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Experimental and statistical analysis of spruce timber beams reinforced with CFRP fabric

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HIGHLIGHTS

- We made experiments on reinforcement of Norway spruce beams with CFRP fabric.
- Load-bearing capacity of four-point bending tests and stiffness were determined.
- Detailed statistical analysis of measurement data were conducted.
- Test specimens were grouped and evaluated according to their mechanical behaviour.
- Reinforcement increases load-bearing of spruce beams by 30%, stiffness by 16%.

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ABSTRACT

Enhancement of timber beams with fibre reinforced materials gained momentum in the last few decades producing a wide range of materials, techniques and modelling methods. Experiments show that the potential improvement of structural behaviour is greatly affected by the type of reinforcement, wood species, etc. In this study a series of experiments were conducted on sawn Norway spruce beams reinforced with various amounts of CFRP sheets (carbon fibre reinforced plastic) followed by a statistical analysis. A moderate increase of load-bearing capacity and ductility (approx. 30%) and a small increase of elastic stiffness (approx. 16%) can be achieved. Statistical analysis of the results has shown that the performance of reinforced spruce beams is affected by the presence of knots in the material.

1. Introduction

Application of fibre reinforced plastic materials for reinforcement in structural engineering has now a history of several decades, however, reinforcing timber structures in this way has come in focus in the last twenty years. Early works in this field reach back to the 1960's when pioneering studies on the feasibility of application of fibreglass (GFRP) on timber structures were conducted (see e.g. [1]). Later attention turned to investigations into the use of carbon fibre reinforced plastics (CFRP), too [2]. Use of FRP materials proved a promising approach in various engineering problems, e.g. enhancing structural performance of sawn timber beams (e.g. [3–8]) or glued-laminated (glulam) beams [9–11], and also for repairing or strengthening old historic beams in existing structures or bridges [12–14]. A wide range of reinforcing elements has been devised, usually sheets or rods parallel to grains but shear elements, connectors or pultruded elements as well. The reinforcing material is commonly fitted to the tension side but often inserted into slots or grooves in the wood, e.g. [13–18]. Materials applied for reinforcement is mostly glass fibre or carbon fibre, rarely aramid or basalt [19,20]. An important aspect of the behaviour of the composite material is the bond between wood and the fibre reinforced plastic. Investigation started several years ago [21]. The concern of interface failure under various loading was addressed in [22] and guidelines for characterization was given. The concept of reinforced laminated wood products with the simultaneous moulding of the composite and adhesion of wood was investigated in [18]. Pull-out tests of FRP bars or plates glued in wood or glulam were carried out by several authors [23–26], and shear behaviour of FRP-timber joints was studied by [27].

Studies on reinforcement of timber aiming to improve behaviour with respect to flexural capacity, stiffness, and ductility

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yielded results in quite a wide range. Most of them report increase of capacity in the range of approx. 20–50%, (e.g. [28,4]), however higher values are also reached [13,29,7,14]. In terms of stiffness most authors agree in insignificant or no increase at all [12,30,31], however some research conclude considerable (near 30% or even higher) increase [5,13,32]. A general observation is the increased ductility of the reinforced beams. However, results to the contrary are also found, see e.g. [19], though here the beam length-to-height ratio was low and pure bending was not ensured. Simultaneously with experimental studies, analytical research and numerical modeling have also been conducted over the last several years. Without attempting to be comprehensive, see e.g. [4,7–9,11,14,22,23,30,33].

Research performed in this field over the last two decades has revealed that a large variety of reinforcement techniques and base materials has been applied for several engineering purposes resulting in a complex mechanical behaviour depending on several factors including materials, dimensions, reinforcement types, etc. Timber material available at different locations are often specific to that particular area and material properties may vary significantly even within the same species limiting the applicability of the results in the case of different structural arrangements. The objective of our research was to examine the composite structure of a timber beam made of spruce, which is commonly available worldwide, and flat fibre reinforced plastic lamellae fitted to the tensile side, an arrangement which is easily applicable in various mechanical problems. The species chosen for the experiments is *Picea abies* (Norway spruce) native to Europe while other species of the genus *Picea* are found in several regions worldwide, and the reinforcement is composed of several amount of carbon fibre fabric embedded in epoxy resin. Since publications on the reinforcement of Norway spruce are scarce, diversity of results on other species cannot provide sufficient guidelines for engineers wishing to design reinforcement of timber of that species. This research aims to determine the increase of the flexural capacity and the stiffness of the composite beams when reinforced with CFRP through a number of experiments and thus to verify the efficiency of reinforcement. Preliminary tests on small scale samples have verified the expected increase and the ability to create a fully functional bond between reinforcement and spruce beams, and an ongoing industrial project also gives further verification. A statistical analysis is performed to quantify the reliability of the tests and to evaluate the results.

2. Tests

2.1. Materials

Timber for the beams was sawn of Norway spruce (*Picea abies*) in rectangular solid cross-sections of 95 mm-by-95 mm with random orientation with respect to growth-rings (i.e. R and T directions were not aligned with the contour of the cross-section). All specimens were dried to moisture content of 12%. Via visual inspection and non-destructive tests it was ensured that the test specimens had no major visible defects or damage, such as drying splits, biological deterioration, etc. Presence of knots was allowed as a natural feature of the species.

Fibre reinforcements were prepared in situ using unidirectional (99% of fibres with respect to surface in warp, 1% in weft) carbon fibre fabric of 300 g/m^2 weight and a two-component epoxy resin applied manually in approximately 0.5 kg/m^2 amount. The epoxy resin was applied on the surface in the prescribed amount following manufacturer's instruction using rollers. The fabric was then placed and impregnated with resin completely manually such that the strengthening took place simultaneously with the bonding to the wood. The product application instructions required no clamps or any mechanical device to apply pressure because the system is designed for retrofitting for concrete or timber even in an overhead position.

2.2. Measurement set-up

Four-point bending tests of a series of specimens have been prepared with supports of 1800 mm span. The geometric parameters of the beams were set to comply with the European standards regarding testing. The experiments were conducted in a laboratory accredited for timber structural testing using a standard MTS testing device with capacity of 250 kN. Load was applied by a single actuator and transmitted to the test specimens at two points via an intermediate beam of 600 mm span centrally aligned, see Figs. 1 and 2.

A total of forty-four specimens were prepared, of which eight without any reinforcement and thirty-six with various amounts of CFRP fabric. Twenty and eight specimens were fitted with a single and a double layer of fabric on the entire width of cross-section, respectively, while the remaining eight specimens were reinforced with a narrower strip (50 mm) of single layer CFRP fabric centrally aligned with respect to the vertical symmetry plane. In all cases the CFRP fabric was glued to the tensile face of the beam at full length and then were cut through just near the supports. The four types of test specimens are denoted by S0, S1, S2, and SN, respectively. A summary of the data are shown in Table 1. One of the specimens with the CFRP strip attached is shown in Fig. 3.

The density of the wood of all specimens were measured giving an average of 476 kg/m^3 with relative standard deviation of 8.5%. The data were grouped and analysed with respect to the division into groups S0, S1, S2, and SN, yielding averages and relative standard deviations as 456 kg/m^3 (5.4%), 495 kg/m^3 (9.2%), 465 kg/m^3 (7.5%), and 459 kg/m^3 (5.6%), respectively. The data are in correspondence with usual values associated with the species.

3. Experiment results

3.1. Loadbearing and stiffness

Measurements of the loading and the deflection of the middle cross-section of the beam have been performed by the testing device and a videoextensometer, respectively, and the data have been recorded digitally for analysis. Fig. 4 shows the load–deflection diagrams for all specimens in the same coordinate system. Curves in test groups S0, S1, S2, and SN are plotted in thick solid, thin dashed, thin dash-dot, and thin solid lines, respectively. Ultimate loads and corresponding maximum deflections for all curves are plotted in Fig. 5.

Beams without reinforcement have been prepared and tested to make a reference. Eight specimens were examined and evaluated. The mean load-bearing capacity of the sample is 23.220 kN with standard deviation 7.696 kN. The mean value of the corresponding maximum deflections is 41.312 mm with standard deviation 15.438 mm. Linear elastic stiffness of the specimens is measured at the initial sections of the load–deflection curves.

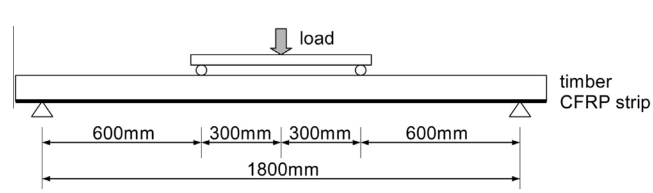

Fig. 1. Four-point bending test arrangement.