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Numerical analysis of fiber composite-steel plate upgraded beam–column sub-assemblages under cyclic loading

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ABSTRACT

In the present study, exterior beam–column sub-assemblage from a regular RC building has been considered. Extremely poor gravity load designed (GLD) beam–column sub-assemblage was upgraded by combinely using FRP and steel plate. Three different upgradation schemes have been proposed. Nonlinear finite element (FE) program has been employed for analysing both existing and upgraded sub-assemblages under cyclic loading. Concrete parts of the FE models were modelled using quadratic brick – and steel plates were modelled using tetrahedral – solid elements. All the FRPs were modelled as 9-noded isoparametric multi-layered shell elements with embedded unidirectional reinforcement to represent the anisotropic material property. Contact elements and bond properties were suitably incorporated. It has been found out that the results obtained from the numerical analysis are well corroborated with those of experimental results. Further, a detailed parametric study has been carried out on type, extent and amount of flexural strengthening, and number of wrapping to identify the scopes of improvement on the proposed upgradation schemes.

1. Introduction

It is of great importance in upgrading the poorly designed GLD structures since the alarming performance of those structures has been witnessed from the previous earthquakes. Reported research works have also confirmed the drastic strength degradation and negligible energy dissipation capacity of the GLD structures. A number of researches has been directed for upgradation of GLD structure/components to improve their seismic performance by using concrete/steel plate jacketing or fiber reinforced plastics (FRP). Different types of concrete jacketing have been proposed to enhance strength, reduce strength degradation and to improve stiffness of RC structural components. Externally bonded steel plates or FRPs are widely used due to (i) being quick, (ii) causing minimal site disruption, and (iii) producing only minimal change in section size. Although behaviour of FRP rebar in reinforced concrete under fire exposure is a crucial issue [1], FRPs are extensively used for upgradation/strengthening of reinforced concrete (RC) structures. Many research works have been conducted to evaluate the performance of civil engineering structures strengthened by FRPs. Besides experimental investigations and analytical propositions, a considerable amount of studies has also been carried out on performance evaluation of existing and upgraded structure/components by employing numerical means.

Li et al. [2] presented the observations from experimental investigations on the behaviour of reinforced concrete beam–column connections strengthened by using hybrid FRP reinforcement (roving cloth, carbon cloth, and chapped strand mat and glass fiber) under static loading. It was noted that the significant increase in stiffness and load carrying capacity of the specimens were achieved by using hybrid FRP composites. Experimental investigation was carried out by Hadi and Li [3] on a number of high strength concrete columns externally reinforced with galvanised steel straps and fiber-reinforced polymers, and subjected to concentric and eccentric loading. Improvement in structural behaviour due to confinement was observed.

An analytical model proposed in [4] by using experimentally obtained bilinear moment–curvature relationship of FRP-strengthened RC sections to predict the load–deflection response of concrete beams reinforced with FRP bars. Si-Larbi et al. [5] addressed the flexural behaviour of concrete beams using mixed steel – and CFRP – reinforcement bars. It was pointed out that higher bending stiffness and strength can be achieved by using mixed CFRP–steel rebar in comparison to traditional steel reinforcement.

A finite element model for analysis of reinforced concrete plate strengthened with external composite materials was presented in [6] where material model for concrete, external uni-directional

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composites, type of shell element and geometric and material nonlinearities were described. Nonlinear finite element (FE) analysis of beam–column joint under monotonic loading has been reported in Hegger et al. [7,8]. To study the effect of several design parameters (effects of axial load in column, beam to column depth) on seismic behaviour of beam-wide column joints, numerical models were proposed in [9] and a cyclic load analysis was performed. Using a nonlinear FE analysis, it has been shown [10] how the analysis of reinforced concrete structures subjected to seismic actions can be improved using nonlinear spring elements to model bond–slip. An FE analysis procedure was brought out [11] for beams retrofitted with composite material as plate reinforcement. A scaled outrigger beam–column frame with as-built details was tested and numerically analysed, and finally an analytical method using strut and tie model was suggested to assess its performance under reversed cyclic loading [12]. From the investigation, a retrofit technique was proposed for the outrigger beam–column frame towards increasing the strength of the beam and the joint to force plastic hinging out of the critical zone. A numerical study has been conducted under monotonic loading [13] on damaged reinforced concrete beams and bridge superstructures coated with sprayed fiber reinforced polymer (SFRP) to evaluate the retrofit and strengthening performance of SFRP. An FE modelling was presented for the nonlinear analysis of monotonically loaded RC joints retrofitted with FRP overlays [14]. In the proposed model, the effects of anchorage slip and anchorage extension of the steel reinforcement in the connection zone were incorporated. With different schemes of upgradations and different types of fibers, beam–column joints were numerically analysed under monotonic loading by Parvin and Granata [15] and it was reported that the choice of the fiber composite materials, the laminate, arrangement and thickness of wrappings play a significant role in the proposed upgradation scheme. A finite element analysis procedure was proposed by Obaidat et al. [16] for evaluating the response of beams strengthened by using Carbon FRP. Linear elastic isotropic and orthotropic models were used for the CFRP, and a cohesive bond model was used for the concrete–CFRP interface. A plastic damage model was used for the concrete. To predict the stresses and strains distribution at failure of FRP-strengthened RC beams, a non-linear local deformation model derived from bond–slip relation was proposed by Ombres [17].

In the present study, a combined fiber composite-steel plate system has been proposed for upgradation of the poorly designed GLD beam–column sub-assemblage called SP-1. Based on the type – and distribution – of material, three different upgradation schemes have been proposed. The experimental investigations (as reported in [18]) were carried out for both original and upgraded specimens under reverse cyclic loading. The behaviour of beam–column sub-assemblages with different variables (upgradation components) can not be fully studied through experimental investigations. Hence, along with the experimental investigations, validated numerical models are required for further studies on the behaviour of beam–column sub-assemblage with different variables which would pave the way for achieving the better and optimised upgradation schemes. In the present study, a nonlinear FE program ATENA which is exclusively formulated for reinforced concrete structures has been used. From the existing literature, it is found out that, though utmost important, numerical studies on FRP upgraded beam–column joint (or sub-assemblage) under cyclic loading has not been paid adequate attention. Hence, a detailed study has been carried out on the performance of the upgraded beam–column sub-assemblages under cyclic loading with parameters such as, type of FRP, distribution of FRP, number of wrapping, and bond behaviour. Description of the original and upgraded specimens, material details, experimental set up, geometric modelling adopted and analysis parameters considered in the numerical analysis, results and discussion and further a detailed parametric study are being presented in the followings sections.

2. Specimen description and experimental details

2.1. Specimen description

Geometric – and reinforcement – details of the original gravity load designed specimen (SP-1) in shown in Fig. 1. Characteristic strength of concrete and yield strength of steel for the specimen was considered as 30 MPa and 500 MPa, respectively. In the subassemblage, height of column was 3800 mm and length of beam was 1700 mm with cross-sections of (300 × 300) mm and (300 × 400) mm, respectively. Table 1 presents the results obtained from the analysis of a 3-bay 3-story RC building under dead load (DL), live load (LL) and the load combinations according to the codal provisions. Finally, the geometry of the components (top and bottom portion of column and beam length from joint face) was chosen, as presented in Table 1, to match the bending moment distribution at the joint for which it was designed.

Three upgraded specimens called SP1-U1, SP1-U2 and SP1-U3, have been proposed (as shown in Figs. 2–4).

The properties of the materials used for upgradation of the 'GLD' specimen are as follows:

- *CFRP fabric*: is a unidirectional, stitched, carbon fiber fabric to be used with impregnated resin. Tensile strength, elastic modulus and elongation at break of the dry fiber are 3800 MPa, 242,000 MPa and 1.55%, respectively. Fiber density is 1.8 gm/cm^3. Impregnated fibers are assumed to have the thickness of 1 mm per layer with elastic modulus of 40,000 MPa.
- *CFRP laminate*: Carbon fiber laminates are produced by pultrusion process. Generally it is available in 50 mm width with 1.4 mm thickness. Elastic modulus, tensile strength and elongation at break of the laminate are 165,000 MPa, 2800 MPa and 1%, respectively.
- *GFRP fabric*: is a unidirectional, stitched, glass fiber fabric to be used with impregnated resin. Tensile strength, elastic modulus and elongation at break of the dry fiber are 2200 MPa, 70,000 MPa and 3.1%, respectively.

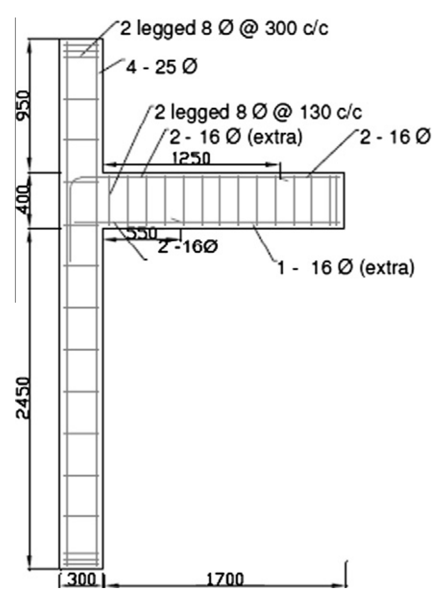

Fig. 1. Geometric and reinforcement details of the gravity load designed specimen (SP-1).