Finite Element Modelling of the Connection for Timber-concrete Composite Beams

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Abstract. The present study investigated the structural behaviour of the connection for timber-concrete composite (TCC) beams using numerical analysis. In the proposed TCC system, a concrete slab was connected to timber girders with mechanical shear connectors developed by the authors of this article. The load-slip behaviour of the connections was characterised in the push out test. Non-linear 3D finite element (FE) models of the tested joints were verified against experimental results. The comparison between the experimental and numerical results indicates that the adopted 3D model can adequately capture the response of the TCC joints.

1. Introduction
Wood is often used for building structural elements. The load-bearing capacity and stiffness of a timber beam may be increased by joining it with an element made of a different material. For this reason, composite structures may be highly efficient. In timber-concrete composite (TCC) beams a timber beam is joined with a concrete slab. The concrete may be poured into trapezoidal decking [1] on the construction site or the concrete slab may be prefabricated [2, 3]. The connection between a wooden beam and a concrete slab may be achieved by: an adhesive layer [4-6], shear connectors, e.g. nails [7], anchor connection [8], composite connectors [9], dowel-type fasters [10, 11], or a concrete plug [12].
There are some interesting composite structures with a timber element, which may provide an alternative for TCC structures, e.g.: steel-timber composite structures [13-16], timber-glass composite structures [17, 18] and aluminium-timber composite structures [19].

2. Problem formulation
This article presents a numerical simulation of the push-out test of the mechanical shear connectors developed by its authors. Push-out tests are often used to investigate resistance and stiffness of connectors [20-22]. The mechanical properties of connections play an essential role in the behaviour of TCC beams. For this reason, the authors of this article prepared laboratory tests of such connectors. The results of the above-mentioned tests were presented in article [23] and they were used to verify the numerical model. The load-slip model of behaviour of the connector obtained from these tests was used for a non-linear analysis of the TCC joints (see Figure 1).
3. Numerical model

The numerical model was prepared in the Abaqus program [24]. The results from the laboratory tests presented in [23] were used to discuss the load-slip behaviour of the connections. An experimental model consisted of: two concrete slabs made of C60/75 concrete, two steel sheets made of 0.7 mm-thick S320GD steel, four shear connectors developed by the authors of this article made of S235 steel, two reinforcing meshes made of 6 mm S235JRG2 steel, round bars and a timber beam made of GL28h timber. The numerical model had two axes of symmetry. For this reason, the authors of this article prepared only 1/2 of the model (see Figure 2). The shear connectors were modelled implicitly using a zero-length spring and the load-slip model from the laboratory tests presented in the article [23].

![Figure 1](image1.png)

**Figure 1.** Non-linear load-slip response for one connector [23]

![Figure 2](image2.png)

**Figure 2.** Connection model in the Abaqus program: a) complete model; b) half of the model;
1 – concrete slab, 2 – timber beam, 3 – steel plate, 4 – steel mesh, 5 – profiled steel sheeting

The concrete slab and the timber beam were divided into eight-node cuboidal finite solid elements (C3D8R), the reinforcing meshes were modelled by means of truss elements (T3D2), and the steel mesh and sheeting were divided into four-node shell elements (S4R). The mesh size was 20 mm. The total number of all such elements was 12 650. Surface-to-surface “hard” contact and friction were defined between the flange of the timber beam and the edge of the concrete slab. The coefficient of friction was 0.3. The meshes were embedded in the concrete slab. The calculations were performed...
using the Newton-Raphson method in the Abaqus program. The load was applied in the form of displacement. Figure 3 presents the boundary conditions used in the computer model.

![Boundary conditions](image)

**Figure 3.** Boundary conditions: 1 – displacement, 2 – displacement in x, y, z directions (blocked), 3 – displacement in y direction (blocked) and rotation around x and z axes (blocked), 4 – connector (spring).

The behaviour of glued laminated timber (GLT) was modelled using an elastic-perfectly plastic model. The non-linear behaviour of concrete was captured using the concrete damaged plasticity (CDP) model available in the Abaqus program and successfully used in [25-29]. The behaviour of the materials is presented in Figure 4.

![Material models](image)

**Figure 4.** Material models

The stress-strain diagram for the analysis of the concrete subjected to compression was adopted from [30], the stress-strain diagram for the analysis of the concrete subjected to tension was taken from [31]. The compressive strength of the concrete was based on own laboratory tests, and the tensile
strength of the concrete was taken from [30]. The value of the fracture energy and the critical crack opening were calculated using the formulas presented in [31–34]. The parameters for GL28h were based on the standard [35]. The material parameters for S235 steel were from the standard [36]. All the parameters of the materials used in the numerical model are presented in Tables 1, 2 and 3.

**Table 1. Parameters of materials used in numerical calculations.**

| Material | Parameter | Value |
|----------|-----------|-------|
| Concrete C60/75 | Young’s modulus $E_{cm}$ [MPa] | 39 000 |
|          | Poisson’s ratio $\nu$ [-] | 0.20 |
|          | Mean value of concrete cylinder compr. strength $f_{cm}$ [MPa] | 68.0 |
|          | Mean value of axial tensile strength of concrete $f_{ctm}$ [MPa] | 4.4 |
|          | Largest nominal maximum aggregate size $d_a$ [mm] | 16.0 |
|          | Fracture energy $G_F$ [N/m] | 103.5 |
|          | Parameter $n$ [-] | 0.7 |
|          | Dilatation angle [°] | 40.0 |
|          | Eccentricity [-] | 0.1 |
|          | $f_{b0}/f_{c0}$ [-] | 1.16 |
|          | Parameter $\kappa$ [-] | 0.667 |
|          | Viscosity parameter [-] | 0.001 |
| GL28h     | Young’s modulus $E_{0,mean}$ [MPa] | 12 600 |
|          | Poisson’s ratio $\nu$ [-] | 0.3 |
|          | Compression strength, parallel to grain $f_{c,0,k}$ [MPa] | 26.5 |
| S235      | Young’s modulus $E$ [MPa] | 210 000 |
|          | Poisson’s ratio $\nu$ [-] | 0.3 |
|          | Yield strength [MPa] | 235.0 |

**Table 2. Material parameters used in the CDP model for the C60/75 concrete subjected to compression.**

| Stress [MPa] | Crushing strain [-] | Concrete compression hardening | Concrete compression damage |
|--------------|---------------------|-------------------------------|----------------------------|
| 22.300       | 0.00000000          | 0.000                         | 0.00000000 |
| 46.285       | 0.00011321          |                               | 0.0011321 |
| 51.760       | 0.00017283          | 0.000                         | 0.0017283 |
| 56.621       | 0.00024818          | 0.000                         | 0.0024818 |
| 60.780       | 0.00034155          | 0.000                         | 0.0034155 |
| 64.127       | 0.00045573          | 0.000                         | 0.0045573 |
| 66.530       | 0.00059410          | 0.000                         | 0.0059410 |
| 68.000       | 0.00085641          | 0.000                         | 0.0085641 |
| 67.817       | 0.00096111          | 0.003                         | 0.0096111 |
| 67.244       | 0.00107579          | 0.011                         | 0.0107579 |
| 66.244       | 0.00120143          | 0.026                         | 0.0120143 |
| 64.774       | 0.00133912          | 0.047                         | 0.0133912 |
| 62.785       | 0.00149013          | 0.077                         | 0.00149013 |
| 60.221       | 0.00165587          | 0.114                         | 0.00165587 |
| 57.018       | 0.00183800          | 0.162                         | 0.00183800 |
| 53.102       | 0.00203842          | 0.219                         | 0.00203842 |
| 48.386       | 0.00225933          | 0.288                         | 0.00225933 |
Concrete compression hardening

| Stress [MPa] | Crushing strain | Concrete compression damage |
|--------------|-----------------|----------------------------|
| 42.771       | 0.00250331      | 0.371                      |
| 36.138       | 0.00277339      | 0.469                      |
| 28.348       | 0.00307314      | 0.583                      |
| 19.234       | 0.00340682      | 0.717                      |
| 8.5970       | 0.00377957      | 0.874                      |
| 2.6330       | 0.00398248      | 0.961                      |

**Table 3.** Material parameters used in the CDP model for the C60/75 concrete subjected to tension (n=0.7).

Concrete tension stiffening

| Stress [MPa] | Cracking strain | Concrete tension damage |
|--------------|-----------------|-------------------------|
| 3.900000     | 0.0000000       | 0.0000000               |
| 2.947157     | 0.0001244       | 0.001244                |
| 2.5020962    | 0.0001854       | 0.0001854               |
| 2.218909     | 0.0002431       | 0.0002431               |
| 1.814188     | 0.0003535       | 0.0003535               |
| 1.070363     | 0.0008226       | 0.0008226               |
| 1.028382     | 0.0008736       | 0.195992                |
| 0.955266     | 0.0009755       | 0.253156                |
| 0.893613     | 0.0010771       | 0.301357                |
| 0.840809     | 0.0011784       | 0.342640                |
| 0.774267     | 0.0013301       | 0.394664                |
| 0.577958     | 0.0020352       | 0.548142                |
| 0.510162     | 0.0024369       | 0.601146                |
| 0.259079     | 0.0064434       | 0.797447                |

4. Results and discussions

The results from the laboratory test [23] and numerical simulation are presented in Figure 5. The adopted 3D model adequately captured the response of the TCC joints.

**Figure 5.** Force-slip diagrams from the push-out tests: 1 – Laboratory test [23], 2 – FEA analysis
The first part of plot 1 presented the cyclic load. This phase of the test was used to eliminate clearances. In the numerical simulation, the first part of the test was modelled using the springs with low stiffness (see Figure 1). For this reason, the first part of plot 2 (from 0.0 kN to the point where the load reached 8.0 kN) presented the initial slip. The load-slip model of behaviour of the connector obtained from the laboratory test was successfully used for a non-linear analysis of the TCC joints. This model could also be used in a non-linear analysis of the TCC composite beams, which requires further investigation.

5. Conclusions
The main conclusions of this paper include:

- The mechanical properties of connections play an essential role in the behaviour of TCC joints.
- The load-slip model of behaviour of the connector, obtained from laboratory tests, may be successfully used for a non-linear analysis of the TCC joints.
- The adopted 3D FE model adequately captured the response of the TCC joint.

Future tests should focus on using such connection in timber-concrete composite beams.

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