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Emergency repair of severely damaged reinforced concrete column elements under axial compression: An experimental study

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HIGHLIGHTS

- A hybrid FRP strengthening is proposed for emergency repair of RC columns.
- Efficiency of different repairs on performance improvement of RC columns is studied.
- Effect of quick setting cement, NSM laminates and hybrid repair technique is studied.
- Hybrid strengthening uses longitudinal NSM laminates and externally bonded fabric.
- Hybrid strengthening fully restored the strength and displacement capacity.

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ABSTRACT

Reinforced concrete (RC) columns in a framed construction can be severely damaged under earthquake, blast, fatigue and other loads. It is essential to quickly restore the strength and stiffness of columns after its damage for maintaining the serviceability of the building. The objective of this study is to assess the efficiency of different strengthening techniques on emergency repair of the severely damaged RC columns under axial compression. Six short RC columns elements were cast and tested under axial compression until 20% drop in the peak strength. Thereafter, these severely damaged columns were repaired using strengthening schemes, namely (i) repairing the damaged portions using quick setting cement mortar, (ii) Near Surface Mounting (NSM) of CFRP (Carbon Fiber Reinforced Polymer) laminates and (iii) Hybrid strengthening technique. The hybrid strengthening technique uses the combination of CFRP NSM laminates as additional longitudinal reinforcement and external bonding with CFRP fabric for confinement. The hybrid strengthening scheme was found to be the most efficient in restoring the lost strength and initial stiffness when compared to the only NSM strengthening or repair with quick setting cement mortar.

1. Introduction

The presence of severe damages in the columns of important bridges and buildings (airports, government offices, schools, hospitals) can have significant negative social and economic impact. In order to restore the access of these facilities, it is essential to develop a quick and efficient strengthening techniques that can be implemented for restoring the strength and deformation capabilities of columns. Sometimes before achieving global retrofitting measures, a quick temporary repair strategy would be needed for the severely damaged columns to make them safe for access and working conditions. Previous studies on the repair strategy of columns were carried out by enhancing shear or flexural capacity with continuous CFRP wrapping emphasizing more on the bridge columns. Effective confinement schemes using steel jacket, Fiber Reinforced Polymer (FRP) wrapping for moderately damaged columns were developed by Sieble et al. [1], Stoppenhagen et al. [2,3], and Elkin et al. [4]. These authors found from their experimental results that both severely and moderately damaged reinforced concrete bridge columns could be repaired. Notable amount of works have focused on improving the behavior of deficit RC columns using steel confinement and FRP wrapping [5–7].

Cheng et al. [8] evaluated the seismic performance of repaired hollow bridge piers and concluded that the use of FRP could not fully restore the strength but it could significantly improve the ductility. It was also observed that the mode of failure changed from flexure-shear to flexure dominant. He et al. [9–11] investigated the behavior of severely damaged columns under combined

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loading including torsion. Torsion to moment ratio (T/M ratio) of columns retrofitted by them were 0, 0.2, 0.4, 0.6 and infinity where '0' represents pure flexure and 'infinity' represents pure torsion. This study considered only externally bonded CFRP sheets as the repair method. Only limited work in the past has focused on the repair of damaged columns using FRP confinement [12–17]. They found from their research that FRP confinement was able to restore the original capacity of the columns subjected to different levels of damage under axial compression. Moreover, CFRP confinement was also successfully implemented as retrofitting technique for improving the overall behavior of bridge piers under seismic loading [18,19]. The review of literature indicates that no previous studies have focused on the behavior of severely damaged RC columns under compression loading. The current study focusses on the evaluation of efficiency of different schemes to strengthen the severely damaged RC columns under axial compression.

2. Research motivation

An innovative hybrid FRP strengthening using a combination of NSM CFRP laminates and EB CFRP fabric is proposed for emergency repair of square column elements under axial compression [20–22]. The broader objective of the work is to study the behavior of severely damaged RC columns under all combinations of axial compression and bending loads. However, the scope of the current study is limited to axial compression behavior of severely damaged columns after strengthening. It is essential to understand the efficiency of hybrid strengthening under pure compression before extending it to combined axial and bending loads. Previous studies have established that only NSM strengthening is very efficient in increasing the bending strength. Similarly, strengthening of columns with only external FRP confinement is very efficient in improving the compressive strength and ductility but not the pure flexural strength. It is also worth mentioning that efficiency of external confinement reduces significantly for non-circular sections with larger aspect ratio. Thus, the broader objective was to develop an efficient strengthening scheme to improve the strength for all combinations of bending and compression loads, though the present study focuses only on pure axial compression.

3. Experimental study

3.1. Preparation of column specimen before damage

Six RC square column elements were cast with cross section dimensions of 230 mm and were restricted to a height of 450 mm due to constraints in the testing equipment. Longitudinal reinforcement consists of 8 bars of 12 mm diameter corresponding to reinforcement ratio of 1.73%. The transverse reinforcement included lateral ties of 10 mm diameter at a spacing of 100 mm corresponding to a transverse reinforcement ratio of 0.73%. Both the longitudinal and transverse reinforcement ratio typically resemble that of mid-rise building columns. Specimen and sectional details are shown in Fig. 1.

3.2. Material properties

3.2.1. Concrete mix

The concrete mix was designed for a target cubic compressive strength of 48.25 MPa (M40). The design was carried out as per Indian standards IS10292-2009 [23]. A Poly carboxylic ether based water reducing agent (Glenium B233) was used to improve the workability. After casting of three trial mixes, the final mix proportion of concrete is obtained as follows: cement – 360 kg/m^3; fine aggregate (sand) – 752 kg/m^3; coarse aggregate – 1196 kg/m^3 and super plasticizer (admixture) – 3.6 kg/m^3.

3.2.2. Steel and FRP properties

A FE500 grade steel was used for both longitudinal and transverse reinforcements. Coupon specimens were prepared for testing the reinforcements under tension. The yield stress and the ultimate strain corresponding to failure were found to be 512 MPa and 7.8%, respectively. CFRP used in the study were utilized in two different forms, namely laminates and fabric, respectively. Three different laminates of dimensions (12.5 mm $\times$ 1.4 mm) were joined together with epoxy to configure a combined CFRP laminate strip (12.5 $\times$ 4.2 mm) with the modulus of elasticity of 150 GPa. CFRP fabric of 230 Grams per Square Meter (GSM) was used for the confinement of laminates having unidirectional fibers. The width of wrap was 450 mm with 0.20 mm thickness. The coupon testing of FRP in compression and tension was carried out as per ASTM standards [24,25] as shown in Fig. 2 and the results are tabulated in Table 1. The general stress strain curve for CFRP laminates under both tension and compression is depicted in Fig. 3. Previous work on CFRP laminates and GFRP bars under axial compression indicated that the compressive strength of FRP are not negligible and is about 50–60% of its tensile strength [20,26–28]. Therefore, the contribution of NSM FRP is not negligible under axial compression and will be highly significant under combined compression and bending loads [22] Moreover, NSM laminates have proven their efficient under bending loads [29–33] and the efficiency in improving the behavior of columns under axial compression is less understood and is the scope of this work.

3.2.3. Casting of control columns

The reinforcement cage with the desired specification was prepared for casting of the control columns. Each reinforcement cage had eight rebars of 12 mm diameter as the longitudinal reinforcement and five lateral ties of 10 mm diameter at a spacing of 100 mm as transverse reinforcement. Strain gauges of 5 mm gauge length and 120 Ω resistance were installed on both the longitudinal and tie reinforcement to measure the strain variation during the testing. The prepared reinforcement cages were placed in the casting molds and concrete was poured. All the specimens were water cured for a period of 28 days. Details of casting procedure is explained in Fig. 4.

4. Test setup and instrumentation

A servo-controlled compression testing machine of 5000 kN capacity was used to apply a compressive load on the column elements. Two control Linear Variable Displacement Transducers (LVDT's) of 10 mm stroke were used for displacement controlled testing. The rate of loading was fixed at 0.48 mm/min to enable better capture of post-peak behavior. The column elements were attached with four LVDT's of 20 mm stroke (180 mm gauge length) to capture the surface strains and displacements. Strain gauges of 5 mm gauge length and 120 Ω resistance were attached to the longitudinal and transverse reinforcements. DAQ (Data Acquisition System) was used for acquiring all the data like load, strain and displacement measurements as shown in Fig. 5.

5. Pre-damage and strengthening details

5.1. Testing of control specimens

All the control RC columns were loaded and tested to failure until 20% drop in load from its peak strength and up to a minimum compressive strain of 0.004 (failure strain of concrete). Capping