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ORIGINAL ARTICLE

Strengthening of defected beam–column joints using CFRP

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ABSTRACT

This paper presents an experimental study for the structural performance of reinforced concrete (RC) exterior beam–column joints rehabilitated using carbon-fiber-reinforced polymer (CFRP). The present experimental program consists of testing 10 half-scale specimens divided into three groups covering three possible defects in addition to an adequately detailed control specimen. The considered defects include the absence of the transverse reinforcement within the joint core, insufficient bond length for the beam main reinforcement and inadequate spliced implanted column on the joint. Three different strengthening schemes were used to rehabilitate the defected beam–column joints including externally bonded CFRP strips and sheets in addition to near surface mounted (NSM) CFRP strips. The failure criteria including ultimate capacity, mode of failure, initial stiffness, ductility and the developed ultimate strain in the reinforcing steel and CFRP were considered and compared for each group for the control and the CFRP-strengthened specimens. The test results showed that the proposed CFRP strengthening configurations represented the best choice for strengthening the first two defects from the viewpoint of the studied failure criteria. On the other hand, the results of the third group showed that strengthening the joint using NSM strip technique enabled the specimen to outperform the structural performance of the control specimen while strengthening the joints using externally bonded CFRP strips and sheets failed to restore the strengthened joints capacity.

Introduction

Occasionally, long after the structure has been completed, it is discovered that a contractor has left out some steel or some details are inadequately executed or the concrete is not what was specified. Fiber reinforced polymer, FRP, can be used in order to replace the missing steel or compensate the low concrete strength or structural faults in design. That is because FRP in the form of plates or fabric sheet has its strength in the direction of the fibers only and can be engineered to place the strengthening in the needed direction only. It addition, it can

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provide an improved load carrying capacity and a higher rate of stiffness than that of un-strengthened specimens [1].

FRP composites have become more popular in the last two decades due to the reduction in their cost, combined with newer understanding of the versatility and benefits of the material properties. CFRP strips and fabric are generally constructed of high-performance carbon fibers which are placed in resin matrix. These composites can easily be externally bonded to RC elements. Strengthening with fiber-reinforced polymeric composite applications is one of the recent retrofitting and strengthening techniques [2].

The beam–column joint is considered as the most critical zone in a reinforced concrete moment resisting frame. It is subjected to large forces during earthquake excitation and its behavior has a significant influence on the response of the entire structure. As a result, a great attention has to be paid for good detailing of such joint. The absence of transverse reinforcement in the joint, insufficient development length for the beam reinforcement and the inadequately spliced reinforcement for the column just above the joint can be considered as the most important causes for the failure of the beam–column joint under any unexpected transverse loading on the building. Antonopoulos and Triantafillou [3] demonstrated that externally bonded FRP reinforcement is a practical solution towards enhancing the strength, energy dissipation, and stiffness characteristics of poorly detailed, in shear, RC joints subjected to simulated seismic loads. Abdel-Wahed et al. [4] studied experimentally and analytically different CFRP strengthening configurations for beam–column joints having inadequate transverse reinforcement in the joint.

In the literature, many researches had been conducted experimentally in order to address the effectiveness of using FRP laminates for the strengthening of beam–column joints [5–9]. In addition, Ravi and Arulraj [10] studied numerically the behavior of beam–column joints retrofitted with carbon fiber reinforced polymer sheets. In the continuation, the effectiveness of composite fiber reinforced polymer layers for exterior beam–column connections was studied numerically considering strength and ductility enhancement of the RC joints [11].

Despite the fact that the defect of inadequate transverse reinforcement in the beam–column joint has been studied extensively in literature, other defects have to be studied in details. The current study conducts an experimental investigation on different strengthening configurations using CFRP for three defects encountered in the detailing of the exterior beam–column joints. In addition to the defect caused by the absence of transverse reinforcement in the beam–column joint, the insufficient bond length for the beam main reinforcement and inadequately spliced implanted column were also studied.

Strengthening material

One of the most important factors affecting the successful strengthening technique of structures is the selection of the strengthening material. The need to lower the cost of maintenance, repair and strengthening techniques, while extending the service life of the structures, has resulted in new systems, processes, or products to save money and time. The fiber-reinforced polymer (FRP) systems are recently used in the field of strengthening and restoration of the buildings. The most commonly utilized fiber-reinforced polymers (FRPs) are fibers made of carbon (C) or glass (G). These materials can be designed and used in the form of laminates, rods, dry fibers (sheets) adhesively bonded to the concrete, wet lay-up sheets mounted on the surface, or near surface mounted bars or laminate strips in the concrete cover [12]. The carbon fiber-reinforced polymer (CFRP) materials have a high potential for manufacturing effective strengthening systems to increase the flexural or shear strength of RC beams. The CFRP materials have a very low weight to volume ratio, are immune to corrosion, and possess high tensile strength. FRP systems may have thermal expansion properties that are different from those of concrete. In the fiber direction, CFRP systems have a coefficient of thermal expansion near zero, however previous research work [13] has indicated that the thermal expansion differences do not affect the bonding for small ranges of temperature change ($+/-50$ °C). Also, due to their electrical conductivity, Ghali et al. [14] concluded that carbon based FRP materials should not come in direct contact with steel to avoid potential galvanic corrosion of steel reinforcement and, a minimum concrete cover of about 10 mm was recommended.

The performance of the FRP system over time in an alkaline or acidic environment depends on the matrix material and the reinforcing fiber. Unprotected carbon fiber resists both alkali and acid environments while bare glass fiber can degrade over time in these environments [15]. However, a properly applied resin matrix may isolate and protect the fiber from the alkaline/acidic environment and retard deterioration.

Compared to the traditional strengthening techniques (externally bonded steel plates, near surface mounted steel bars and concrete jackets), the cost of the externally bonded CFRP system is relatively high but, in some special circumstances, and regarding the aforementioned advantages, the choice of the CFRP as a strengthening material may represent the best solution.

Experimental

Test specimens

A total of eleven half-scale beam–column *T*-joints were prepared and cast in the current study. The first specimen, J0, was considered as the base control specimen. It had an extruded beam of 900 mm length and cross-sectional dimensions of 200×300 mm. This beam was connected to a column at its mid-height point. The cross-section of the column was 200×300 mm. The total length of the columns was 2.3 m divided into two equal parts, lower part and upper part.

The upper and lower reinforcement of the beam in addition to the main longitudinal steel reinforcement of the column were made from high tensile steel. The main steel reinforcement of the beam was three bars of 16 mm diameter, while the secondary steel reinforcement was two bars of 12 mm diameter. On the other hand, the column was reinforced with four bars of 16 mm diameter at each corner of the column cross-section. The stirrups for both beam and column were mild steel bars of 8 mm diameter and spaced every 100 mm and 150 mm for the beam and the column, respectively. In addition, three stirrups were added at the beam–column joint. Fig. 1 shows the concrete dimensions and reinforcement detailing for the base control specimen provided that the loading