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Novel non-invasive seismic upgradation strategies for gravity load designed exterior beam-column joints

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ABSTRACT

Existing gravity load designed (GLD) structures are vulnerable to seismic event due to their inherent weaknesses. The present study, focuses on the development of non-invasive and feasible strategies for seismic upgradation of these non-seismically designed structures. Three novel schemes, namely (i) single haunch upgradation scheme (U1), (ii) straight bar upgradation scheme (U2) and (iii) simple angle upgradation scheme (U3) are proposed for seismic upgradation of GLD specimens. The efficacy and effectiveness of these upgradation schemes are evaluated by conducting the reverse cyclic load tests on control and upgraded GLD exterior beam-column sub-assemblages. The performance of the upgraded specimens is compared with that of the control GLD beam-column sub-assemblage, in terms of load–displacement hystereses, energy dissipation capacities and global strength degradation behaviour. Tremendous improvement in the energy dissipation capacity to the tune of 2.63, 2.83 and 1.54 times the energy dissipated by the control GLD specimen is observed in single haunch upgraded specimens, straight bar upgraded specimen and simple angle upgraded specimen respectively. The specimen with single haunch upgradation performed much better compared to the GLD specimens upgraded with the other two schemes, by preventing the brittle anchorage failure, delaying the joint shear damage and redirecting the damage partially towards the beam.

1. Introduction

Prior to the introduction of modern seismic codes, the structures were designed to cater for gravity loads, i.e. the self-weight of the structural components and possible imposed vertical load acting on the structure. Hence, structural components of GLD structures do not have adequate reinforcement to cater for the seismic forces. Further, joints of GLD buildings lack confinement, transverse reinforcement

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and hence possess inadequate shear resistance. Insufficient anchorage of the beam bottom reinforcement of GLD frames leads to the anchorage failure or brittle bond failure under seismic loading, leading to huge strength degradation. Particularly, exterior joints of GLD building are more vulnerable and critical as they do not possess a robust force transfer mechanism. Hence, seismic upgradation of beam-column sub-assemblages of GLD buildings has to be addressed immediately to prevent collapse of the existing GLD buildings under seismic excitations.

Plenty of studies were reported in the literature on upgradation/retrofitting of non-seismically designed beam-column sub-assemblages using jacketing, near surface mounting technique, fibre reinforced polymer (FRP) wrapping, haunch retrofitting, joint enlargement, etc. Seismic retrofitting/upgradation using jacketing is a decade old method. Upgradation or retrofitting of beam-column joints was carried out by reinforced concrete jacketing [1,2], steel jacketing [3,4], high performance fibre reinforced concrete jacketing [5–7], hybrid jacketing i.e. combination retrofit strategies with jacketing [8,9]. Seismic retrofit/upgradation using fibre reinforced polymer wrapping or anchoring or the combination of the both was proved as an effective technique by El-Amoury and Ghobarah [10], Prota et al. [11], Akguzel and Pampanin [12], Sezen [13], and Realfonzo et al. [14]. Furthermore, Vecchio et al. [15] proposed a new strength capacity model to predict the increase in strength provided by FRP systems in the seismic retrofit of poorly detailed corner joints. The accuracy of the proposed model was assessed by comparing the predicted results of the model with large database of experimental tests. Near surface mounting technique is frequently complemented with the FRP retrofit schemes for the effective retrofitting of the parent member. Prota et al. [11] upgraded under-designed interior beam-column joints by combined use of externally bonded fibre-reinforced polymer (FRP) laminates and near surface-mounted (NSM) FRP bars. The upgradation scheme involves different combinations of FRP laminates around column/beam with or without NSM bars.

The concept of haunch retrofit solution was perceived by Yu et al. [16] for steel moment resting frames in view of significant failure of welds during Northridge earthquake. The concept of this haunch strengthening scheme was adopted and implemented for GLD RC structures by Pampanin et al. [17,18]. Genesio et al. [19] and Sharma et al. [20] investigated the performance of haunch system connected to the beam and column through post-installed anchors. This was termed as fully fastened haunch retrofit system. Sharbatdar et al. [21] retrofitted the damaged exterior beam-column joints using steel prop and curb by providing two each at the top and bottom faces of the beam and connecting the beam and the column. It was reported that there was a significant increase in ultimate load and decrease in degradation of retrofitted damaged joints. Further, they reported that the energy absorption was enhanced and the cracks were minimized due to retrofitting. Shafaei et al. [22] proposed an innovative seismic retrofit scheme for strengthening of non-seismically detailed beam column joints by the use of prestressed steel angle sections. It was found from their experimental study that with proper implementation of strategy, the plastic hinge can be relocated into the beam region. Campione et al. [23] used steel cages for strengthening of the exterior beam-column sub-assemblages and proposed a simplified analytical model that can be used for pushover analysis. The results obtained from their study highlighted the effectiveness of the external steel cage as strengthening system, which increases the flexural strength and facilitate to shift the failure mode from the column to the beam.

Most of the reported works were successful in achieving the desired seismic performance level either completely or partially. However, when it comes to implementation on the existing deficient structure, almost it is very difficult to implement the reported retrofitting schemes as they need to access column, beams and joints from all the four sides. The expediency of any retrofitting scheme could be fully exploited only when it is feasible to practice. Unless the retrofitting scheme is implementable, it would become useless even though the scheme is so robust. For this reason, in the present study emphasis has been laid for the development of implementable novel seismic upgradation scheme for GLD structures. In an existing structure, the bottom portion of the floor beam and adjacent column would be easily accessible which is the key for the development of upgradation strategies in the present study. The GLD beam-column joints are susceptible to sudden anchorage failure under load reversals and hence require systematic seismic upgradation. For this reason, the primary aim of the present work is to avoid anchorage failure of beam bottom reinforcement bars of GLD structure and delaying the joint damage as far as possible under seismic loading. The seismic upgradation of the exterior beam-column sub-assemblages are carried out using three novel schemes, namely (i) single haunch upgradation scheme (U1), (ii) straight bar upgradation scheme (U2) and (iii) simple angle upgradation scheme (U3). The first two upgradation schemes provide an alternate force path and thereby reduce the demand on the components of sub-assemblages whereas the third scheme involves strengthening of the beam bottom to prevent brittle anchorage failure of beam bottom reinforcement bars. The efficacy of these novel upgradation schemes is evaluated by conducting reverse cyclic load tests on the retrofitted GLD exterior beam-column sub-assemblages. The performance of the upgraded GLD specimens is compared with the control GLD beam-column sub-assemblage, in terms of load–displacement hystereses, energy dissipation capacities and global strength degradation behaviour.

2. Details of the beam-column sub-assemblage specimens

An exterior beam-column sub-assemblage of a typical three storied RC framed building as shown in Figs. 1(a) and (b) is taken up. The general dimensions of beam-column sub-assemblage are as follows: height of column segment is 3800 mm and length of beam segment is 1700 mm. The cross sectional dimensions adopted for beam and column sections are $300\ \text{mm} \times 400\ \text{mm}$ and $300\ \text{mm} \times 300\ \text{mm}$ respectively, and the reinforcement details of GLD specimen are shown in Fig. 1(c). It is important to mention here that the beam bottom bars in gravity load designed specimen project straight into the joint region. Four such specimens are cast and one of them is