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Original Research Article

AN ANALYSIS OF THE LOAD-BEARING CAPACITY OF TIMBER-CONCRETE COMPOSITE BEAMS WITH PROFILED SHEETING

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Abstract

This paper presents an analysis of timber-concrete composite beams. Said composite beams consist of rectangular timber beams and concrete slabs poured into the steel sheeting. The concrete slab is connected with the timber beam using special shear connectors. The authors of this article are trying to patent these connectors. The article contains results from a numerical analysis. It is demonstrated that the type of steel sheeting used as a lost formwork has an influence on the load-bearing capacity and stiffness of the timber-concrete composite beams.

Keywords: composite timber-concrete structures, composite beams, FEM, Abaqus

1. INTRODUCTION

Wood has been used as a building material for thousands of years. After a period of stagnation, this material has recently been often used for structural elements and is very competitive in the construction market. All building materials have improved. The use of high-performance concrete is one of the newest trends in concrete structures [1, 8, 16]. There are new types of reinforcement such as basalt fibre-reinforced polymer bars [21]. Designers have started using high performance steel with a strength of more than 460 MPa [9] for steel structures. They also use steel thin-walled structures [3, 4, 27] or aluminium structures [29], because of their lightness (tendency to design light- weight structures). Despite

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the significant development of other building materials, wood is still used and has also developed. Glued-laminated timber is used for long-span structures, because it permits the creation of structural members much larger than trees [18]. However, it is combustible material. The cross-section area of the timber beam is large and the rate of charting of the beam's surfaces is slow. For this reason, glued-laminated timber exposed to fire can carry loads substantially longer than unprotected steel. The fire and flame spread resistance of glued-laminated timber can be enhanced through the application of fire-resistant surface coatings or pressure impregnation with fire retardants. The durability of glued-laminated timber depends on the types of timber, glue, preservative and application method. One instance where glued-laminated timber is chosen for its durability is in swimming pool roofs – this is a particularly corrosive environment with high humidity and chlorine levels and glued-laminated timber provides a durable low-maintenance solution. Glued-laminated timber may be also used for bridges, roof systems for single-story warehouses, shopping centres and factories, due to its good strength to weight ratio. The most obvious advantage of timber is that it is a locally available, sustainable material [5, 6]. It does not need to be mined and subjected to high- energy-demand manufacturing processes that steel and cement require. The energy consumption ratio for timber structures is only 0.76 GJ/m^2, whereas for steel structures – 3.24 GJ/m^2 and for concrete structures – 2.13 GJ/m^2 [30].

A wooden roof or ceiling with glued-laminated timber beams has steel sheeting lying on the beams. This solution may be developed by pouring concrete into the steel sheeting, which improves load-bearing capacity and stiffness of the timber beams. The profiled sheeting may serve as both the formwork and tensile reinforcement. It is possible to save construction materials and construction time, and reduce slab height. Timber-concrete composite structures may be competitive to steel, concrete or steel-concrete composite structures. The aluminium beam and the concrete slab should be joined with shear connectors. The shear connectors used is steel-concrete structures are presented in [2, 13]. The authors of this article prepared a special connector which consisted of two parts – a headed stud and a wooden screw (see Fig. 1) [28]. It is a new solution.

The idea of timber-concrete composite structures is not new. Schafers and Seim tested timber-concrete composite beams consisting of two glued-laminated timber beams bonded to an ultra-high performance concrete slab using an adhesive [26]. To join a timber beam with a concrete slab it is also possible to use: connection mesh made of surface-untreated waterproof plywood [7], nails, screws, steel plates [17] or anchor connection [10].

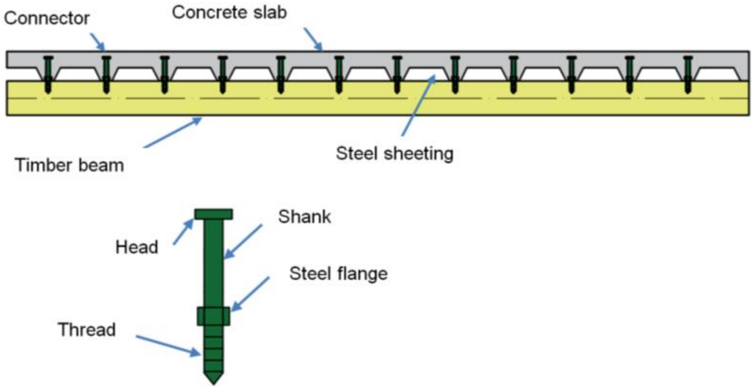

Fig. 1. Connector for timber-concrete composite structures

The preliminary analysis showed that the load-bearing capacity of the bending element increased significantly after joining the beam with the slab. In the preliminary analysis, the authors of this article made an assumption that there was full connection between the timber beam and the concrete slab and they used the plastic method for calculating resistance (see table 1).

Table 1. The plastic bending resistance of the timber-concrete composite beam

Parameter	Value
Dimensions of the cross-section of the timber beam [cm]	20.0 x 30.0
Glued-laminated timber	GL28h
Glued-laminated timber bending resistance [MPa]	28.0
Glued-laminated timber tension resistance [MPa]	19.5
Tensile force in the timber beam [kN]	1170.0
Moment of inertia of the timber beam I_y [cm^4]	45 000
Section modulus of the timber beam W_y [cm^4]	3000
Elastic bending resistance of the timber beam $M_{c,Rk}$ [kNm]	84.0
Maximum load of the timber beam *2P*[kN]	98.9
Height of the concrete slab [cm]	15.0
Width of the concrete slab [cm]	70.0
Thickness of the concrete part over steel sheeting [cm]	9.1
Compressive force in the concrete slab [kN]	2057.5
Position of the plastic axis [cm]	5.17
Plastic load-bearing capacity $M_{c,pl,Rk}$ [kNm]	320.7
Maximum load of the composite beam *2P* [kN]	377.3

The preliminary analysis showed that the load-bearing capacity of the composite beam is four times higher than the load-bearing capacity of the timber beam. However, the load-bearing capacity of the composite beam may be limited by the type of connection and steel sheeting.

The authors decided to evaluate the impact of the type of steel sheeting on the bending resistance of the timber-concrete composite beam. The concrete slab may be poured into steel sheeting. There are two most often used types of steel sheeting: open trough profiled steel sheets and re-entrant profiled steel sheets [11].

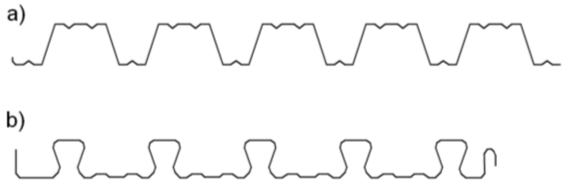

Fig. 2. Types of steel sheets used for composite slabs: a) open trough profiled steel sheets, b) re-entrant profiled steel sheets

The steel sheeting may act as permanent formwork for the concrete slab and through mechanical or frictional interlock may be a part of the composite slab (the sheet provides all, or part, of the main tension reinforcement to the slab). Many composite beams with profiled sheeting are partial composite beams, because of the limitation of the rib width of profiled sheeting. The number of shear connectors of a composite beam with profiled sheeting is in most cases lower than the number required for a full composite design. The additional deflection induced by the shear slip effect at the interface should be taken into consideration [19, 20]. The tests of steel-concrete composite beams with steel sheeting presented in [20] shown that the degree of shear connection, the arrangement of shear studs, the orientation of the profiled sheeting (placed in a downward position or placed in the upward position) have an impact on the load-bearing capacity and stiffness of the beam. In the composite beams with profiled steel sheeting there may occur horizontal cracks in the concrete troughs near the support of the beams. At the collapse load, the profiled sheeting in the shear span may separate from the concrete, and some shear studs may be broken off. The typical failure modes of the ribs include lateral failure and diagonal failure. Longitudinal cracking may appear due to the longitudinal shear splitting force and transverse cracking at the weaker section of the concrete slab. The transverse cracking may be caused by the local negative moment in the slab resulting from the eccentricity of the longitudinal compression forces. These failure modes may also appear in timber-concrete structures when the concrete slab is poured into the steel sheeting. The authors used the numerical simulation to verify this hypothesis. They analysed two models of timber-concrete composite beams. In the first model, T 55-230-1 open trough profiled steel sheets were used, whereas the second model employed F 59-140-1– re-entrant profiled steel sheets (see Fig. 3).

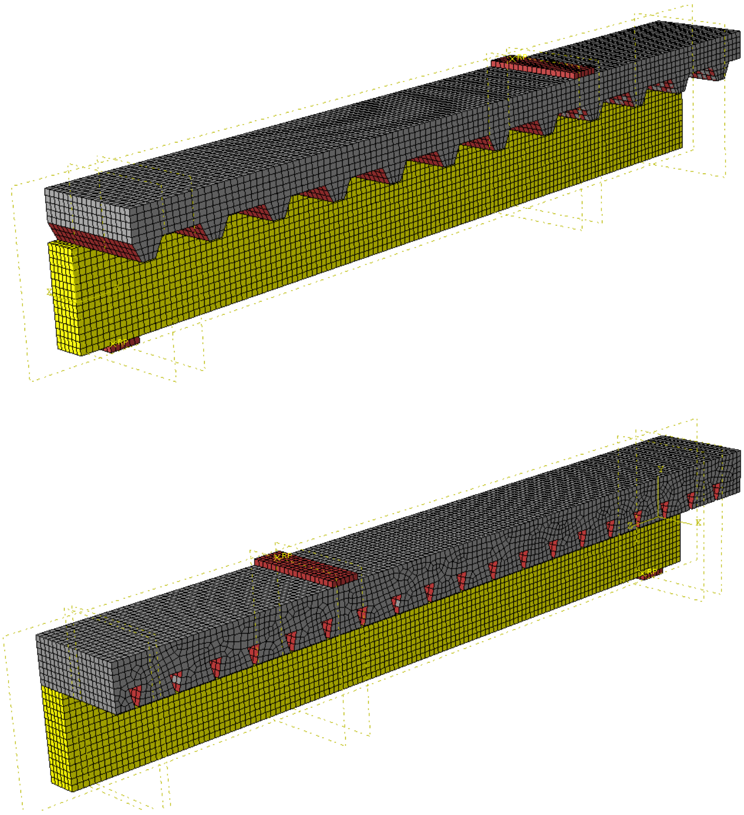

Fig. 3. Analysed models

2. NUMERICAL ANALYSIS

The authors of this article analysed 5.1-meter-long timber-concrete composite beams. Numerical models were prepared in the Abaqus program. Calculations were performed using the Newton-Raphson method. The models had two axes of symmetry – for this reason, the authors of this article prepared only ¼ of each model. The models consisted of a timber beam, a concrete slab and connectors. The cross sections of the timber beams were rectangular (200 mm x 300 mm). The timber beams were made of GL28h glued-laminated timber and the concrete slabs were made of C30/37 concrete. The material parameters and dimensions of a single composite beam are presented in table 2.

Table 2. Material parameters and dimensions of the composite beam

Parameter	Value
Beam span *L* [m]	5.1
Height of the concrete slab [cm]	15.0
Height of the concrete part above the sheeting [cm]	9.1
Width of the concrete slab [cm]	70.0
Cross section of the timber beam [cm]	20.0 x 30.0
Material of the timber beam	GL28h
Bending strength of the timber [MPa]	28.0
Tensile strength of the timber [MPa]	19.5
Compressive strength of the timber [MPa]	26.5
Concrete	C30/37
Compressive strength of the concrete f_c [MPa]	38.0
Diameter of the connector [mm]	19.0
Material of the connector	S235
Yield strength of the connector [MPa]	235.0
Steel sheeting in model 1	T 55-230-1
Steel sheeting in model 2	F 59-140-1
Thickness of the sheeting [mm]	1.0

In the first model, open trough profiled steel sheeting was used, whereas in the second model – re-entrant profiled steel sheeting. The concrete was poured into the steel sheeting. The height of the concrete slab was 15.0 to determine the position of the plastic axis above the steel sheeting. Three different materials were taken into account during numerical calculations (see Fig. 4).

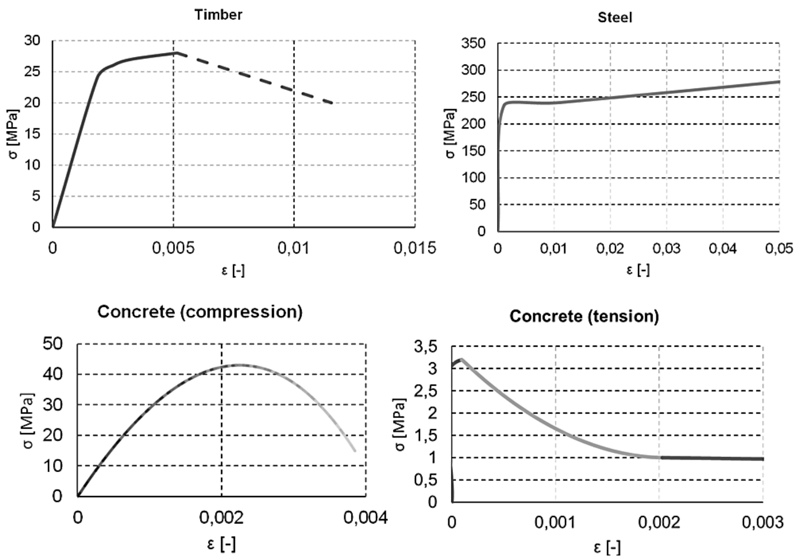

Fig. 4. Stress-strain relations for used materials

In the numerical calculations, steel was an elastic-plastic material with strain hardening, concrete was an elastic-plastic material with isotropic damage and timber is first behaved as linear elastic material and then as a non-linear elastic material. The parameters of the materials were taken from the standards [22, 23, 24, 25]. A concrete damaged plasticity model was used for concrete in the Abaqus program, to take into account concrete strength degradation [12, 14, 15]. The load was applied in the form of displacement. The displacement was applied to a flat steel plate just as in a four-point bending test. Thanks to this method of load application, the authors managed to obtain a decrease on the force-deflection diagram and a limited load (load-bearing capacity of the beams). In the FEM model, four types of finite elements were used. The concrete slab and the timber beam were divided into eight-node cuboidal finite solid elements (linear hexahedron type C3D8R). The steel sheeting was modelled as the skin of the concrete slab and it was divided into four-node shell elements (linear quadrilateral type S4R) (see Fig. 5).

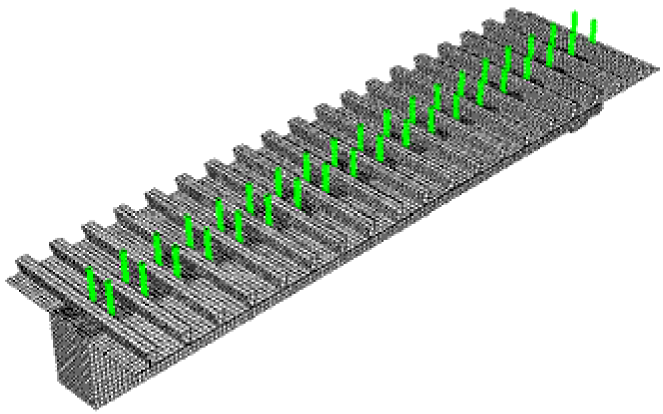

Fig. 5. Timber beam with connectors and steel sheeting as the skin of the concrete slab

The connectors were modelled as wires and divided into beam elements (linear beam type B31). The first part of the connector was embedded in the concrete slab. The second part was embedded in the timber beam. The reinforcement was embedded in concrete and it was divided into truss elements (linear line type T3D2). There was hard contact between the timber beam and the concrete slab. The friction between these elements was also taken into account. The size of the cell was 20 mm. The total number of all the finite elements was about 72 000.

3. RESULTS

As a result of numerical calculations, force-deflection diagrams were obtained (see Fig 6).

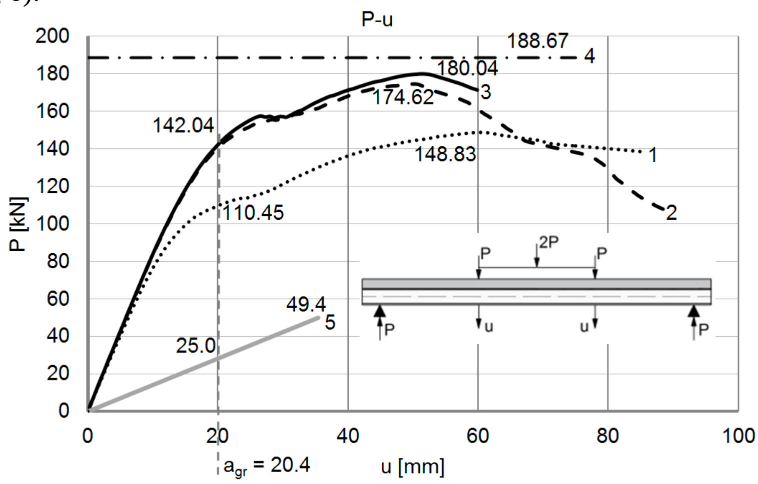

Fig. 6. Force-deflection diagram of analysed beams: 1 – timber-concrete composite beam with open trough profiled steel sheeting, 2 – timber-concrete composite beam with re-entrant profiled steel sheeting, 3 – timber-concrete composite beam with monolithic concrete slab, 4 – plastic load-bearing capacity of timber-concrete composite beam, 5 – timber beam

The first diagram presents the relations between force *P* and deflection *u* for the timber-concrete composite beam with open trough profiled steel sheeting. The maximum load for this beam P = 148.8 kN was obtained when deflection a = 60.5 mm. The maximum load for the timber-concrete composite beam with re-entrant profiled steel sheeting (diagram 2) P = 174.6 kN was obtained when deflection a = 50.3 mm. There were more connectors in the composite beam with the re-entrant steel sheeting, because there were more ribs. The load-bearing capacity obtained using [24] and the plastic method of calculation amounted to 188.7 kN. The load-bearing capacity of the timber-concrete composite beams with profiled steel sheeting did not achieve the plastic resistance calculated from [24]. For a better comparison, the numerical analysis was complemented with the calculations where a timber-concrete beam with the monolithic concrete slab was analysed (see Fig. 7).

The load-bearing capacity obtained using numerical calculation for the timber-concrete composite beam with the monolithic concrete slab (P = 180.0) was close to the one obtained using [24] and the plastic method of calculation (P = 188.7 kN).

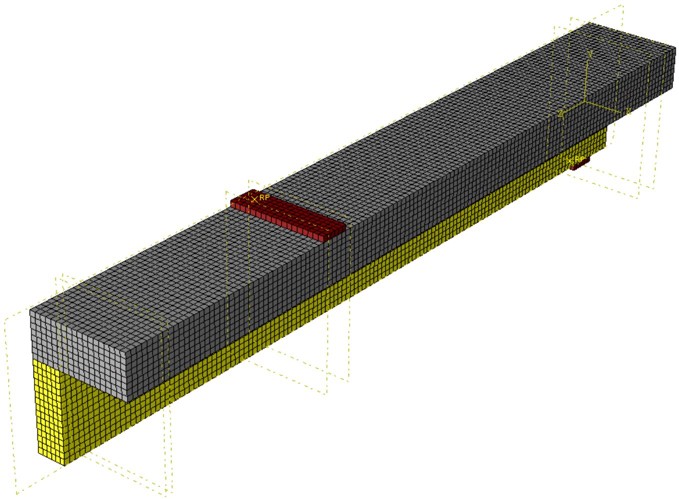

Fig. 7. Timber-concrete composite beam with monolithic concrete slab

Thanks to the concrete damaged plasticity model used in the Abaqus program it was possible to evaluate cracking of the concrete. In the timber-concrete composite beams there were lateral cracks on the top of the concrete slab in the support, and many lateral and diagonal cracks in the ribs (see Fig 8).

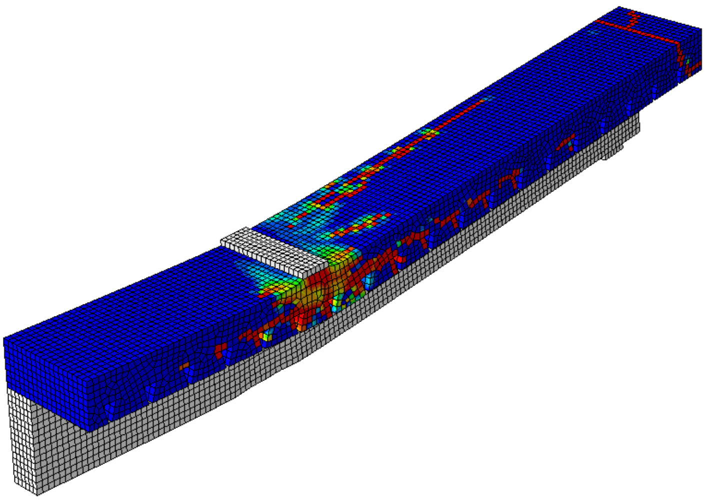

Fig. 8. Cracks in the timber-concrete composite beam with re-entrant profiled steel sheeting

There was also a lateral crack along the axis of the connectors, connected with their work. These types of failures were also presented in [20]. The number of shear connectors obtained from [24] was required for a full composite design. However, taken into account the form of failures obtained from numerical calculations, the number of shear connectors was lower than the number required for a full composite design. The load-bearing capacity was limited because of the connection.
The authors of this article additionally analysed strains in the cross-section of the composite beams with profiled steel sheeting (see Fig. 9).

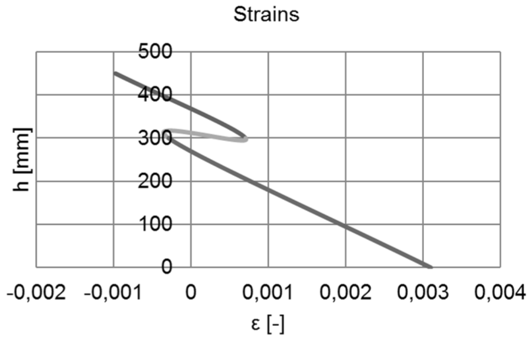

Fig. 9. Strains in the cross-section of the timber-concrete composite beam

The diagram presented in Figure 9 shows that the analysed composite beams with profiled sheeting were partial composite beams, because of the limitation of the rib width of thee profiled sheeting. There was no continuity of displacements at the contact point of the timber beam and the concrete slab. There were two neutral axes in the composite beams. The additional deflection induced by the shear slip effect at the interface caused decreasing of the load-bearing capacity and stiffness. Strain diagrams are non-linear. The flat cross-section hypothesis was impossible to use in the analysed examples.

4. CONCLUSIONS

The type of steel sheeting used as a formwork for the concrete slab had an impact on the load-bearing capacity and stiffness of the timber-concrete composite beams. The composite beam with re-entrant profiled steel sheeting had higher load-bearing capacity than the composite beam with open trough profiled steel sheeting. There were more connectors (more ribs) in the composite beam with the re-entrant steel sheeting. The difference between the load-bearing capacity of the timber-concrete composite beam with the monolithic concrete slab and the timber-concrete composite beam with re-entrant profiled steel sheeting was only 5.42 kNm. The re-entrant profiled steel sheeting allowed a better cooperation

between the sheeting and the concrete (when the slab was subjected to bending) than the open trough profiled steel sheeting. The strain diagram showed that the analysed composite beams with profiled sheeting were partial composite beams. The additional deflection induced by the shear slip effect at the interface caused a decrease in the load-bearing capacity and stiffness. Despite the fact that the load-bearing capacity of composite beams with steel sheeting is limited, their use is still advantageous. When the serviceability limit state was taken into account, the maximum load for the timber-concrete beam with the monolithic concrete slab and the timber-concrete composite beam with the re-entrant profiled steel sheeting was almost the same (about 142.0 kN). The difference between the maximum loads for the timber-concrete composite beam with the re-entrant profiled steel sheeting and the timber-concrete composite beam with open trough profiled steel sheeting was about 30 kN when the serviceability limit state was taken into account. The initial stiffness of the analysed composite beams was the same. Then, when the load was higher than 70.0 kN, the stiffness of the timber-concrete composite beam with open trough profiled steel sheeting decreased.
The compressive strength of the concrete and the tensile strength of the timber beam was not achieved during the numerical calculations. The load-bearing capacity of the partial composite beams was 3.0 to 3.5 times higher than the load-bearing capacity of the timber beam. When the serviceability limit state was taken into account, the maximum load for the timber-concrete composite beams with the steel sheeting was 4 to 6 times higher than the maximum load for the timber beam.
To verify the aforementioned results, laboratory tests are necessary. More problems connected with timber-concrete composite structures remain to be solved, e.g. the one related to the behaviour of timber subjected to long-term load.

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ANALIZA NOŚNOŚCI BELEK ZESPOLONYCH DREWNIANO-BETONOWYCH Z PŁYTĄ BETONOWĄ NA BLASZE FAŁDOWEJ

Streszczenie

Analizie poddano belki zespolone drewniano-betonowe składające się z prostokątnej belki drewnianej oraz płyty betonowej wylanej na blasze fałdowej. Współpracę belki z płytą zapewniają specjalne stalowe łączniki, które są przedmiotem zgłoszenia patentowego. W referacie przedstawiono wyniki analiz numerycznych dotyczących wpływu rodzaju stalowych blach fałdowych, na których wykonywane są płyty żelbetowe współpracujące z drewnianymi belkami. Okazuje się, że rodzaj blachy fałdowej służącej jako deskowanie i jako element mogący współpracować z betonową płytą, ma istotny wpływ nie tylko na wytrzymałość samej płyty, ale również na nośność i sztywność belki zespolonej drewniano-betonowej

Słowa kluczowe: konstrukcje zespolone drewniano-betonowe, belki zespolone, MES, Abaqus

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