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Size effect in uncracked and pre-cracked reinforced concrete beams shear-strengthened with composite jackets

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ABSTRACT

The paper deals with the size effect on shear behaviour of reinforced concrete beams strengthened with fiber reinforced polymer jackets. Continuous U-jackets were made of glass or carbon fiber fabrics and epoxy composite materials. Twelve uncracked or pre-cracked strengthened reinforced concrete beams and six beams without strengthening, all of them in 6 different sizes, were tested. The results indicate that fabric-epoxy continuous U-jackets have reduced the brittleness of the shear failure of beams, tensile strains in stirrups, and, in a significant way, also the width of shear cracks at the failure state. Although similar strengthening was used for both, uncracked and pre-cracked beams, activation of jackets significantly differed. While jacket strains and their strengthening effectiveness were affected by the sizes of uncracked, retrofitted beams, they remained almost constant in pre-cracked, repaired beams of varying sizes. In contrast to repaired beams, stirrups in retrofitted beams did not yield at failure. Degree of strengthening, defined as the ratio of strengthened-to-unstrengthened beam shear capacities, was studied. It was found out that consideration of the degree of strengthening would provide relations reflecting real behaviour of reinforced concrete beams strengthened with fiber reinforced polymer U-jackets or U-jacketed strips.

1. Introduction

In addition to traditional materials and techniques (e.g. externally bonded steel plates, steel or concrete jackets and external post-tensioning), fiber reinforced polymers (FRP) have recently become quite a popular alternative for retrofitting (i.e. strengthening of uncracked) reinforced concrete (RC) structural members and repairing/rehabilitation (i.e. strengthening of pre-cracked) structural members. Even if it has been known that the external side bonded, U-jacketed or fully wrapped FRP strips or sheets increase the shear resistance of RC beams, the problem of shear strengthening of RC members with FRP is actually far more complex, far from having been resolved and, consequently, still under investigation [8,9,11,14,20,21–23,26,28,32–34,39].

Shear resistance of RC beams is influenced by interaction of several factors, among which the size of beams (mainly the depth of the beam in the load direction) is dominant. The fact that the average ultimate shear stresses in “large“ beams were smaller in comparison with the average ones in “small” beams was first dealt with about 50 years ago. Since then, this phenomenon (the size effect in shear) has not only become the subject of many research works [1,5,19,24,30,36] but has also been implemented in design rules over the last 20 years [7,10,16].

Relatively few works dealing with the size effect in RC beams strengthened by U-shaped or fully wrapped FRP strips have been published up to now [3,17,25,35]. It is also worth mentioning that the researches either focused on the strengthening of uncracked (non-damaged) beams only, or they did tests of pre-cracked beams, but without the investigation of the size effect [13,29]. Different behaviour of uncracked and pre-cracked strengthened beams, however, implies differences in the effect of beam sizes on the strengthening effectiveness and on the interaction between FRP jackets and steel stirrups. Nevertheless, no thorough investigation of the size effect on the shear resistance of beams strengthened with continuous U-jackets by using fiber fabrics has been done yet.

The primary aim of the paper was to contribute to the knowledge of the size effect on shear behavior (interaction among stirrups, rebars and strengthening systems) and resistances of uncracked and pre-cracked RC beams strengthened with glass and

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carbon fiber reinforced continuous U-jackets of thicknesses varying proportionally to the beam cross-section heights. The secondary aim was to specify empirical relations reflecting interactions between steel reinforcement and strengthening systems of reinforced concrete beams strengthened with fiber reinforced polymer continuous U-jackets or U-jacketed strips.

2. Experimental investigation

2.1. Materials

Test beams were made from concrete, which contained: cement PC40 (490 kg/m^3), natural sand (0–4 mm, 720 kg/m^3), coarse aggregate (22 mm, 1225 kg/m^3), water (167 l/m^3) and plasticizer (5 l/m^3). Average compressive concrete strengths $f_{c,cube}$ and splitting tensile strengths $f_{sp,cube}$ (cube edge of 150 mm) were 31.2 MPa and 2.35 MPa for group G1, and 29.4 MPa and 2.15 MPa for group G2, respectively. Mechanical properties of steel reinforcement were determined based on tensile tests of six samples. Average yield stress and tensile strength in longitudinal rebars were 420 MPa and 590 MPa, respectively, and the respective values for stirrups were 350 MPa and 510 MPa. Modulus of elasticity of steel reinforcement was 200 GPa. Unidirectional glass or carbon fiber fabrics (GFF or CFF) were of 1.0 and 1.3 mm in thickness, respectively. In GFF, glass fibres were placed in the direction of 0° and additional yellow glass cross fibres at the angle of 90° (Fig. 1a). In CFF, carbon fibres and additional glass cross fibres were placed at the angles of 0° and 90°, respectively (Fig. 1b). Mechanical properties of fabrics and steel reinforcement are presented in Table 1.

2.2. Test specimens

A total of 18 beams were divided into 2 groups (G1 and G2), each of which comprised 6 RC beams strengthened by FRP jackets and 3 control RC beams without strengthening. The group G1 included uncracked beams which were strengthened by GFRP jackets, while the group G2 included pre-cracked beams strengthened by GFRP and CFRP jackets. Beams in either group were arranged to 3 subgroups of different sizes (small, medium and large beams), each comprising 3 beams of the same size. Span L and width b of beams, as well as width w_f and thickness t_f of FRP jackets, were changed proportionally with the heights h of the beams.

The shear span to effective depth ratio a/d was 1.7 and 2.0 for beams of group G1 and G2, respectively. Shear span was considered as the distance between the loading point and the center of the nearest support. Steel rebars of 10, 14, 20, 22 and 25 mm in diameter were used as the longitudinal tensile reinforcement. As shear reinforcement, steel stirrups of 6 mm and 8 mm in diameter were used. They were placed in distances of 300, 150 and 180 mm for group G1, and 350, 320 and 320 mm for group G2. Rebars of 8, 10, 12, 14 and 16 mm in diameter were used for the top reinforcement. Flexural reinforcement ratio $\rho_s = 1.8\%$ and shear reinforcement ratio $\rho_{sw} = 0.19\%$ were identical for all G1-group beams. The respective parameters for 9 beams of the G2-group were as follows: $\rho_s = 2.4\%$; and $\rho_{sw} = 0.16\%$. Dimensions and reinforcements of the beams tested are summarized in Table 2. Geometry, steel reinforcement and the arrangement of the specimens strengthening are shown in Figs. 2–4.

Prior to bonding the fiber fabrics, the concrete surface, was roughened by the hand-grinder and the abrasive paper till aggregates were exposed. In order to reduce the concentration of stresses at the bottom beam edges, they were rounded with the radiuses of 10, 15, and 20 mm, corresponding to varying beam sizes. Compressed air cleaning was performed to remove dust and loose particles.

After the required standard of the quality of the concrete surface was attained, the epoxy resin was mixed in accordance with the manufacturer's instructions and applied to the concrete surface. Afterwards, fabrics were placed on and coated subsequently with the epoxy resin by means of a plastic roller in order to create continuous 1-, 2- or 3-layer FRP jackets. Large entrapped air bubbles between concrete and the epoxy-fabric composites or particular layers of fabrics were avoided. Preparation of test beams was performed at room temperature. At least 7 days were allowed for the resin to attain its full strength prior to beams testing. After 28 days of concrete hardening, uncracked G1-group beams were strengthened (retrofitted beams). G2-group beams, however, have been loaded after the 28 days of hardening, up to the occurrence of inclined cracks. Respective pre-cracking load forces $P_{pre\text{-}cr}$ are presented in Table 3. Finally, beams were unloaded and strengthened with FRP jackets (repaired beams).

2.3. Test procedure and instrumentation

Simply supported beams were tested under two concentrated loads (Fig. 3). Five linear variable differential transformers (LVDTs) were used to determine deflections at mid-spans, at loading points, and at the supports of the beams. Three gauges were used for

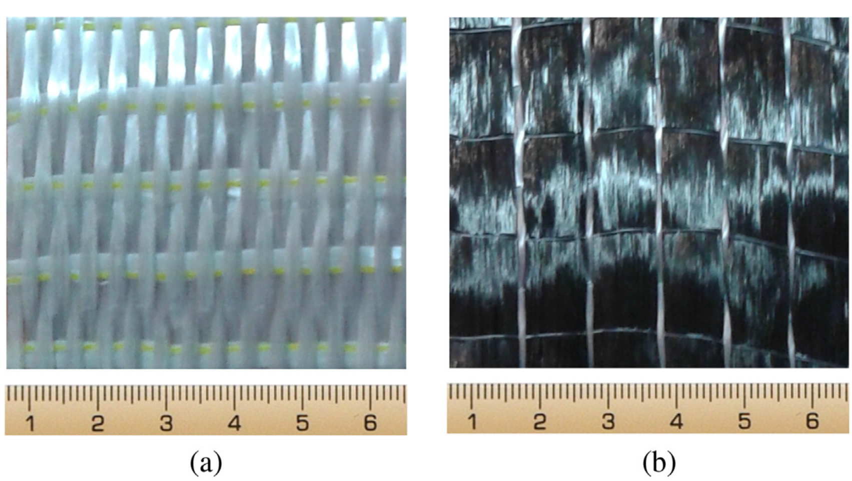

Fig. 1. Unidirectional fabrics with: (a) glass fibres; (b) carbon fibres.