EVALUATION OF TIMBER BEAMS REINFORCED WITH FRP FABRICS

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ABSTRACT

The principle of reinforcing and strengthening timber elements can be considered to be a specific application. In the area of reinforcement, factors related to anisotropic timber properties must be taken into consideration. The authors of this article focus on evaluating the increased load bearing capacity of timber elements using FRP materials. Various marginal conditions, which have an impact on the value of strengthening, have been assessed in the experiments. These conditions included the type of fabric, its thickness, and the type of timber material. (solid and glued laminated timber, glulam). Furthermore, the types and causes of individual failures of both beams and FRP materials were analysed. The elasticity and flexibility characteristics of materials strengthened by such methods were determined. The relationships achieved were compared with a numerical model using a finite element method in the ANSYS program. However, the resultant values are not the only important considerations to be included in any proposal concerning the strengthening of timber constructions. To provide optimum behaviour of the strengthened construction it is also important to achieve an effective cooperation between fabric and timber surface. The experiment also involved an analysis of the influence of moisture content of the timber during fabric application.

KEYWORDS
Timber structures, strengthening, FRP materials.

INTRODUCTION

Within building constructions we can encounter composite materials in many variations. Most commonly these are fibre composites in the form of fabrics, lamellas or rods with carbon, glass or aramid fibres. Although a lot of research is being done with FRP–timber reinforcement, (Johnsson et al, 2006), the utilization of those materials for strengthening timber constructions has been rather limited. Along with the evolution of modern engineered wood materials and wood-based materials in terms of utilization, the requirements concerning strengthening of major stress points or complete elements have increased as well. Another significant area of utilization of such materials can be the additional strengthening of timber elements during repairs and building restorations.

EXPERIMENT

Materials

To strengthen timber beams, fabrics with carbon and glass fibres have been chosen. In the process the fibres have been oriented in one direction. This unidirectional orientation with timber beams can be considered sufficient with regards to the prevailing tensile effect during experimental stressing. In the case of both types of fibres, fabrics with two different thicknesses have been selected. These were applied on timber beams having uniform dimensions of 100×120×2300 mm. Two-component epoxy adhesives were used which consist of epoxy resin and two amine groups (Polyoxypropylenediamine and Polyetheramine). In both cases, spruce wood, (Picea abies) has been selected, both solid and glued laminated. Glued laminated timber beams consist of three laminations 40 mm thick, each was lengthened by finger joints. The number of test pieces with specifications for the fabrics used is shown in Table 1.
To verify the influence of wood moisture content for application of fabrics we also used spruce wood, from which test prisms with dimensions of 75×75×40 mm were made. Glass fibre fabric was then applied on these test samples.

METHOD OF SOLUTION

Technology of application

Prior to the experiment the timber beams to be strengthened were dried to an equilibrium moisture content corresponding to laboratory conditions. Following the acclimatization the timber beams showed moisture content between 9.1 and 10.2%. Prior to application the timber surfaces were properly polished and cleaned of dust and other fine particles. Consequently these wood surfaces were penetrated with epoxy resin. At the same time both sides of the fabric strips were penetrated as well. Using a roller, the fabric was placed on the timber beam surfaces to be strengthened. It was not possible to achieve sufficient fibre coverage with one application, so that once the composite was cured, a second layer of epoxy resin was applied.

The same process was used when applying fabric on the timber prisms. The impact of wood moisture content on fabric retention was analysed using these timber prisms. The fabric was applied under different levels of moisture content of the prisms, which was achieved by exposure of the samples in a humidity cabinet ERICHSEN Hygrotherm 519.

Geometry and Loading

Within the experiment, strengthened beams having a cross section of 100×120 mm, were loaded in accordance with the diagram specified in Figure 1. The rate of beam loading was set to achieve the highest load within $300 \pm 120$ s with the frequency of recording 5 Hz.

![Figure 1. Diagram of loading of strengthened beams on four-point bending pursuant to EN 408](image)

In the case of samples intended for analysis of the impact of wood moisture content on retention ability, circular removable discs with diameter of 50 mm were glued, using epoxy resin, on the finish cured CFRP surface. After resin curing the CFRP fabric was cut around the circular disc down to the timber surface and then the disc was inserted into a clamping device. The loading process started, and the maximum tensile force corresponding to the separation of the disc from the surface was recorded.

Assumptions

According to the analytic calculation, strengthening in the direction of the element fibres should only have little impact on load bearing capacity and rigidity (up to 20%). The taller the beam, the less impact strengthening will have.

RESULTS AND DISCUSSIONS

Reinforced Beams

The load-bearing test of the beams with a cross section of 100×120 mm included the experimental testing of six series of samples reinforced with glass and carbon fibre fabrics. The samples were made of solid wood and glued laminated wood. The procedure was carried out in accordance with EN 408, and determined both the effective local, $(E_{m,l})$ and global $(E_{m,g})$ flexural modulus of elasticity and shearing modulus of elasticity $(G)$. Used for the calculation of the effective bending stiffness $(EI)_{eff}$ and shear stiffness $(GA)_{eff}$ of the composite beam. The observed values of reinforced timber beams including the FRP fabric specification are shown in the following Table 1.
Table 1. The achieved results of timber beams reinforced with the CFRP and GFRP fabrics

<table>
<thead>
<tr>
<th>Specimen</th>
<th>FRP fabric</th>
<th>Composite beam stiffness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Material</td>
<td>Fibre</td>
</tr>
<tr>
<td>1 R1 – R3</td>
<td>glulam (unreinforced)</td>
<td>31.0</td>
</tr>
<tr>
<td>2 R4 – R6</td>
<td>solid (unreinforced)</td>
<td>34.3</td>
</tr>
<tr>
<td>3 C1 – C6</td>
<td>glulam carbon</td>
<td>1.00</td>
</tr>
<tr>
<td>4 C7 – C12</td>
<td>glulam carbon</td>
<td>0.17</td>
</tr>
<tr>
<td>5 G1 – G6</td>
<td>solid glass</td>
<td>1.30</td>
</tr>
<tr>
<td>6 G7 – G12</td>
<td>solid glass</td>
<td>0.66</td>
</tr>
<tr>
<td>7 C13 – U18</td>
<td>solid carbon</td>
<td>1.00</td>
</tr>
<tr>
<td>8 G19 – G24</td>
<td>solid carbon</td>
<td>0.17</td>
</tr>
</tbody>
</table>

* tensile strength of the composite (including resin) parallel to FRP fibre

The experimental results achieved were compared to the values of reference samples. These values represent the relative percentage of growth of the load bearing capacities and rigidities of the elements. Then, these were compared with the calculated theoretical values, and graphically specified in Figures 2 to 5. In the case of reinforcement using carbon fibres there was a greater variability of the results achieved, as the samples had a tendency to fail due to brittleness in the reinforced layer at high deflection values. However in real constructions such high deflection is not acceptable, and therefore the elements reinforced with carbon fibres can also be used.

As for the assessment of the influence of the load bearing capacity it was experimentally verified that the fabric thickness has an essential impact on the resultant rigidity of the reinforced beam, which is proven by the higher load bearing capacity values achieved for reinforced beams with thicker types of the CFRP and GFRP fabrics. This applies to solid wood as well as glulam. A substantial increase in load bearing capacity has been identified with glued laminated beams with carbon fabric having a thickness of 1.0 mm (see Figure 3).

In the case of glued laminated wood, the impact of fabric thickness on the deflection and modulus of elasticity for members with a load bearing capacity of 20 kN was proven. When using thicker carbon fabrics the modulus increased by the value of 23.8%.

The experimentally achieved values corresponded best with the theoretical calculations for bearing capacity and stiffness with beams reinforced by glass fibres (Fig. 4). The glued laminated wood elements showed higher load bearing capacities when compared to the theoretical calculations.
Comparison of achieved values with numerical model

The numerical analysis was carried out to obtain a more accurate prediction of reinforced beam behaviour than the analytical approach and to compare real test data with simulation results (Fig.6). The real stress-strain relationships of wood specimens were used for the non-linear material model. The deflection of glass-fibre reinforced beams corresponds to the numerical result up to 60 mm. However, in some cases (Fig.7 – G16) premature failure occurred due to the brittle behaviour of wood in the tension zone which immediately impacted the reinforcing layer.

Figure 6. Comparison between numerical simulation and real behaviour of reference specimens

The stiffness of carbon-fibre reinforced beams (Fig. 8) was slightly less than the numerical prediction. It may be caused by the slip in the contact area which was neglected in the finite element model and which will be more significant in thin carbon layers with a high modulus of elasticity than in glass-fibre reinforcement.

Characteristics of failure

The important aspect during loading of the reinforced beams is the type of failure of the beams at the failure limit. The individual types of failures of solid and glued laminated wood are specified in Table 2. Generally it can be said that reinforcements at the bottom part of the beams have increased the load bearing capacity of the beams during deflection. Even to such a degree that in several cases with solid wood beams a failure on the...
compression side was identified. Nevertheless, in most cases the most frequent type of failure was a brittle failure of the applied composite along with the failure of the tension side of the wood (Figures 9 and 10). In the case of glued laminated wood the reinforcement of the lower edge prevented failure of the finger joint. Nevertheless there were some cases observed when a premature failure occurred precisely in the spot of the lamellas finger joints. Another timber characteristic substantially influencing the location and type of failure was the presence of knots. Though in the majority of cases healthy knots in beams were noticed, the failure occurred directly in the places of knot occurrence.

Table 2. Types of failures during loading on the failure limit

<table>
<thead>
<tr>
<th>Designation</th>
<th>Type of failure</th>
<th>Number of occurrences</th>
<th>Description of failures</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Drawn side – crack is going in the &quot;neutral&quot; plane</td>
<td>11/6</td>
<td>A</td>
</tr>
<tr>
<td>B</td>
<td>Shear failure in neutral plane</td>
<td>5/6</td>
<td>B</td>
</tr>
<tr>
<td>C</td>
<td>Failure of finger joint</td>
<td>0/4</td>
<td>C</td>
</tr>
<tr>
<td>D</td>
<td>Fibrous and/or blunt cross fracture</td>
<td>1/3</td>
<td>D</td>
</tr>
<tr>
<td>E</td>
<td>Failure in the area of knot imperfection</td>
<td>10/3</td>
<td>E</td>
</tr>
<tr>
<td>F</td>
<td>Shear failure going from the surface to the &quot;neutral&quot; axis</td>
<td>8/2</td>
<td>F</td>
</tr>
<tr>
<td>G</td>
<td>Shear failure along the entire width of the beam</td>
<td>2/2</td>
<td>G</td>
</tr>
<tr>
<td>H</td>
<td>Delamination with failure in the wood</td>
<td>0/2</td>
<td>H</td>
</tr>
<tr>
<td>I</td>
<td>Delamination of the composite with the failure in the wood</td>
<td>0/1</td>
<td>I</td>
</tr>
<tr>
<td>J</td>
<td>Collapse due to compression on the pressure side</td>
<td>5/0</td>
<td>J</td>
</tr>
</tbody>
</table>

Figure 9. Typical illustration of brittle failure of the CFRP and destruction of wood in neutral axis

Figure 10. Typical illustration of brittle failure of the CFRP and destruction of wood in neutral axis

Figure 11. Typical illustration of destruction in the area of knot imperfection (E)

Figure 12. Illustration of delamination of glued laminated wood (H)
Influence of the Wood Moisture Content

The remarkable decrease of adhesion of the applied fabric to the wood can be identified only in cases where the moisture content value of 30.0% is exceeded. This moisture content limit of the wood corresponds to the value of the fibre saturation point, when water in wood can be found only in cell walls even though the cell lumens do not contain any water. Once this moisture content is exceeded, free water penetrates into the cell lumens and prohibits a good penetration of lumens with resin. In cases when the moisture content of wood exceeded 30.0% the retention ability test results showed this, and there were linear reductions of adhesion. With moisture content up to 30% the values of adhesion considerably differed one from another. Therefore, based on the results achieved, more precise classification of adhesion up to this limit cannot be significantly derived. However, on the basis of the results achieved it can be stated that in the case of application on a real construction that is exposed to a common moisture microclimate in a protected construction, reinforcement with FRP materials can be done where the moisture of timber elements does not exceed the fibre saturation point.

CONCLUSIONS

When strengthening curved beams with carbon or glass fibre fabrics laid in the direction of the wood fibres the increase in the load bearing capacity or decrease in deflection compared to the non-strengthened element will not be substantial, (less than 20% of the original values). Such application is meaningful especially with restorations and repairs of older timber constructions (Schober and Rautenstrauch, 2006), where the strengthening of the tension edge of the element substantially restricts spreading and occurrence of new cracks. The elements can also be strengthened with fabrics having fibres laid perpendicularly to the element fibres. The strengthening will be evident particularly in areas subjected to tension perpendicular to the fibres. One example is the possibility to decrease the minimum pitch of connecting devices or to decrease the radius of bending of glued frames and arched beams.

The real influence of the strengthening can differ from the calculated theoretical value due to a lower shear rigidity or load bearing capacity in a glued joint. The resultant values can be influenced by the applied technology of gluing and initial moisture content of the wood. Changes in the shape of a timber element, (for instance swelling, shrinking or visco-elastic creep), can also influence cohesion of the connected materials unfavourably. The most appropriate method to determine the real influence of strengthening on the load bearing capacity and deformation is an experimental test carried out on an element having the same real dimensions as those which will be used within the construction.

The composites with carbon fibres attained better results than materials with glass fibres. However, their price in relation to the achieved characteristics of the construction must be taken into account.

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