2 Theoretical analysis

The model for the internal forces and moments, and stresses is shown in Fig. 1 for concrete in compression and concrete in tension, respectively. Due to a rather weak shear connection, the concrete plate is, on the conservative side, assumed to be cracked in both compression and tension. This means that the concrete plate is assigned only axial stiffness and no bending stiffness.

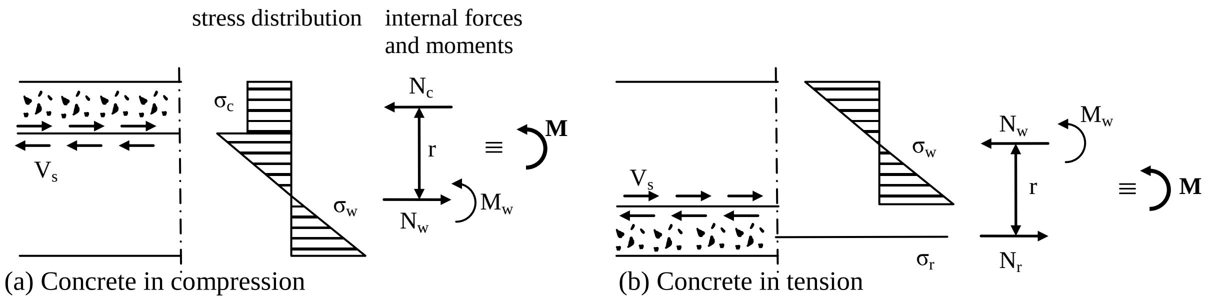


Figure 1. Model for stresses and internal actions.

According to Girhammar and Pan [1], the deflection (w), internal normal forces and moments, and slip forces per unit length can be expressed as

$$w_{\max} = \frac{PL^3}{48EI_\infty}\{1+\frac{12}{(\alpha L)^2}(\frac{EI_\infty}{EI_0}-1)[1-\frac{2}{\alpha L}\tanh(\tfrac{1}{2}\alpha L)]\} \quad (1)$$

$$N_c = \frac{L}{2r}(1-\frac{EI_0}{EI_\infty})[1-\frac{2}{\alpha L}\tanh(\tfrac{1}{2}\alpha L)]P = N_w \quad (2)$$

$$M_w = \frac{E_w I_w}{EI_0}\{1-(1-\frac{EI_0}{EI_\infty})[1-\frac{2}{\alpha L}\tanh(\tfrac{1}{2}\alpha L)]]\}P \quad (3)$$

$$V_s = (1-\frac{EI_0}{EI_\infty})[1-\frac{1}{\cosh(\tfrac{1}{2}\alpha L)}]\frac{P}{2r} \quad (4)$$

where

$$\alpha^2 = \frac{Kr^2}{EI_0(1-\frac{EI_0}{EI_\infty})} \quad (5)$$

$$EA_0 = E_c A_c + E_w A_w \quad ; \quad EA^2 = E_c A_c \times E_w A_w \quad (6)$$

$$EI_0 = E_w I_w \quad ; \quad EI_\infty = EI_0 + \frac{EA^2 r^2}{EA_0} \quad (8)$$

where K is the slip modulus, L the span length, r the distance between the centroids of the two sub-components, I_w the moment of inertia of the wooden beams, A_w and A_c the cross-sectional area of the wooden beams and the concrete plate, respectively. Using these forces and moments, the stresses can be obtained according to the Navier formulation. The failure modes are timber bending, nail-plate shear, concrete compression and rebar tension.

3 Experimental testing

3.1 Composite timber and concrete element

The wall element, Fig. 2, is a composite element that consists of a concrete plate (corresponding approximately to C40) and two or more timber beams (corresponding approximately to C40) fixed to each other by means of nail plates. The nail plates act as shear connectors and partial composite action will develop, and transversal separation will be prevented between the timber studs and concrete plate. In this study, only bending will be considered.

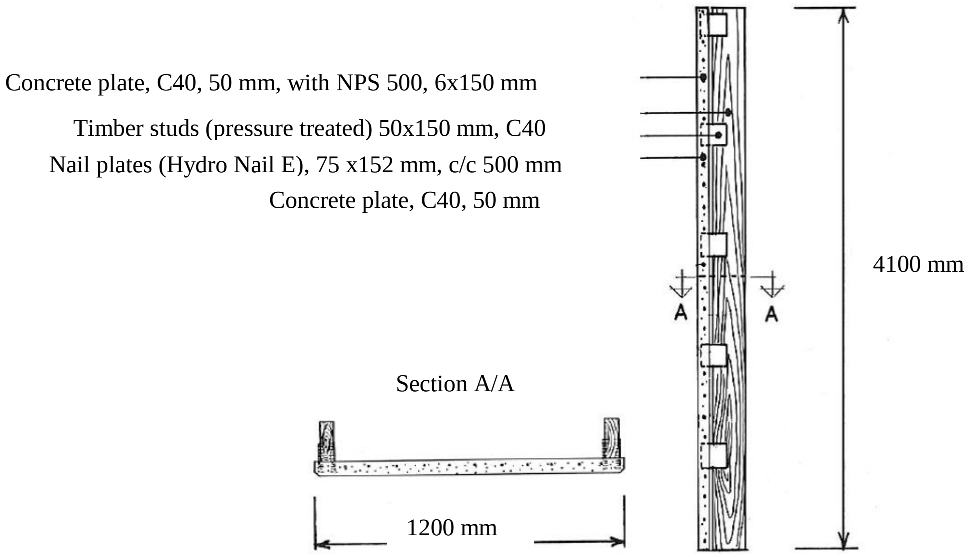


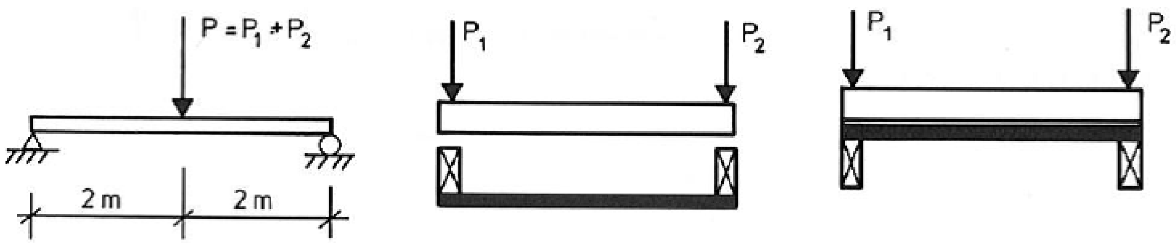
Figure 2. Schematic drawing of a part of the composite wall-element. NPS is the type of reinforcement used for the concrete plate, welded wire fabric.

The parameters for the composite element are as follows: EA_0 = 2316 MN; EA^2 = 0.337 (GN)^2; EI_0=293 kNm^2; EI_∞=1747 kNm^2.

The experiments include bending tests on simply supported composite elements with concrete in both compression and tension (Fig. 3b and c). The specimens are subjected to a mid-point load according to Fig. 3a. Also, shear tests on the nail-plates according to Fig. 4 were conducted. The purpose of the tests is to evaluate the strength and stiffness and the corresponding failure modes, and to verify the theoretical model.

3.2 Bending tests of the composite element

The load was applied by means of two load cylinders acting on each timber beam (P_1 and P_2) via a loading beam, Fig. 3. Two loading cases were studied, concrete plate in tension and in compression as defined in Fig. 3(b) and (c), respectively. The tests were performed under deformation control and, therefore, different load values P_1 and P_2, were obtained and no torsional deformations in the concrete plate occurred.



(a) Simply supported element (b) Concrete plate in compression (c) Concrete plate in tension

Figure 3. Bending tests of the composite wall element. (a) Loading case for the simply supported beam (b) Concrete plate in tension. (c) Concrete plate in compression.

3.3 Slip modulus

The timber beams were cut and loaded in a shear mode directly on the finished wall-element according to Fig. 4. The number of nail plates on the cut timber beam varied from 1 to 5 (together on both sides). The tests were conducted both in the "inner part" as well as at the end of the element (to evaluate the effect of end distance).

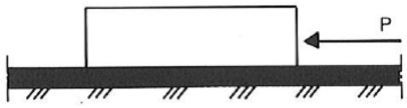


Figure 4. Shear experiments for evaluation of the slip modulus.

4 Experimental and theoretical results

4.1 Shear connector tests

The shear test results can be idealized as a bilinear load-slip relationship as shown in Fig. 5. The slip modulus in the elastic and strain-hardening stages was measured to K_e = 9 MPa and K_s = 1 MPa, respectively. Below, the experimental results for the composite element will be evaluated, both in the serviceability and ultimate limit states. In this paper, the elastic part of the curve is used to evaluate the service load conditions, and both the elastic and strain-hardening stages to evaluate the ultimate load conditions. The linear elastic theory described in Section 2 will be applied to the linear conditions in both stages; in the ultimate limit state this needs to be done in two steps, one for the elastic part and, then, added on one for the strain-hardening part.

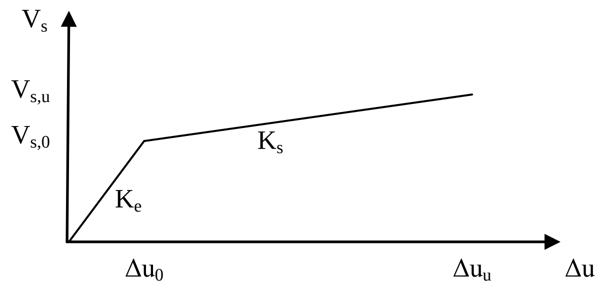


Figure 5. Idealized load-slip characteristics for the nail-plates.

4.2 Bending tests

As mentioned above, two orientations of the composite element will be used in the bending tests: (1) the concrete plate in compression; and (2) the concrete plate in tension according to Fig. 3. Three tests of each type were conducted. In addition to comparing the experimental and theoretical results for the composite beams with partial composite interaction (PCA), the extreme cases of full (FCA) and non-composite (NCA) action will also be evaluated and presented together with the experimental load-deflection curves.

The test results are shown in Fig. 6 and Fig. 7 in case of concrete in compression and tension, respectively. As can be seen, the different curves are reasonably close before failure, but near and after the failure, the scatter is rather high. As expected, the ductility is much larger in case of concrete in tension than for concrete in compression. The final failure of the component is consecutive failures of the two timber beams. In one test, splitting of the concrete corner near the end nail-plate occurred. Also, major cracking of the concrete plate is indicated in both figures.

The theoretical results with respect to non-, partial and full composite action are also included in Figs. 6 and 7. It is evident that the partial composite action theory predicts the strength and stiffness very well. It should be reminded that the theoretical model according to Section 2 is a conservative model, especially for the case of concrete in compression, which is evident from Fig. 6. The details of the test results are presented below.

4.2.1 Concrete plate in compression

From Fig. 6 it is observed that cracking of the concrete plate at the lower side occurs, even though it is on the compression side, for deflections in the interval of $w = 0.02 - 0.04$ m. This corresponds to applied loads giving tensile stresses in the concrete plate approximately equal to the tensile strength of the concrete (stadium I; the tensile strength is about 10 % of the compressive strength).

The composite element failed when first, one of the timber beams failed and then the other. The failure of the timber beam occurred with a loud sound followed by a sudden reduction in the load-bearing capacity according to Fig. 6. The load-carrying capacity is almost exhausted after the failure of the timber beams. The timber failure is more pronounced for concrete plate in compression than for concrete plate in tension. Usually, the bending failure of the timber beams is initiated in the region where defects (e.g. a knot) are dominant, on the tension side of the beam.

Table 1 shows the results from the theoretical analysis for the three cases under consideration, both with respect to service and ultimate loads. All failures were due to bending failure of timber beams. Only in the case of partial composite action, the concrete plate was non-cracked in the service load stage. Values in parentheses refer to the transition stage when the nail-plates leave the elastic stage to enter the strain-hardening stage. It is evident from Fig. 6 and Table 1 that there is good agreement between experimental and theoretical results (as mentioned on the conservative side) and that the composite action is significant and in between the extreme cases of full and non-composite action.

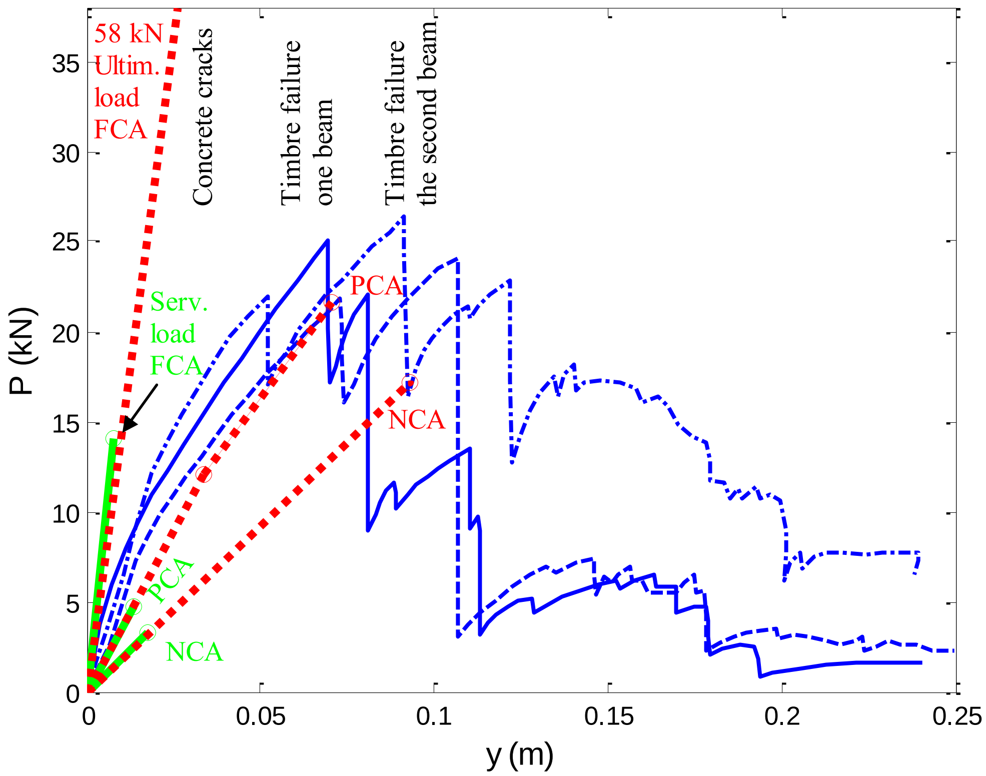


Figure 6. Load versus deflection for the concrete plate in compression. The solid, dashed and dashed-dotted lines represent three tests, A, B, and C, respectively. Dashed coloured lines correspond to the theoretical results: service load – green dashed line and ultimate load – red dashed line.

Condition	Service load [kN]	Deflection [m]	Failure mode	Ultimate load [kN]	Deflection [m]	Failure mode
Non-composite action	4.2	0.019	Timber (Cracked concr.)	17.2	0.078	Timber
Partial composite action	5.9	0.015	Timber (Non-cracked c.)	(13.0) 21.4	(0.033) 0.068	(Nail-plate) Timber
Full composite action	14.1	0.009	Timber (Cracked concr.)	57.8	0.037	Timber

Table 1. Results from theoretical calculations. Concrete plate in compression.

4.2 Concrete plate in tension

Fig. 7 shows the load-displacement curves for the case of concrete plate in tension. Cracking of the concrete plate occurs first when the tensile/bending strength of the concrete is reached (stadium I). Splitting of the concrete corners around the nail plates near the end takes place in these tests. After that, the timber beams fail, but the load-carrying capacity is essentially maintained for some additional deflection. This favourable ductile behaviour is due the yielding of the reinforcement bars. The failure in the timber beams is initiated by compression failure (crushing of the upper side of the beams). The final failure of the timber beams is due to failure on the tension side. Both the yielding of the rebars and crushing of the timber beams on the compression side contribute to the ductility of the composite element.

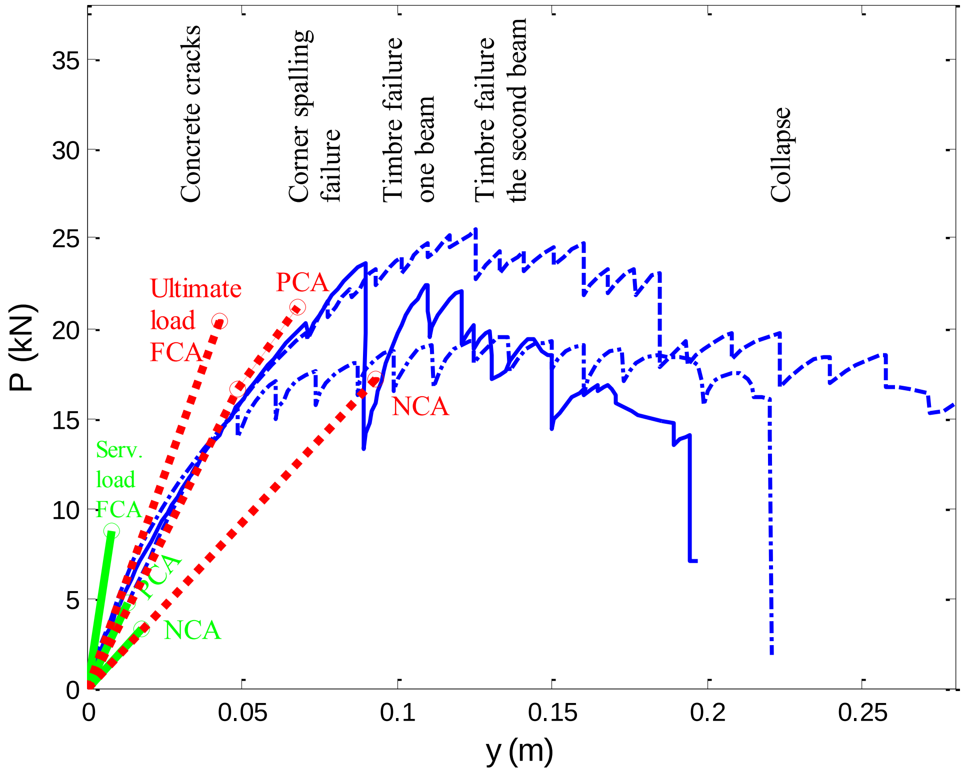


Figure 7. Load versus deflection for the concrete plate in tension. The solid, dashed and dashed-dotted lines represent three tests, A, B, and C, respectively. Dashed coloured lines correspond to the theoretical results: service load – green dashed line and ultimate load – red dashed line.

Table 2 shows the results from the theoretical analysis for the three cases under consideration, both with respect to service and ultimate loads. All failures were due to bending failure of timber beams, except in the case of full composite action, in which the yielding of the rebars was the failure mode. Due to this change of failure mode, the load-carrying capacity for full composite action was smaller than that for partial composite action as is evident from Table 2. It is also clear from Fig. 6 and 7 as well as Table 1 and 2 that the theoretical values are closer in case of concrete in tension than in compression, i.e. the model assuming zero bending stiffness for the concrete plate is closer to the real behaviour in the case of concrete in tension.

Condition	Service load [kN]	Deflection [m]	Failure mode	Ultimate load [kN]	Deflection [m]	Failure mode
Non-composite action	4.2	0.019	Timber (Cracked concr.)	17.2	0.078	Timber
Partial composite action	5.4	0.016	Timber (Cracked concr.)	(16.6) 21.2	(0.049) 0.068	(Nail-plate) Timber
Full composite action	7.2	0.015	Timber (Cracked concr.)	20.4	0.043	Rebar

Table 2. Results from theoretical calculations. Concrete plate in tension.

5 Discussion and Conclusion

The experimental and analytical results show very good agreement. If bending stiffness of the concrete plate is included in the model, more accurate results would be obtained in the case of concrete in compression.

It is somewhat surprising that the load-bearing capacity of the composite element is of the same order for both cases of concrete in compression and in tension. It suggests that the composite element can be further improved and optimized. It is obvious that the slip modulus should be increased by using closer spacings for the nail-plates. Increasing the shear connection stiffness will also justify the inclusion of the bending stiffness of the concrete plate in the theoretical model.

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References

[1] Girhammar, U. A., Pan, D. H. Exact static analysis of partially composite beams amd beam-columns. *International Journal of Mechanical Sciences* 49 (2009) 239-255.

[2] Branco, J., P. Cruz, M. Piazza. Experimental analysis of laterally loaded nailed timber-to-concrete connections. *Construction and building materials*, Vol.1, n. 23, pp. 400-410 (2009)

[3] Brunner M., Romer M., Schnüriger M. Timber-concrete-composite with an adhesive connector (wet on wet process). *Mater. Struct.*, Vol. 40, pp. 119-126 (2007).

[4] Bathon L.A., Graf M. A continuous wood-concrete composite system. *Proceedings of the World Conference on Timber Engineering* (2000).

[5] Bathon L. A. Green Technologies for Structural retrofit and prefabrications with wood. *UMass 2007 Wood Structures Symposium*, University of Massachusetts, Power-Point presentation (2007).

[6] Deam B. L., Fragiacomo M., Buchanan, A. H. Connections for composite concrete slabs and LVL flooring systems. *Materials and Structures*, Vol. 41, no. 3, pp. 495-507, (2008)

[7] Deam B.L., Yeoh D., Fragiacomo M., Buchanan A. H. Crews K., Haskell, J. Development of Semi-Prefabricated Timber-Concrete Composite Floors in Australasia. *10th World Conference of Timber Engineering*, Miyazaki, Japan (2008).

[8] Clouston P., Bathon L. A., Schreyer, A. Shear and bending performance of a novel wood–concrete". *Journal of structural engineering*, Vol. 131, pp. 1402-1412 (2005).

[9] Tajnik M., Dobrila P., Premrov M. Analysis of composite T beam composed of timber, concrete and carbon strip, *WSEAS transactions on applied and theoretical mechanics*, Vol. 2, no. 9, pp. 177-186(2007).

[10] Girhammar U.A. Nail-plate as shear connectors in composite timber and concrete structures. *IABSE 12 Congress*, Vancouver, Final report. (1984).

[11] Girhammar U.A. Composite timber-concrete wall element. *IABSE 12 Congress*, Vancouver, Final report. (1984).

[12] Yeoh D., Fragiacomo M., De Franceschi M., Boon K. H. State of the Art on Timber-Concrete Composite Structures: Literature Review. *J. Struct. Eng*, Vol. 137, 108 (2011).

[13] Girhammar, U. A. Testing of Rabo wall element. Luleå University of Technology, Research Report TULEA 1979:29, Luleå, Sweden, 1979. (in Swedish)

[14] Girhammar, U. A. Rabo wall element – Theoretical and experimental study of composite elements of timber and concrete. Luleå University of Technology, Research Report TULEA 1980:30, Luleå, Sweden, 1980. (in Swedish)