STRENGTHENING OF RC BEAMS WITH AN INNOVATIVE TIMBER-FRP COMPOSITE SYSTEM

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The results of a theoretical and experimental research project on the use of an innovative technique for strengthening concrete beams are presented. A spacer element is inserted between the tension side of a beam and the composite material to increase its lever arm and to enhance the overall stiffness of the strengthened beam. The main aim of this exploratory project was to increase the ultimate failure load of strengthened beam specimens, whilst guaranteeing acceptable overall deflections at the serviceability limit states. This resulted into a significant reduction in the amount of FPR required and in a better utilization of the materials employed. A preliminary theoretical study was carried out to investigate the effect of Young’s modulus, failure strain, and thickness of the element to be used as a spacer in order to determine the best possible candidate material. Three tests on 2.5-m-long beams were carried out, and different anchorage techniques were used to try and prevent the debonding of the strengthening system. The results from this pilot study are very promising, as the strengthening system ensures an adequate initial stiffness along with an improved ultimate flexural capacity.

Introduction

The flexural strengthening of RC structures by externally bonding a FRP reinforcement to their tension side has become a well-established procedure, and it is often preferred to more conventional strengthening techniques. Several performance issues, especially concerning serviceability conditions, however, require the use of large amounts of external reinforcement to ensure that deflection and cracking requirements are met. Thin can often result in an uneconomical use of strengthening materials and yield an undesired, or unintentional, large increase in the ultimate capacity of an element or structure, which needs to be considered carefully, because it might affect or alter its ultimate failure mode. The new strengthening technique discussed in this paper attempts to address the above-mentioned issues by using a combination of purposely chosen materials, so as to optimally exploit their mechanical properties. A spacer is positioned between the beam and the external reinforcement to provide the necessary stiffness at the serviceability limit state (SLS) and to improve the performance at the ultimate limit state (ULS), owing mainly to the resulting increased lever arm of internal forces. The effects of mechanical properties of the material to be used as a spacer were investigated in a preliminary feasibility study. The cost and availability of candidate materials were

also taken into account. The spacer material must be stiff enough to control the deflection of the strengthened beam and light enough to limit the amount of the additional weight. Timber was selected for this project and was used as a spacer material for the beams tested during the experimental programme reported here.

Although the system investigated differs from those used in other applications, important insights can be gained by examining the available literature on the use of FRPs in combination with timber and concrete. One of the main concerns when combining different layers of structural materials is guaranteeing the development of an adequate composite action. Thus, the magnitude of the shear stresses developed at the interface layers, as well as within the materials, needs to be controlled.

Brody et al. [1] conducted a study on the strengthening of glulam beams with concrete and FRP and reported that the ability of the glulam beam to transfer shear stresses was critical in guaranteeing a successful application of this technique. A theoretical increase of about 500% in the bending moment capacity of the strengthened beam was estimated if full composite actions could be ensured.

Craig et al. [2] studied the behaviour of FRP-glulam-concrete bridge girders. The gain in the service load was estimated to be about 500% over that of conventional noncomposite timber beams. Although a relative slip between the materials used, leading to a strain discontinuity at the timber-concrete interface, was noticed due to the fatigue damage, no significant loss in the ultimate capacity or ductility was observed. Results of the two studies mentioned above have shown that the use of a combination of concrete, timber, and FRPs can significantly enhance the overall structural performance of an element.

Brunner [3] studied the influence of various types of timber-concrete connections and concluded that adhesive connections allow a better distribution of shear stresses over a larger surface, whilst the use of mechanical connectors may result in the development of critical stress concentrations. Moreover, if the relative slip of concrete-timber is eliminated by using adhesive connections, the bending stiffness of the element increases, and smaller overall deflections are observed.

**Theoretical Investigation**

A preliminary analysis was conducted to investigate the influence of various parameters that can affect the overall behaviour of a reinforced concrete beam strengthened with the timber-FRP system proposed here. As the primary objective of this simple analysis was to determine the required stiffness provided by a spacer to effectively control deflections under service loads, a linear elastic analysis was considered to be appropriate. In addition, a nonlinear finite-element analysis was carried out to gain additional insights into the ultimate behaviour of the strengthened element and to investigate the effect of spacer geometry on the distribution of stresses along the end anchorage regions.

**Sectional analysis.** The geometrical and mechanical properties of the strengthening system investigated through the implementation of a sectional analysis were the spacer thickness, Young’s modulus, the ultimate strain of the spacer material, and the amount of FRP. Figure 1 shows the moment–curvature diagram for a cross-section of a beam strengthened with a timber-FRP element. For low levels of applied load, the overall behaviour of the beam is controlled mainly by the nature of the spacer material, which must provide a sufficient stiffness and effectively limit the curvature and deflections. When the maximum strain in the spacer reaches its ultimate value, the material, which was modelled according to a brittle elastic formulation, fails, and the internal bending moment is resisted only by the compressed concrete and the stretched FRP. The transition between the two stages is marked by a sudden drop in the resisted moment, along with a rapid increase in the curvature of the section.

An appropriate combination of the geometry and mechanical properties of the spacer with the amount of FRP reinforcement can result in the development of a pseudo-ductile behaviour of the beam, for which the ultimate load is similar to the load that induces failure of the spacer, yet allowing much greater deflections. A stiffer spacer material would allow a greater control of deflections under service conditions, but would result in a brittle-like behaviour (see Fig. 2), as the FRP cannot accommodate higher values of moment before the crushing of concrete. After the rupture of spacer, the increase in the ultimate moment can be attributed only to the higher lever arm.

The effect of the level of strain that can be developed in the spacer material before failure was also examined, and the results obtained are summarized in Fig. 3. The higher the ultimate strains mobilized in the spacer, the higher bending moments