Experimental Analysis of Composite Timber-Concrete Beam with CFRP Reinforcement

O. Vlcek

Abstract—The paper deals with current issues in research of advanced methods to increase reliability of traditional timber structural elements. It analyses the issue of strengthening of bent timber beams, such as ceiling beams in old (historical) buildings with additional concrete slab in combination with externally bonded fibre - reinforced polymer. The paper describes experimental testing of composite timber-concrete beam with FRP reinforcement and compares results with FEM analysis.

Keywords—Timber-concrete composite, strengthening, fibre-reinforced polymer, experimental analysis.

I. INTRODUCTION

DETAILED analysis of composite timber-concrete beam with CFRP reinforcement corresponds with comprehensive research activities at Institute of Metal and Timber Structures of the Faculty of Civil Engineering of Brno University of Technology. One of main research topics is usage of progressive high-strength materials with traditional materials in one structural member. Analysis of composite timber-concrete beam with CFRP reinforcement relates with already passed research of composite externally CFRP-reinforced timber beams. The experimental verification of ultimate and serviceability limit state of these structural elements provided a number of results, basic principles and parameters, which were later used as initial conditions for this study. The paper introduces different principles of beam analysis. Specific data of ultimate limit state and short-term deflection were evaluated.

The primary argument for the interest of this type of reinforcement can be found for example for existing timber ceilings in historic buildings. If there is a demand for increased load capacity of ceiling and object is historically preserved, combination of reinforcement with concrete slab and CFRP lamella can be an option. It can be used in case, when traditional types of reinforcement are insufficient.

In the first part paper briefly summarizes prior research dealing with the bearing capacity of timber beam reinforced with carbon FRP lamella. The following section defines composite timber-concrete beam with FRP reinforcement and introduces different principles of beam analysis. Specific data of ultimate limit state and short-term deflection were evaluated.

O. Vlcek is with the Institute of Metal and Timber Structures, Brno University of Technology, Veveri 331/95, 602 00 Brno, Czech Republic (phone: +420 541 147 313; e-mail: vlcek.o@ fce.vutbr.cz).

II. DESCRIPTION OF COMPOSITE TIMBER-CONCRETE BEAM WITH CFRP REINFORCEMENT

For the following theoretical and experimental research it was considered, that timber beam is coupled with concrete slab, placed above the timber beam. Coupling is provided with nail type steel fasteners. External carbon fibre reinforced polymer lamella is glued with epoxy resin at the bottom of timber beam. Geometry of composite beam can be found in Fig. 1.
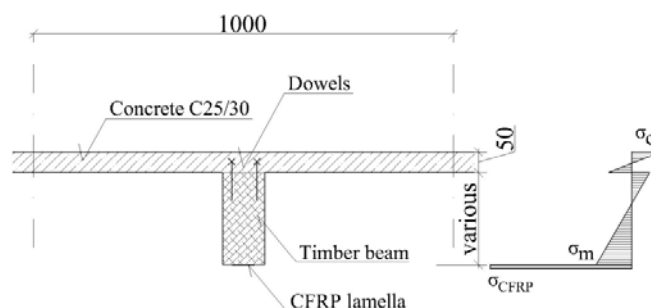

Fig. 1 Scheme of composite timber-concrete beam with CFRP reinforcement

Following dimensions and physical characteristics were used for calculation. Three profiles – 100/180, 100/200 and 100/220 were used for timber beam. Physical characteristics of timber were adapted from experimental tests of externally CFRP-reinforced timber beams and approximately respond with C16 strength class from [3]. Dimensions of concrete slab are 1 000 x 50 mm and material is considered as C25/30. Concrete slab is joined to timber beam with dowel type fasteners. The rigidity of joint, based on profile and quantity of fasteners, was included in both theoretical and numerical analysis. The value of spring constant was calculated using method in [3], Appendix B. Carbon fibre reinforced polymer lamella is 50 mm wide and 1,2 mm thick. Yield strength of lamella is 3 000 MPa and Young`s modulus is 155 GPa.

III. THEORETICAL ANALYSIS OF BEAM BEARING CAPACITY AND DEFLECTION

The method in [3], Appendix B is conservative general method for calculation of composite timber-concrete or timber-timber beam bearing capacity and deflection. With conclusions from beam with CFRP reinforcement analysis [2], method from [3] was used in combination with elastic theory for CFRP lamella. Quantity of nail type fasteners is variable, providing full bearing capacity of composite beam without limitation of joint bearing capacity. This method was also used

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in [6].

A. Determination of Effective Flexural Rigidity

First step for theoretical analysis of beam is to calculate effective flexural rigidity, using:

$$(EI)_{eff,t} = \Sigma\left(E_i I_i + \gamma_i E_i A_i a_i^2\right) \qquad (1)$$

where E_i is Young´s modulus of elasticity for each type of material, I_i is the second moment of area, γ_i is parameter of slippage (considered only for concrete slab), A_i is cross section area and a_i distance between global centre of gravity and material centre of gravity.

For long term deflection and bearing capacity, influence of creep and joint slippage have to be considered. Effective Young´s modulus and slippage modulus should be calculated using following formulas.

$$E_{c,eff}(t) = E_c(t_1)/(1 + \varphi_c(t - t_1)) \qquad (2)$$

$$E_{t,eff}(t) = E_t/(1 + \varphi_t(t - t_1)) \qquad (3)$$

$$K_{eff} = K_{ser}/(1 + \varphi_t(t - t_1)) \qquad (4)$$

Time dependent value of creep coefficient γ_c can be found in [3]. For timber, current standard (3) determines only final value of creep coefficient, named k_{def}. Parameter of slippage for concrete slab is calculated as

$$\gamma_c = [1 + \pi^2 E_c A_c s/(K_{ser} l^2)]^{-1} \qquad (5)$$

where s is nail joint spacing, K_{ser} is slippage modulus, which can be for nails given as

$$K_{ser} = \rho_m^{1,5} d/23 \qquad (6)$$

B. Normal Stress in Different Parts of Beam

Normal stress in beam should be according to (3) calculated with following formulas

$$\sigma_i = \gamma_i E_i a_i M/(EI)_{eff,t} \qquad (7)$$

$$\sigma_{m,i} = 0,5 E_i M/(EI)_{eff,t} \qquad (8)$$

C. Longitudinal Shear Stress

Longitudinal shear stress should be calculated as

$$\tau_{2,max} = \left(\gamma_3 E_3 A_3 a_3 + 0,5 E_2 b_2 h_2^2\right) V/b_2(EI)_{eff,t} \qquad (9)$$

IV. NUMERICAL ANALYSIS OF BEAM BEARING CAPACITY AND DEFLECTION

Numerical analysis was created in RFEM 3D programme. The most accurate FEM model was tuned using comparison with experimental deflection values from prior research [2] and calculated deflection of numeric model. For timber, orthotropic elastic material model was used, providing the most similar results in comparison. For CFRP lamella, the linear elastic isotropic model was used and for concrete

isotropic elastic-plastic material model was used, according to [5]. Timber-concrete joint was modelled as contact solid with attributes of elastic Coulomb friction. Joint between carbon FRP lamella and timber beam is considered as fully solid, according to results from [1] and [4]. Finally 2D FEM model was used for calculation with modified Newton-Raphson method for large deformations. Maximal load for beam ultimate limit state was calculated using theoretical analysis and then deflection of numerical model is discovered for this load. Three composite timber-concrete beams with carbon FRP lamella were compared.
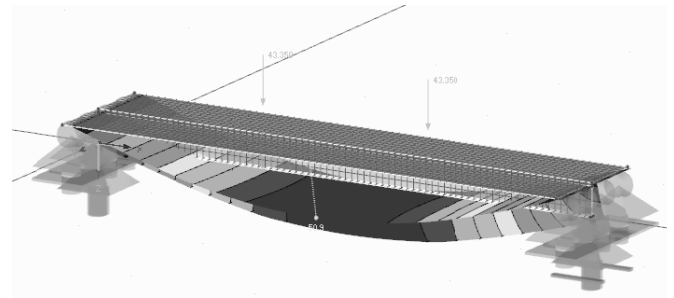

Fig. 2 Results of numerical model of composite beam

V. COMPARISON OF THEORETICAL BEAM DEFLECTION

TABLE I
COMPOSITE BEAM BEARING CAPACITY AND DEFLECTION

Timber beam [mm]	Maximum bearing capacity [kNm]	Theoretical value of deflection [mm]	Numerical value of deflection [mm]
100/180	41.85	41.14	58.70
100/200	47.83	36.68	54.02
100/220	57.80	34.93	50.89

At Table I are calculated deflections for all three timber profiles. In first column the dimensions of timber beams are named. Maximum bearing capacities, calculated using theoretical analysis, are listed in second column. In last two columns are presented values of deflection. These values significantly differentiate between each other and the divergence is up to 47%.
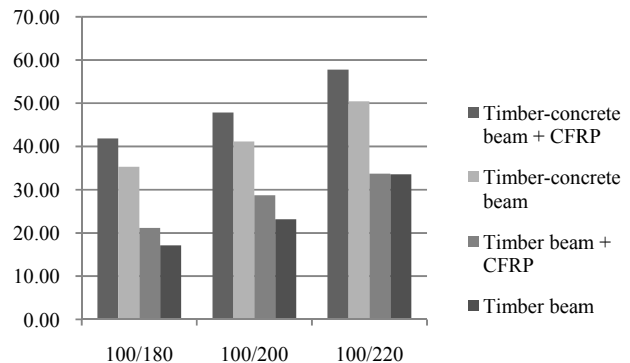

Fig. 3 Comparison of beam bearing capacity with different types of reinforcement

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On Fig. 3 are compared bearing capacities of timber beams, reinforced with CFRP lamella, with concrete slab and with concrete slab together with CFRP lamella. For these profiles, CFRP reinforcement increases bearing capacity by 14-18%. If well designed, FRP reinforcement can significantly increase bearing capacity of concrete-timber composite beam especially at shorter spans and it has also benefit for lowering ceiling deformation. Nevertheless it is necessary to reflect an economical aspect of reinforcing with FRP in comparison of influence on ceiling load capacity.

VI. FRP REINFORCEMENT TYPES PARAMETRIC STUDY

Seven examples of historic timber ceiling were used for following theoretical parametric study. Timber beams with different profile had same centre distance 1,0 m and 30 mm thick plank cover. Profiles and spans were chosen according to following method. Load capacity of beam was self-weight and imposed floor load 1,5kN, but deflection was bigger than recommended values (L/250). For safety reasons, strength class C16 (EN 338) was used for calculation, because strength tests of beam are usually difficult to perform on already built ceilings. Types of beam profiles and beam spans can be seen in Table II.

TABLE II
INPUT DATA OF ORIGINAL CEILING BEAMS

Profile [mm]	Span [m]	M_{ed} [kNm]	M_{rd} [kNm]	$w_{net,fin}$ [mm]	$L/w_{net,fin}$ [-]
120/160	3.9	4.87	5.04	20.92	L/186
120/180	4.4	6.24	6.38	24.02	L/183
120/200	4.9	7.78	7.88	27.17	L/180
160/180	5.0	8.20	8.51	30.84	L/162
160/200	5.6	10.36	10.5	35.78	L/156
180/200	5.9	11.61	11.82	39.75	L/148
200/220	6.8	15.72	15.89	48.75	L/139

Five different types of ceiling reinforcement were compared. The first option is traditional reinforcement using coupled concrete slab. On the plank cover is placed concrete C 20/25 layer 50 mm thick, coupled with nails with 6,3 mm, 7,1 mm and 8 mm diameter and different spacing. Next four types of beam reinforcement combine coupled concrete slab with glass and carbon fibre reinforced polymer lamella. GFRP lamellae have profiles 100x5 mm, 100x10 mm and 100x15 mm and material characteristics f = 1000 MPa (yield strength) and E = 46 GPa (Young`s module). CFRP lamella have profile 50x1,2 mm and material characteristics f = 3000 MPa (yield strength) and E = 155 GPa (Young`s module). Lamellae are glued on the bottom margin of timber beam. Theoretical calculation of the bearing capacity and deflection was carried out according to [3], Annex B. Slippage in the joint between timber beam and concrete slab was reflected using γ_i slippage coefficient. Joint between timber beam and GFRP lamella was considered without slippage based on elastic behaviour of timber beam.

A. Comparison of Bearing Capacity and Deflection of Reinforced Timber Ceiling

Values of bearing capacity of each timber beam reinforced with different type can be seen on Fig. 4. Maximal bearing capacities were calculated using [5] and were influenced by deflection limitation L/250. Values of deflection were considered for 50 years operating life including creep and shrinkage of concrete and creep of timber. Self-weight, floor weight 1kN/m² and variable imposed floor load were used for deflection analysis.
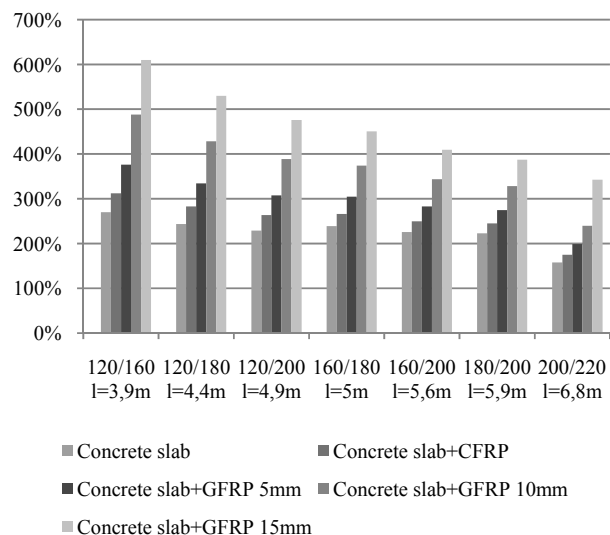

Fig. 4 Percentual increase of bearing capacity using different types of reinforcement

Increase of bearing capacity is most significant with smaller profiles and shorter spans, where, depending of used lamella, bearing capacity of original timber ceiling raised by 600%. In comparison with ceiling stiffened only with coupled concrete slab, using FRP reinforcement brings 17% to 340% higher values of bearing capacity.

B. Influence of FRP Reinforcement on Long-Term Deflection

Next comparison was made for influence of different types of reinforcement to original ceiling deflection. Same load model with self-weight and 1,5 kN imposed floor load was used as for original ceiling. As seen from Fig. 5 each type of slab reinforcement has significant influence on long-term deflection. Using both coupled concrete slab and FRP reinforcement in the other hand doesn´t have such a big impact in comparison with only coupled concrete slab. Deflection is lower using CFRP lamella by 9,3%, GFRP lamella 100x5mm by 9,8%, GFRP lamella 100x10mm by 15,2% and GFRP lamella 100x15mm by 18,9%. Other results of parametrical study can be found in [6].

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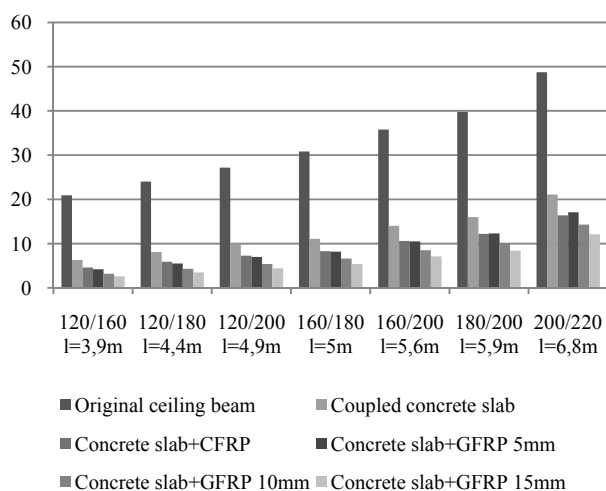Vol:8, No:11, 2014

Fig. 5 Long-term deflection of original and reinforced ceiling from self-weight and 1,5kN imposed floor load

VII. Conclusion

If well designed, FRP reinforcement can significantly increase bearing capacity of concrete-timber composite beam especially at shorter spans and it has also benefit for lowering ceiling deformation. Nevertheless it is necessary to reflect an economical aspect of reinforcing with FRP in comparison of influence on ceiling load capacity. For this theoretical analysis was chosen method from [5] reflecting also slippage in joint between timber beam and concrete slab. After pre-analysis research, this method seems to be most reliable for timber-concrete composite slab reinforced with FRP. To confirm this declaration it is necessary to run planned experimental research.

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