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Strengthening of shear-critical RC beams: Alternatives to externally bonded CFRP sheets

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HIGHLIGHTS

- 12 shear-critical beams strengthened with different systems.
- Comparison of effectiveness of cement-based systems vs. epoxy-based system.
- All strengthening systems considered were effective in increasing load capacity.
- Cement-based systems were more efficient as a function of ultimate tensile strength.

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ABSTRACT

Extensive research has been conducted on strengthening of shear-critical RC beams. This previous research has helped to better understand the behaviour of shear strengthening systems and has improved their performance. However, there is still a potential to further improve upon the performance of existing shear strengthening systems. A cement-based composite system is an innovative strengthening system that shares many of the benefits of fiber reinforced polymer (FRP) systems (such as light weight, ease of installation and non-corroding) while overcoming some of the draw backs of epoxy-based FRP systems (including poor compatibility with concrete substrate, lack of vapour permeability and fire resistance). The current paper presents the results of an experimental study conducted to investigate the effectiveness of cement-based composite systems in comparison to an epoxy-based system (carbon fiber reinforced polymer, CFRP) to strengthen shear-critical RC beams. Two types of cement-based systems were investigated in this study: carbon fiber reinforced polymer (CFRP) grid embedded in mortar and carbon fabric reinforced cementitious mortar (CFRCM). The results showed that the cement-based systems (CFRP grid in mortar and CFRCM) perform better compared to the epoxy-based system (CFRP sheet) in terms of increase in shear capacity relative to ultimate strength of the strengthening systems. In addition, the CFRP grid embedded in mortar is the most efficient shear strengthening system due to its excellent bond to concrete.

1. Introduction

Reinforced concrete (RC) structural members may be shear deficient for a number of reasons, including deterioration or damage, construction or design errors, or changes in loading. One of the most common rehabilitation techniques includes bonding fiber reinforced polymer (FRP) sheets to the concrete surface using an epoxy resin, with the fibers oriented perpendicular to the longitudinal axis of the RC member. FRP has grown in popularity as a rehabilitation technique largely due to its ease of installation, good mechanical properties, and corrosion resistance. The effectiveness of FRP systems for the rehabilitation and strengthening of shear-critical RC members have been demonstrated in studies reported in the literature as well as by worldwide field applications [1,6]. Guidelines on the design of external FRP strengthening systems are provided in ACI 440.2R-08.

In spite of its wide use and effectiveness, epoxy may not be an optimal bonding agent for FRP strengthening systems for some

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applications due to poor compatibility with concrete substrate, limited or no moisture diffusion, requirement for special handling/protection equipment for manual workers, and most importantly because of challenges associated with post-repair inspections and assessment of the structure once the structural element is hidden by the FRP system. Therefore, alternative systems that overcome some of these challenges have been developed in recent years and have been the subject of interest within the research community.

Cement-based composites are a relatively new strengthening and rehabilitation system. They have almost all of the same benefits of typical FRP systems such as low weight, ease of installation and non-corroding properties, but overcome some of the drawbacks such as poor compatibility with concrete substrate, lack of vapour permeability and fire resistance of using epoxy as a bonding agent in FRP systems. A cement-based composite system replaces the epoxy with cementitious mortar and the fiber sheets are replaced with fabrics or FRP grids.

Two types of cement-based systems have been reported in the literature. The first type of cement-based composite system consists of flexible fabric and mortar. This type of cement-based system has been referred to in the literature as fabric reinforced cementitious matrix (FRCM), textile reinforced concrete (TRC), and textile reinforced mortar (TRM). The majority of the studies on the non-FRP strengthening of shear-critical RC beams have been conducted using this type of cement-based system [3,5,8–10,13,14]. FRCM systems have demonstrated good potential for the shear-strengthening of RC beams; Azam & Soudki [5], for example, found that FRCM systems increased the shear capacity of RC beams by up to 105%. Recently, guidelines for the design of FRCM strengthening systems have become available [2].

A second type of cement-based composite system has been developed which consists of rigid FRP grid and mortar. This type of system has been referred to in the literature as mineral-based composites (MBC) systems, and relatively few studies have investigated the potential of this type of system. Only one study has been reported in the literature to date to investigate the behaviour of shear-critical RC beams strengthened with this type of strengthening system [7]. The shear capacity of the strengthened beams was, in some cases, more than double those of the unstrengthened beams.

A few studies have been reported in the literature to investigate the effectiveness of cement-based strengthening systems in comparison to existing epoxy-based systems to strengthen shear-critical RC beams [7,12–14]. These studies have reported contradictory results: Tzoura and Triantafillou [14] and Triantifillou and Papanicolaou [13] found that a cement-based composite system was less effective compared to FRP, while Blanksvard et al. [7] found that a cement-based composite system was more effective than FRP. It is important to note that different types of cement-based systems were used in these studies. Tzoura and Triantafillou [14] and Triantifillou and Papanicolaou [13] used dry carbon fabric/textile embedded in mortar, whereas Blanksvard et al. [7] used CFRP grid embedded in mortar. The different types of cement-based systems could have been the source of the contradictory results. This indicates that further studies are required to investigate the effectiveness of the cement-based systems in comparison to the epoxy-based system.

The current study is designed to investigate the effectiveness of both types of cement-based composite systems in comparison to the epoxy-based system to strengthen shear-critical RC beams. Each system is evaluated based on several performance criteria including the load-deflection response; the ability to control diagonal or shear crack width; the internal stirrup strain response and the overall efficiency of the strengthening system. This study is part of a larger research program on strengthening of reinforced concrete structures using cement-based strengthening systems.

2. Experimental program

A total of twelve reinforced concrete beams were tested. The test matrix is given in Table 1. The variables included three strengthening systems (CFRP grid embedded in mortar, CFRCM and CFRP sheet) and the amount of internal transverse shear reinforcement. The test beams were divided into three series: series S0 (beams without stirrups), series S150 (beams with 6 mm stirrups @ 150 mm c/c) and series S250 (beams with 6 mm stirrups @ 250 mm c/c). Each series contained four beams: one control unstrengthened beam and three strengthened beams.

2.1. Test specimens

The details of the test specimens are presented in Fig. 1 and Table 2. All beams had dimensions of 250 mm width, 400 mm height and 2700 mm length. The longitudinal tensile reinforcement for each beam was comprised of six 25 M bars in the tension zone and three 25 M bars in the compression zone. The side and vertical covers to the longitudinal reinforcement were 40 mm for all beams. The internal transverse steel reinforcement was comprised of either none, 6 mm stirrups at a spacing of 150 mm c/c, or 6 mm stirrups @ 250 mm c/c. Three additional stirrups were provided in the anchorage zone for the longitudinal reinforcement.

The beams are designated using the following notation: YY-ZZ with YY = steel reinforcement and ZZ = strengthening system. The steel reinforcement is specified as S0 (beams without stirrups), S150 (beams with 6 mm stirrups @ 150 mm c/c) and S250 (beams with 6 mm stirrups @ 250 mm c/c) and the strengthening system is specified as N (none), CGM (CFRP grid embedded in mortar), CM (CFRCM) and CP (CFRP sheet).

2.2. Material properties

The beams were cast using concrete with a compressive strength of 61 ± 1 MPa. The yield strengths of the longitudinal and transverse steel were 494 MPa and 365 MPa, respectively, as reported by the supplier.

The CFRP grid had an area of 87.2 mm^2/m, corresponding to a tensile modulus of 234.5 GPa and elongation at rupture of 0.76%. The ultimate tensile strength of the CFRP grid was 160 kN/m in both directions. The orthogonal spacing of the CFRP grid was 41 $\times$ 46 mm (Fig. 2). The carbon fibers used to make the carbon fabric (used in CFRCM) had a tensile modulus of 230 GPa and elongation at rupture of 1.6%. The dry fiber area was 176.7 mm^2/m. The ultimate strength of the carbon fabric was 650 kN/m and 500 kN/m in the longitudinal and transverse directions, respectively. The orthogonal spacing of the fabric tows was 10 $\times$ 18 mm (Fig. 2). Note that the properties of the CFRP grid and the carbon fabric listed above are as reported by the respective material manufacturers, C-Grid and SGL Group. Sika Monotop 623 cementitious mortar with a compressive strength of 58 ± 2.8 MPa was used as the bonding agent in the strengthening layer.

SikaWrap Hex 230C carbon fiber sheets and Sikadur 330 epoxy resin were used in the CFRP strengthening system (Fig. 2). The dry carbon fibers used in the CFRP sheet had a tensile modulus of 230 GPa and elongation at rupture of 1.5%, with an area of 255.6 mm^2/m. The cured CFRP had a tensile modulus of 65.4 GPa and an elongation at rupture of 1.33%, with an ultimate tensile strength of 881 kN/m (as reported by the manufacturer).

2.3. Installation of strengthening systems

Nine beams were strengthened with the three strengthening systems described in the previous section: three beams were