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# Rapid repair of severely damaged reinforced concrete columns under combined axial compression and flexure: An experimental study

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## HIGHLIGHTS

- Effectiveness of different repair schemes under combined compression and flexure is studied.
- Repair effectiveness of quickset cement mortar, NSM and hybrid FRP technique is studied.
- All the repaired columns are tested under concentric and eccentric compression (e/d = 0.63).
- The effectiveness of repair is estimated through stiffness, strength and displacement indices.
- Hybrid FRP technique fully restored the strength and ductility of columns.

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## ABSTRACT

Reinforced concrete (RC) columns are in general subjected to combination of axial compression and bending loads. A rapid repair technique for effectively restoring the original strength and stiffness of severely damaged RC columns under combined bending and compression loads is investigated. In total, six RC columns are tested under uniaxial eccentric compression at an eccentricity (e) to depth ratio (d) of 0.63. The columns are initially subjected to severe damage corresponding to a concrete compressive strain ($\varepsilon_c$) of 0.0035. Damaged columns had buckling of longitudinal reinforcement and concrete crushing. After severe damage, the columns are repaired with three different techniques using (i) quick set cement grout mortar (QS), (ii) near surface mounting (NSM) of CFRP laminates and (iii) hybrid FRP strengthening using a combination of NSM and external bonding (EB) of CFRP fabric. The specimens are tested under high ratio of eccentric compression (e/d = 0.63) in a displacement controlled mode. The performance of different repair techniques under eccentric compression is compared with the similar specimens tested under concentric compression. Test results revealed that hybrid FRP strengthening is very efficient in fully restoring the original strength and failure displacement under combined compression and bending loads. Only NSM strengthening is found to be very efficient under eccentric compression than in concentric compression.



## 1. Introduction

Damage of reinforced concrete (RC) columns under earthquakes and in accidents due to fire and blast loading can lead to catastrophic failure of the entire RC structure [1–4]. Columns are the main load bearing elements in the structural system and cannot undergo severe damages in order for the buildings to remain functional [5,6]. The current design code allows limited damages in RC columns such as cracking and local concrete spalling under extreme loading conditions [7–9]. Moreover, the immediate occupancy after earthquakes is necessary for certain important buildings. Thus, it is necessary to restore the original capacity of columns in a quick time before adopting global repair solutions. The repair technique adopted can be deemed to be successful only if the columns can be brought to service in a short time after severe damage. Conventional strengthening strategies such as steel jacketing and concrete enlargement has been used in the past by many researchers [10–13]. However, their high dead weight and increased cost of labour have made FRP strengthening as effective repair solution [14,15]. Various FRP strengthening techniques such as external bonding (EB) [16–22], near surface mounting (NSM) [23–31] have been used to improve the behavior of RC elements under different loading conditions. However, only limited studies

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are available in the literature on evaluation of repair effectiveness of RC columns using different FRP techniques under different combinations of bending and compression loading.

The effectiveness of FRP confined columns for restoring the original capacity of RC columns under concentric compression has been investigated by some researchers [32–39]. They concluded that the FRP confinement helps in complete restoration of the original capacity without much reduction in ductility under different levels of compression. Elkin et al. [40] investigated the seismic repair efficiency of FRP confined columns with moderate and severe damage. They found that the repair using CFRP confinement restored the strength and displacement capacity of moderately damaged columns whereas the displacement capacity of severely damaged columns is not restored. Saadatmanesh et al. [41] studied the flexural repair efficiency of columns using CFRP wrapping. They found that the repair with CFRP wrapping improved the hysteretic behavior of columns and completely restored the original strength and ductility. Repair efficiency of CFRP wrapping technique for RC columns under torsion, combined torsion and bending loads have been recently investigated by some researchers [42–45]. They concluded that the damaged columns repaired using CFRP wrapping technique performed better than the original specimens. Seismic repair of RC bridge columns using CFRP shells and epoxy anchored headed steel bars is carried out recently [46]. The performance of column elements under combined axial and bending loads has also been extensively studied [47,48]. From the research work carried out in the past, it is clear that the repair efficiency of severely damaged columns using FRP under combined axial and bending loads has not been adequately investigated. The present study focusses on filling the knowledge gap on the effectiveness of different repair strategies for severely damaged RC columns under combined compression and bending.

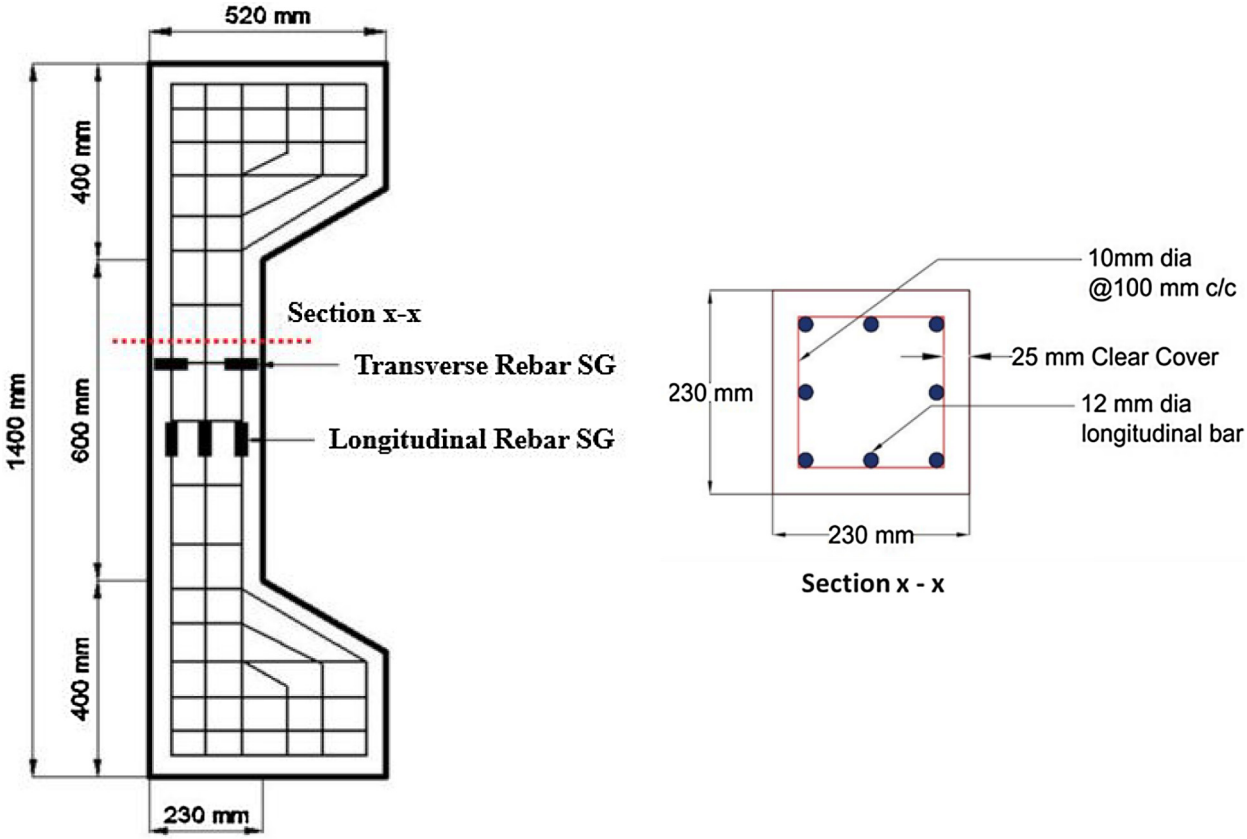


**Fig. 1.** Schematic details of RC column elements.

**Table 1**
Details of test matrix.

| Specimen ID | Dimensions (mm) | | | Repair Technique Used |
|---|---|---|---|---|
| | b | d | h | |
| RCC-0 | 230 | 230 | 450 | – |
| RCC-R-QS-0 | | | | Quick Set High Strength Grout |
| RCC-R-NSM-0 | | | | NSM CFRP Laminates |
| RCC-R-HYB-0 | | | | CFRP Laminates + CFRP Fabric |
| RCC-145 | 230 | 230 | 600 | – |
| RCC-R-QS-145 | | | | Quick Set High Strength Grout |
| RCC-R-NSM-145 | | | | NSM CFRP Laminates |
| RCC-R-HYB-145 | | | | CFRP Laminates + CFRP Fabric |

**Note:* The values 0 mm and 145 mm are used to represent the level of eccentricity in the test specimen. The details of test specimen under concentric compression are used only for comparison purposes [32].