Analysis of the connection of the timber-fiber concrete composite structure

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Abstract. This paper deals with an implementation of the material parameters of the connection to complex models for analysis of the timber-fiber concrete composite structures. The aim of this article is to present a possible way of idealization of the continuous contact model that approximates the actual behavior of timber-fiber reinforced concrete structures. The presented model of the connection was derived from push-out shear tests. It was approved by use of the nonlinear numerical analysis, that it can be achieved a very good compliance between results of numerical simulations and results of the experiments by a suitable choice of the material parameters of the continuous contact. Finally, an application for an analytical calculation of timber-fiber concrete composite structures is developed for the practical use in engineering praxis. The input material parameters for the analytical model was received using data from experiments.

1. Introduction

Slender, aesthetic and durable constructions can be achieved by combining timber and fiber reinforced concrete (FRC). Especially an application of the ultra-high performance fiber reinforced concrete (UHPC) enables to design very slender decks, an architectonic surface of the concrete without a need of any special treatment. The structural behavior of timber-(fiber) concrete composite members is governed by the shear connection between timber and concrete in general.

2. Experiment basis

The push-out shear tests were carried out in order to determine characteristics of the connection between timber and fiber concrete members. Specimens (see Figure 1) were formed as a solid timber beam of strength class C24 coupled in five cases with a FRC slab of thickness 60 mm, and in four other cases with a UHPC slab of thickness 35 mm. The connection between the timber and fiber-concrete parts was carried out by special coupling screws TCC diameter 7.3 mm and length 150 mm embedded at an angle of 45 degrees to the timber beam. The comparison of relevant material properties of the used fiber-concretes see in Table 1.

A record of the push-out shear test represents a relationship between the connection slip and the transferred force on the contact area. A start-up inclination of the record diagram caused by pushing of supports was eliminated for purposes of the numerical simulation. This was achieved by moving
asymptotes that pass through the origin of the coordinate system. Such modified test records transferred to the stress-slip diagram are shown in Figure 2.

![Figure 1. Dimension of specimen and direction of loading.](image)

### Table 1. Material properties of the used fiber-concretes.

| Material properties                  | FRC  | UHPC |
|--------------------------------------|------|------|
| Compressive strength (MPa)           | 45   | 150  |
| Flexural strength (MPa)              | 4,4  | 14   |
| Equivalent tensile strength (MPa)    | 1,6  | 5,4  |
| Modulus of elasticity (MPa)          | 29016| 50600|

![Figure 2. Stress-slip diagram for modified records of the push-out shear tests.](image)

Results of the push-out shear tests show that a different thickness and different material properties of fiber-concrete components FRC x UHPC does not affect the structural behavior of the connection (specifically regarding a tangential stiffness, a shear strength and a strain softening), because the failure of the connection generally occurs in the area of the timber beam, the concrete remains undamaged.

3. **Simulation of experiment**

An implementation of correct material models of the connection is essential in terms of relevancy of the analysis of the timber-concrete structures. If the connection strain remains in the linear elastic
range until the timber or concrete members fail, a linear-elastic behavior of the connection may be assumed. However, if the connectors reach their load carrying-capacity, a nonlinear behavior of the composite structure should be considered.

### 3.1. Material model

The push-out shear tests were simulated with a nonlinear numerical analysis in program ATENA (Červenka Consulting, s.r.o.). A continuous contact spread over area of the contact between both composite members was applied, because the continuous contact is more suitable by use in the complex models than a model of the connection based on discrete coupling elements, which leads to a high number of finite elements and means a high computational difficulty.

The material model of the contact in program ATENA is based on the Mohr-Coulomb theory. The model of the contact is defined by parameters representing real physical properties of the contact on the one hand. That constitute a shear strength (cohesion) \( c \), a tensile strength \( f_t \) and a coefficient of friction \( \phi \). On the other hand, additional parameters, which are basic and minimum values of the axial and tangential stiffness \( K_{nn} \), \( K_{nn,\text{min}} \) and \( K_{tt} \), \( K_{tt,\text{min}} \) are defined for numerical purposes.

![Figure 3. Schema of material model used for continuous contact spread over area in program ATENA.](image1)

![Figure 4. Screenshot of simulation of the push-out shear test in program ATENA – visible deformation of the connection caused by eccentricity between load and support.](image2)

The contact surface is primarily subjected to shear in the push-out shear test, therefore the shear material parameters have a major influence in this case. A basic value of the shear stiffness determines the start inclination of asymptote of the slip-stress diagram. A value of the shear strength determines the apex of the slip-stress diagram. The shear softening can be approximated by a function defining a decrease of the cohesion depending on increasing displacement. The coefficient of friction between timber and concrete has an insignificant effect in the case of push-out shear test, because the contact surface is not pressed by external load. Although, the coupling elements are installed with an inclination of 45 degrees. Some axial stresses in the contact surface occur due to an eccentricity between the support and the introduced force. The upper part of the connection is pulled and...
the bottom part is pushed (see Figure 4). The coefficient of friction was considered with a conservative value 0.2.

It would be necessary to perform a tensile test of the connection (an additional experiment) to determine the axial stiffness and the tensile strength of the contact relatively exactly. However, the tensile strength value is usually about half of the shear strength value. Therefore, the tensile strength was derived from the shear strength. The decrease of the tensile strength (a tensile softening) should approximately correspond to the shear softening. It is recommended that the axial stiffness should be the same as the shear stiffness according to the experience of the authors of the ATENA software.

3.2. Adjustment of parameters

Basically, it can be used more ways how to achieve a good compliance of the simulation with the experiment. One approach is based on the assumption that the concrete and timber do not deform, they behave as rigid bodies. Any deformation depending on the introduced force is simulated exclusively by the material model of the contact in this case. Although, this model approximates the push-out shear test very well, it is not suitable for further application in complex models, because of its tendentious interpretation of the determining material parameters (modulus of elasticity E and Poisson's ratio v of the timber and concrete members must be adjusted).

It is more apt to implement the material characteristics E and v of the composite members unchanged and vary only the parameters of the connection. However, the calculation converges more difficult and do not reach such accordance with the experiment - see "corrugations" in stress-slip diagram (see Figure 5).

It was found that it is possible to eliminate the "corrugations" in stress-slip diagram also by reducing of the axial stiffness of the contact (see Figure 6). The smooth curve in stress-slip diagram is achieved by reducing of the axial stiffness with respect to the tangential stiffness and the model approximates the tests very well. Similarly to the experiments, a certain "jump" can be observed at the beginning of loading. The start-up inclination of the experiment record diagram caused by pushing of supports was eliminated for the purposes of numerical simulation. It is apparently, that the part
of the gradual start-up inclination is caused due to a deformation of the material of composite members.

![Graph showing effect of normal stiffness adjustment on simulation of push-out shear test.](image)

**Figure 6.** Effect of an adjustment of the normal stiffness on the simulation of the push-out shear test.

4. Complex models

4.1. Linear elastic analysis

The ultimate strength of the timber and the concrete members is mostly reached before it is achieved a nonlinear part of the stress-slip diagram. The connection can be advantageously considered as linear elastic in this case.

A simplified design method for mechanically jointed beams according to Annex B of Eurocode 5 is usually used for design purposes. This simplified design method called “γ-method” is based on the differential equation for the partial composite action with continuous constant slip stiffness. It was developed for simply supported beams subjected to loads giving a bending moment varying sinusoidal, because for such case the differential equation of the partial composite action has a simple analytical solution. However, the γ-method is sufficiently accurate also for loads giving a bending moment varying parabolic and for a slip stiffness varying according to the shear force.

A program resulting from a need of the design profession for easy and quick design and optimizing of the dimensions of the composite timber–fiber concrete structures was created in MS Excel. The program works on the basis of the γ-method. The input material characteristics of the connection received directly from the experiments are included. It is planned to create a database of the material characteristics of the connection for different arrangements of coupling elements.

4.2. Verification of nonlinear material model

A verification of the material model of the connection was made on the simply supported beam with a T-shaped cross-section loaded with a uniformly distributed load. Adjustment of the material model of the connection was made primarily in program ATENA 2D. The results were compared to 3D model in ATENA 3D and to linear calculation on the basis of the γ-method.

The T-shaped cross-section (see Figure 7) was composed of timber beam of structural timber class C24 with width 14 cm and height 24 cm coupled with fiber concrete slab of a compressive strength of 45 MPa and modulus of elasticity of 29 GPa of width 94 cm and height 6 cm. A linear elastic material model was used for timber and FRC composite members. Connection between timber and fiber-
concrete members was carried out by special coupling screws TCC diameter 7.3 mm and length 150 mm embedded at an angle of 45 degrees to timber beam. Span of simply supported beam was 4 m.

![Figure 7. Dimension of T-shaped cross-section.](image)

A change of the axial stiffness and the tensile strength of the connection has not a decisive influence on the structural behavior of the bent structure (it is logical, because a vertical load presses the joint). The curves for variants $K_{nn} = K_{tt}$, $K_{nn} = 0.5K_{tt}$, $K_{nn} = 0.1K_{tt}$, $0.5f_{t0}$, $2f_{t0}$ overlap each other in the load – deflection diagram and differ from each other in the order of hundredths (see Figure 8).

![Figure 8. Load-deflection diagram of simply supported beam with uniformly distributed load for cross-section in the middle of span. Comparison of calculation with several material parameters of connection in ATENA 2D with ATENA 3D and γ-method.](image)

In the opposite to the simulation of the push-out shear tests, the coefficient of friction $\mu$ has a considerable influence on the structural behavior of the bent beam (see Figure 8, default value $\mu = 0.2$, yellow variant $\mu = 0$). Friction takes an effect after reaching of the shear strength $c$.

The ultimate strength of the timber beam and the UHPC/FRC deck has been reached before it was achieved a non-linear part of stress-slip diagram.

5. Conclusion
An implementation of correct material models of the connection is essential in terms of relevancy of the analysis of the timber-concrete structures. If the connectors reach their load carrying-capacity, a nonlinear behavior of the composite structure should be considered. It was approved by use of the nonlinear numerical analysis in program ATENA (Červenka Consulting, s.r.o), that it can be achieved a very good compliance between results of numerical simulations and results of the experiments by a suitable choice of the material parameters of the continuous contact. It was verified that
the material parameters of the connection model derived from the experiment could be effectively applied in a complex model for elements subjected to bending. If the connection strain remains in the linear elastic range until the timber or concrete members fail, a linear-elastic behavior of the connection may be assumed. A program based on the γ-method for easy and quick design and optimizing of the dimensions of the composite timber–fiber concrete structures was created in MS Excel. The input material characteristics of the connection received directly from the experiments are included. It is planned to create a database of the material characteristics of the connection for different arrangements of coupling elements.

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