DE GRUYTER OPEN
CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS
ISSN 2080-5187 CEER 2017; 27 (4): 131-141
DOI: 10.1515/ceer-2017-0056
Original Research Article

PRELIMINARY ANALYSIS OF THE ALUMINIUM-TIMBER COMPOSITE BEAMS

Maciej SZUMIGAŁA, Marcin CHYBIŃSKI, Łukasz POLUS[1]
Poznan University of Technology, Poznań, Poland

A b s t r a c t

This paper presents a new type of composite structures - aluminium-timber beams. These structures have an advantage over other existing composite structures, because they are lighter. However, their application may be limited due to the high price of aluminium alloys. The authors of this article made an attempt to calculate the load-bearing capacity of an aluminium-timber beam.

Keywords: composite aluminium and timber structures, composite beams, FEM, Abaqus

1. INTRODUCTION

Steel and concrete composite structures are often used in civil engineering, both in buildings [3] and bridges [16]. However, the combination of steel and concrete is not the only one possible. A steel beam may be replaced with an aluminium beam [25] or a timber beam [29], while a concrete slab may be replaced with a timber slab [12]. The use of an aluminium beam instead of a steel beam improves corrosion resistance [15] and reduces the self-weight of a construction [30].

The weight of a composite beam may also be reduced by using timber-concrete composite structures instead of steel-concrete composite ones. In timber-concrete composite structures, the concrete slab is designed to resist compression, the

[1] Corresponding author: Poznan University of Technology, Institute of Structural Engineering, Faculty of Civil and Environmental Engineering, Piotrowo st 5, 60-965 Poznan, Poland, e-mail: lukasz.polus@put.poznan.pl, tel.+48616652098

timber beam is designed to resist tension and the shear is transferred through connectors [31]. A timber beam may be made of glued-laminated timber which has: high fire resistance and chemical resistance, high load-carrying capacity with low density and high dimensional stability due to gluing. A concrete slab may be made of ultra-high performance concrete [2, 28] or reactive powder concrete [9]. A timber slab may be used to replace a concrete slab. Steel and timber composite structures are a relatively new development. They can reduce the self-weight of a structure (the self-weight of a timber slab is lower than the self-weight of a concrete slab) and speed up the construction process (there is no need to pour concrete) [14].

The behaviour of all the composite constructions mentioned above depends on the resistance and stiffness of the connection between the two materials used. The shear connections used in steel and concrete composite structures are presented in [4]. The innovative shear connection with composite dowels is shown in [18]. A prototype of a new connector for aluminium and concrete structures is presented in [26]. To join timber and concrete structures it is possible to use metal elements [19], adhesives [28] or glued plywood [8]. The possible connectors for steel and timber composite constructions are proposed in [13]. They are hexagon head wood screws or bolts.

The analysis of the composite structures currently in use inspired the new type of composite structures - aluminium and timber structures. These structures have not been tested in detail yet. The advantages resulting from their use include: shorter construction time (prefabricated timber slabs), lower self-weight of the structure (aluminium alloys are lighter than steel). The durability of these structures may be high due to the corrosion resistance of aluminium alloys, but the timber slab should be protected against biological corrosion [27]. The composite structures, and in particular aluminium and timber structures, are part of sustainable construction [7, 20]. Timber is a natural, renewable, recyclable and energy-efficient building material. High energy consumption during the production of aluminium provides for high embodied energy [5]. Embodied energy is the energy used in all the processes required to obtain a material. However, aluminium may be reused or recycled [11] and embodied energy savings may be as high as 95 %. To join an aluminium beam with a timber slab it is possible to use hexagon head wood screws [10]. What is more, the shape of the upper flange of the I-beam may guarantee the connection between the aluminium beam and the timber slab. The cross-section of the aluminium beam may be of any shape [21]. The height of the cross-section is limited by the height of the aluminium extrusion dies. The modulus of elasticity of aluminium is approximately one third of that of steel, as a result of which aluminium members may be damaged through buckling. However, the aluminium beam in an aluminium and timber composite beam may be designed to resist tension only, therefore the problem with the buckling may be eliminated.

The high price of aluminium alloys may have an adverse impact on the popularity of these structures. For example, 1 kg of I-beam (160 mm-high) made of AW 6060 aluminium alloy cost 3.2 € in 2016. What is more, there are no standards for designing aluminium and timber composite structures similar to the ones for steel and concrete composite structures [22].

The preliminary analysis was used to evaluate the load-bearing capacity of an aluminium and timber composite beam. In this analysis the standards [22, 23, 24] and numerical simulation were used.

2. A PRELIMINARY ELASTIC AND PLASTIC ANALYSIS OF THE LOAD-BEARING CAPACITY OF AN ALUMINIUM AND TIMBER COMPOSITE BEAM

2.1. The analysed composite beam

The authors of this article analysed an aluminium-timber composite beam. The composite element consisted of an aluminium beam and a timber slab. The timber slab was made of Laminated Veneer Lumber (LVL) - bonded 3-mm-thick veneers. Structural LVL is used for: I-Joists - structural wooden I-beams with LVL flanges for floor, wall and ceiling, beams and frames [6].

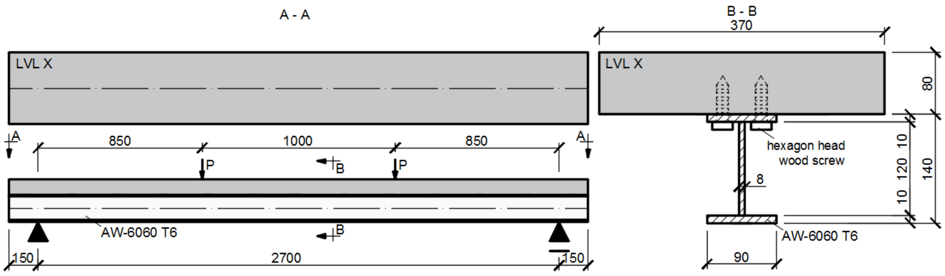

Fig. 1. The analysed aluminium and timber composite beam: A-A - top view, B-B - cross-section

This material has a lot of advantages: practically homogeneous cross-section, availability in a wide range of dimensions, high strength-to-weight ratio, it is easily cut and machined using traditional tools, and it has strong shock resistance (it can resist the fatigue rupture that can arise from cyclic stress), fire resistance superior to that of steel, weather resistance higher than that of other wood materials. The aluminium beam was made of an EN AW-6060 T6 aluminium alloy I-section beam (140-mm-high). This aluminium alloy has high strength, very good corrosion resistance, very good weldability and good cold formability.

The dimensions and mechanical properties of the analysed composite beam are presented in Table 1 and Figure 1. In the preliminary analysis it was assumed that the beam was designed with full shear connection.

Table 1. The dimensions and mechanical properties of the analysed composite beam

Parameter	Value/Description
Span of the beam L [mm]	2700.0
Material of the timber slab	LVL X
LVL compressive strength f_c [MPa]	30.0
Elastic modulus of LVL E [GPa]	10.6
Poisson's ratio of LVL v [-]	0.4
Plastic modulus of the cross section W_{pl} [cm^3]	145.8
Moment of inertia of the aluminium beam I_y [cm^4]	877.2
Cross-section area of the aluminium beam A [cm^2]	27.6
Width and height of the timber slab b, h [mm]	370.0, 80.0
Yield strength of AW-6060 T6 f_0 [MPa]	140.0
Elastic modulus of AW-6060 T6 E [GPa]	70.0
Poisson's ratio of AW-6060 T6 v [-]	0.3

2.2. Simplified calculations

The elastic load-bearing capacity of the composite beam was evaluated (see Table 2). During the calculations, the real cross-section of the composite beam was replaced with the cross-section which had the same mechanical parameters as the aluminium beam, and the timber slab was replaced with a smaller aluminium slab. The aluminium slab had the same rigidity as the timber slab. The plastic load-bearing capacity of the composite beam was also evaluated (see Table 3). During the calculations it was assumed that the cross-section of the composite beam might be at yield, which is not a safe assumption. During the conducted analysis, the authors of this article used the characteristic parameters of the materials. The characteristic resistance of the aluminium beam without the timber slab was $145.8\cdot 14.0 \cdot 10^{-2} = 20.4$ kN·m. This resistance was about 1.3 times smaller than the calculated elastic load-bearing capacity and about 2.5 times smaller than the calculated plastic load-bearing capacity of the composite beam.

Table 2. The elastic load-bearing capacity of the composite beam

Parameter	Value
n Ratio (relation of Young's modulus)	6.6
Width of the replaced aluminium slab [mm]	56.1
Position of the neutral axis x [mm]	81.9
Second moment of area I_y [cm^4]	3184.4
Elastic bending resistance $M_{c,el,Rk}$ [kNm]	32.3

Table 3. The plastic load-bearing capacity of the composite beam

Parameter	Value
Position of the plastic axis x_{pl} [cm] $14.0 \cdot 27.6 + 3.0 \cdot 37.0 \cdot (8.0 - x_{pl}) = x_{pl} \cdot 3.0 \cdot 37.0$	5.74
Plastic bending resistance $M_{c,pl,Rk}$ [kNm] $14.0 \cdot 27.6 \cdot (15.0 - 5.74 / 2) +$ $+ 3.0 \cdot 37.0 \cdot (8 - 5.74) \cdot (5.74 + 2.26) / 2$	56.9

2.3. Numerical calculations

The numerical model was prepared in the Abaqus program [1]. The model had two axes of symmetry. For this reason, the authors of this article prepared only 1/4 of the model (see Fig. 2). Thanks to this, the calculation time was reduced.

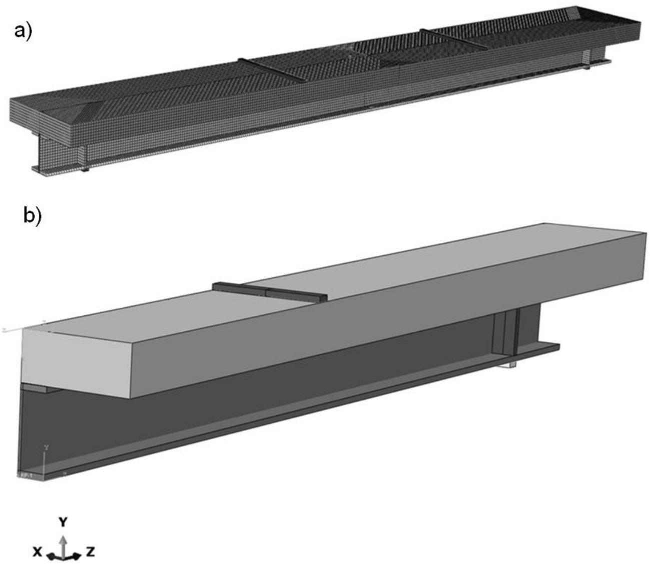

Fig. 2. a) The numerical model of the composite beam, b) The analysed ¼ of the beam

The behaviour of the materials was described as elastic-plastic using the constitutive laws shown in Figure 3.

The calculations were performed using the Newton-Raphson method in the Abaqus program. The load was applied in the form of displacement. The displacement was applied to the flat steel plate located 0.85 m away from the support (four-point bending test). The timber slab was tied to the upper flange of the aluminium beam (full-connection). The timber slab was divided into eight-node cuboidal finite solid elements (C3D8R) and the aluminium beam was divided into four-node shell elements (S4R). The size of the cell was 10 mm. The total number of all the elements was 26 494 (3694 S4R and 22 800 C3D8R) and the total number of nodes was 31 095 (see Fig. 4). Figure 5 presents the boundary conditions used in the computer model.

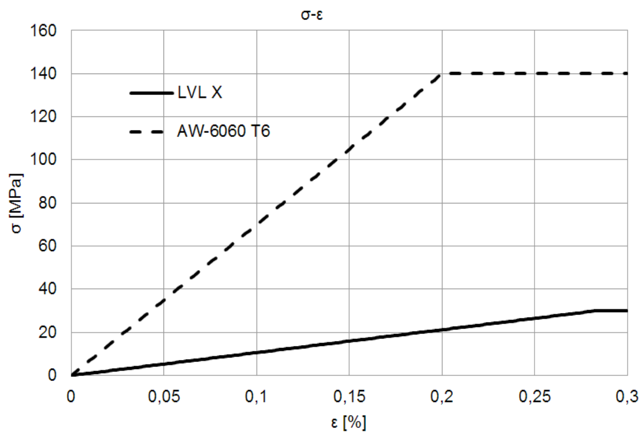

Fig. 3. Stress-strain relations for LVL X timber subjected to compression and AW 6060 T6 aluminium alloy subjected to tension

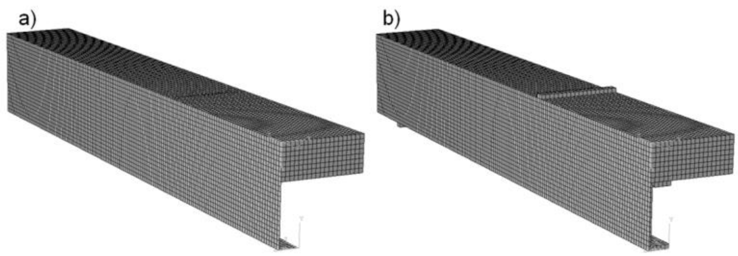

Fig. 4. Meshed composite beam: a) analysed beam b) beam with rendered shell thickness

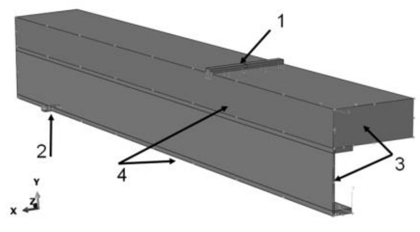

Fig. 5. Boundary conditions: 1 - displacement, 2 - vertical displacement in *y* direction (linearly blocked) in the support, 3 - horizontal displacement in *z* direction (blocked for the entire cross-section) and rotation around *x* and *y* axes (blocked), 4 - horizontal displacement in *x* direction (blocked for the entire longitudinal section)

In the numerical calculations, the elastic load-bearing capacity was obtained when the compressive resistance of timber was exceeded or when yield strength appeared in the aluminium beam. The plastic load-bearing capacity was obtained when the force in the force-deflection diagram decreased.

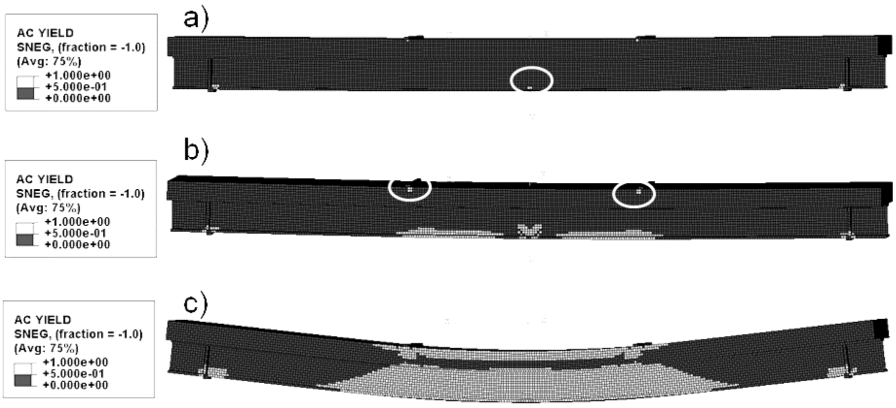

Fig. 6. Yield stress: a) aluminium beam at yield, b) compressive resistance of the timber exceeded, c) plastic hinge in the composite beam

First, there was yield stress in the bottom flange of the aluminium beam (P = 36.9 kN, M = 31.3 kN·m, see Fig. 6a). Then, the compressive resistance of timber was exceeded (P = 49.9 kN, M = 42.4 kN·m, see Fig. 6b). Shortly afterwards, the force in the force-deflection diagram was decreasing (P = 70.9 kN, M_{lim} = 60.3 kN·m) (see Fig. 7). The decrease of the force was connected with the plastic hinge in the composite beam (see Fig. 6c).

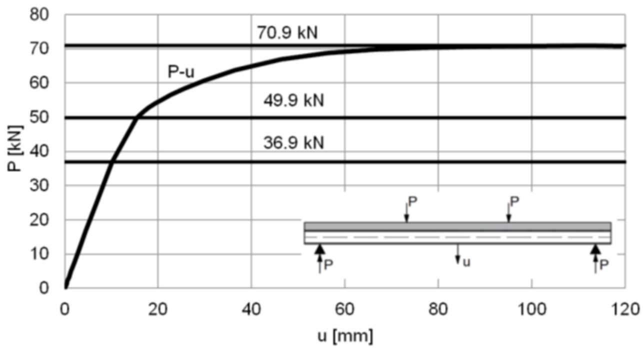

Fig. 7. Force-deflection diagram P-u

3. CONCLUSIONS

In certain situations aluminium and timber composite structures may be used instead of steel and concrete composite beams. From a structural engineering perspective, the application of timber and aluminium in the construction of composite floors can significantly reduce the self-weight of a structure. What is more, aluminium and timber structures may speed up the construction process and significantly reduce its cost. The authors of this article evaluated the load-bearing capacity of an aluminium and timber composite beam only in a simplified way, using calculations and a numerical analysis. The resistance of the composite beam calculated using the Abaqus system was similar to the results obtained using the simplified calculations. The elastic load-bearing capacity obtained in the numerical calculations (31.3 kNm) was about 3.0 % smaller than the one obtained in the simplified calculations (32.3 kNm), while the plastic load-bearing capacity obtained in the numerical calculations (60.3 kNm) was about 6.0 % higher than the one obtained from the simplified calculations (56.9 kNm). However, timber is not a plastic material and the plastic load-bearing capacity is difficult to obtain. The elastic load-bearing capacity obtained in the numerical calculations was connected with the yield stress in the bottom flange of the aluminium beam. The compressive resistance of timber was exceeded some time later (for M = 42.4 kNm). It could be the moment when the composite beam achieved its maximum resistance. To verify the aforementioned results, laboratory tests are necessary. During the calculations it was assumed that there was a full connection between the timber slab and the aluminium beam. However, the resistance of the composite beam may be limited by the resistance of the connectors, which should be checked in the future. What is more, the designers may have a problem to satisfy serviceability criteria, because of a big deflection. Moreover, the coefficient of linear thermal expansion for aluminium is different than the coefficient of linear thermal expansion for timber. The influence of the temperature on the composite beam should be also analysed in the future. It seems that with the current state of knowledge, the elastic model of work of an aluminium and timber beam can be safely used in the design of this type of construction.

REFERENCES

1. Abaqus 6.13 Documentation, Abaqus Analysis Users Guide, Abaqus Theory Guide.
2. Ajdukiewicz A., Radomski W.: *Trends in the Polish research on high-performance concrete*, Cement and Concrete Composites, 24, 2 (2002) 243-251.
3. Biegus A., Lorenc W.: *Projektowanie zespolonych konstrukcji stalowo-betonowych według PN-EN 1994*, in: Konstrukcje zespolone: Jubileuszowa X Konferencja Naukowa, Zielona Góra, 26-27 czerwca 2014, edit. T. Biliński, J. Korentz, Zielona Góra, Oficyna Wydawnicza Uniwersytetu Zielonogórskiego 2014.

4. Biegus A., Lorenc W.: *Development of shear connections in steel-concrete composite structures*, Civil and Environmental Engineering Reports, 15, 4 (2014) 23-32.
5. Broniewicz M.: *Projektowanie oparte na zrównoważonym rozwoju*, in: Problemy naukowo badawcze budownictwa, Tom IV: Zrównoważony rozwój w budownictwie, edit. A. Łapko, M. Broniewicz, J. Prusiel, Białystok, Polska Akademia Nauk, Komitet Inżynierii Lądowej i Wodnej, Wydawnictwo Politechniki Białostockiej 2008, s. 185-206.
6. Chena Z., Leia Q., Hea R., Zhanga Z., Chowdhuryb A.: *Review on antibacterial biocomposites of structural laminated veneer lumber*, Saudi Journal of Biological Sciences, 23, 1 (2016) 142-147.
7. Czarnecki L., Kaproń M., Piasecki M., Wall S.: *Budownictwo zrównoważone budownictwem przyszłości*, Inżynieria i Budownictwo 68, 1 (2012) 18-21.
8. Dankova J., Mec P., Majstrikova T.: *Stiffness analysis of glued connection of the timber-concrete structure*, Open Engineering, 6 (2016) 241-249.
9. Denisiewicz A., Kuczma M.: *Two-scale modelling of reactive powder concreto, Part I: Representative volume element and solution of the corresponding boundary value problem,* Civil and Environmental Engineering Reports, 10 (2013) 41-61.
10. DIN 571:2016-12, Hexagon head wood screws.
11. Gwóźdź M.: *Problemy projektowe współczesnych konstrukcji aluminiowych*, Czasopismo Techniczne, 104, z. 4-A (2007) 281-286.
12. Hassanieh A., Valipour H.R., Bradford M.A.: *Experimental and numerical study of steel-timber composite (STC) beams*, Journal of Constructional Steel Research, 122 (2016) 367-378.
13. Hassanieh A., Valipour H.R., Bradford M.A.: *Experimental and analytical behaviour of steel-timber composite connections,* Construction and Building Materials, 118 (2016), 63-75.
14. Hassanieh A., Valipour H.R., Bradford M.A.: *Modelling of steel-timber composite connections: Validation of finite element model and parametric study,* Engineering Structures, 138 (2017) 35-49.
15. Jasiczak J., Hajkowski M.: *Corrosion susceptible elevations made with aluminium plates working in treatment's plant environment*, Ochrona Przed Korozją, 5, A (2008) 79-85.
16. Karlikowski J., Madaj A., Wołowicki W.: *Mostowe konstrukcje zespolone stalowo-betonowe*, Warszawa, Wydawnictwo Komunikacji i Łączności 2007.
17. Lam F.: *Modern structural wood products*, Progress in Structural Engineering and Materials, 3, 3 (2001) 238-245.
18. Lorenc W., Kubica E., Kożuch M.: *Testing procedures in evaluation of resistance of innovative shear connection with composite dowels,* Archives of Civil and Mechanical Engineering, 10, 3 (2010) 51-63.

19. Łukaszewska E., Johnsson H., Fragiacomo M.: *Performance of connections for prefabricated timber-concrete composite floors*, Materials and Structures, 41 (2008) 1533-1550.
20. Major M., Major I., *Konstrukcje zespolone w budownictwie zrównoważonym*. Budownictwo o Zoptymalizowanym Potencjale Energetycznym, 2, 16 (2015) 51-56.
21. Mazzolani F.M., Mandara A.: *Modern trends in the use of special metals for the improvement of historical and monumental structures,* Engineering Structures, 24, 7 (2002) 843-856.
22. PN-EN 1994-1-1, Projektowanie konstrukcji zespolonych stalowo-betonowych. Część 1-1: Reguły ogólne i reguły dla budynków.
23. PN-EN 1995-1-1, Projektowanie konstrukcji drewnianych. Część 1-1: Reguły ogólne i reguły dla budynków.
24. PN-EN 1999-1-1, Projektowanie konstrukcji aluminiowych. Część 1-1: Reguły ogólne i reguły dla budynków.
25. Polus Ł., Szumigała M.: *A numerical analysis of the resistance and stiffness of the aluminium and concrete composite beam*, Civil and Environmental Engineering Reports, 15, 4 (2014) 109-112.
26. Polus Ł., Szumigała M.: *Tests of shear connectors used in aluminium-concrete composite structures,* in: Recent Progress in steel and composite structures, edit. M. Giżejowski, A. Kozłowski, J. Marcinowski, J. Ziółko, CRC Press-Taylor & Francis Group 2016.
27. Rapp P.: *Metodyka i przykłady rewaloryzacji konstrukcji drewnianych w obiektach zabytkowych*, Wiadomości Konserwatorskie, 43 (2015) 92-108.
28. Schafers M., Werner S.: *Investigation on bonding between timber and ultra-high performance concrete (UHPC),* Conctruction and Buiding Materials, 25, 7 (2011) 3078-3088.
29. Szumigała E., Szumigała M., Polus Ł.: *A numerical analysis of the resistance and stiffness of the timber and concrete composite beam*, Civil and Environmental Engineering Reports, 15, 4 (2014) 139-150.
30. Szumigała M., Polus Ł.: *Applications of aluminium and concrete composite structures*, Procedia Engineering, 108 (2015) 544-549.
31. Yeoh D., Fragiacomo M., Carradine D.: *Fatigue behavior of timber-concrete composite connections and floor beams*, Engineering Structure, 56 (2013) 2240-2248.

ANALIZA WSTĘPNA BELEK ZESPOLONYCH ALUMINIOWO-DREWNIANYCH

S t r e s z c z e n i e

W artykule omówiono nowy rodzaj konstrukcji zespolonych - aluminiowo-drewnianych. Podano ich zalety na tle istniejących konstrukcji zespolonych oraz wymieniono problemy, które mogą stanowić ograniczenie dla stosowania tych konstrukcji. Podjęto próbę wstępnej oceny nośności na zginanie przykładowej belki zespolonej aluminiowo-drewnianej.

Słowa kluczowe: konstrukcje zespolone aluminiowo-drewniane, belki zespolone, MES, Abaqus

Editor received the manuscript: 10.10.2017