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EXPERIMENTAL INVESTIGATIONS ON SEISMIC RETROFITTING OF REINFORCED CONCRETE BEAM-COLUMN JOINTS

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ABSTRACT

Beam-column joints are recognized as the critical and vulnerable zone of a Reinforced Concrete (RC) moment resisting structure subjected to seismic loads. During an earthquake, the global response of the structure is mainly governed by the behaviour of the joints. If the joints behave in a ductile manner, the global behaviour generally will be ductile, whereas if the joints behave in a brittle fashion then the structure will display a brittle behaviour. The joints of old and non-seismically detailed structures are more vulnerable and behave poorly under the earthquakes compared to the joints of new and seismically detailed structures. Therefore, more often than not, the joints of such old structures require retrofitting in order to deliver better performance during earthquakes. Various researchers have proposed different methods to retrofit the beam-column joints of existing RC structures. This paper reports a few experimental investigations carried out for seismic retrofitting of RC beam-column joints using different techniques. The concepts behind each of them and their practical usefulness have been brought out.

Keywords: Seismic Retrofitting, Beam-Column Joints, Jacketing, Wrapping, Haunch elements

INTRODUCTION

Under the action of seismic forces, beam-column connections are subjected to large shear stresses in the joint region. These shear stresses are a result of moments and shear forces of opposite signs on the member ends on either side of the joint core. Typically, high bond stresses are also imposed on reinforcement bars entering into the joint. The axial compression in the column and joint shear stresses result in principal tension and compression stresses that lead to diagonal cracking and/or crushing of concrete in the joint core. These problems have been highlighted in recent past by the damage observed in devastating earthquakes in different countries. The two major failure modes for the failure at joints are (a) joint shear failure and (b) end anchorage failure (Fig. 1). A typical example of a beam-column joint failure during the 1999 Turkey earthquake is shown in Fig. 2 (Ghobarah and Said, 2002). The stresses in the joint core are resisted by the so-called strut and tie mechanism (Paulay and Priestley, 1992). To assure an increase of the shear strength after the cracking of the joint core by diagonal tension and sufficient rotational capacity, joint shear reinforcement is needed, which is therefore prescribed by the newer design codes (ACI 318, 2008; NZS 3101, 1995; IS 13920, 2002). Moreover, these codes prescribe a large anchorage length of the bars terminating in case of exterior joints, so that a bond failure may be avoided.

(a) Joint Shear Failure (b) Inadequate Reinforcement Anchorage

Fig. 1 Major Failure Modes for a RC Beam-Column Joint

Fig. 2 Typical beam-column joint failures (1999 Turkey Earthquake)

However, a vast majority of RC buildings world wide consist of structures designed prior to the advent introduction of modern seismic design codes. It has been identified that the deficiencies of joints are mainly caused by inadequate transverse reinforcement and insufficient anchorage capacity in the joint (Liu, 2006). Fig. 3(a) shows a few typical deficiencies found in the beam-column joints of old structures and Fig. 3(b) shows the corresponding new ductile detailing recommended by new codes.

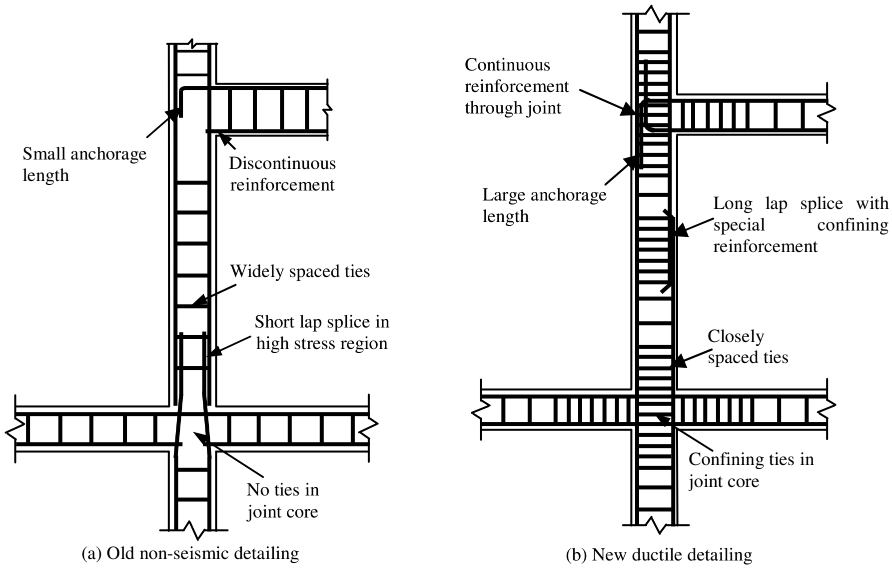


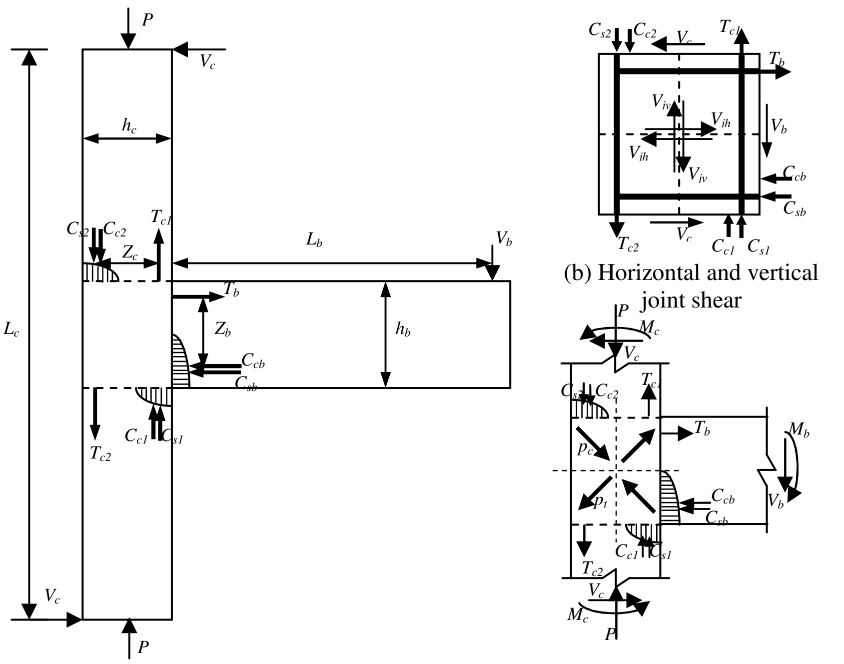
Fig. 3 Typical non-ductile detailing prescribed by older codes of practice

In order to prevent devastating failures of structures not designed as per the current seismic design procedures and not having special seismic detailing, retrofitting is often required. At the global structural level the retrofitting can be performed by strengthening techniques such as addition of shear walls or stiffeners, or by response control techniques such as using base isolation system or installing dampers. Sometimes, these techniques alone may be suitable enough to redistribute the forces (e.g. in case of adding shear walls) or reduce the forces (e.g. in case of base isolation) to an extent that no further retrofitting at member level is required. However, often it may be more suited because of technical or economical reasons to retrofit single members only or in addition to global retrofitting. Such techniques usually target an increase of the ductility of the structure more than a strengthening.

At the member level (i.e. for beams and columns), various retrofitting techniques are available such as concrete jacketing, steel jacketing, wrapping with fibre reinforced polymer (FRP) sheets, external prestressing etc. These techniques have proved over the years to be quite effective with each of the above having its own advantages, disadvantages and limitations. However, retrofitting of beam-column joints is still a major topic of concern. Many researchers have investigated different techniques, with varying degrees of success, for retrofitting of the reinforced concrete beam-column joints. One of the major challenges is to practically implement a retrofitting scheme, because there is only a restricted access, if any, to the real joint core to perform any retrofitting technique. This calls for the need of innovative thinking to develop methods that are technically, practically and economically viable. This paper discusses a few of such techniques with emphasis on their strengths and limitations.

MECHANICS AND SEISMIC EVALUATION OF BEAM-COLUMN JOINTS

Before a retrofitting can be suggested for a particular joint, it is necessary to evaluate the seismic performance of the joint in as-built condition. This needs a basic understanding of the mechanics of stress transfer within a joint. When RC moment frames are subjected to lateral seismic loading, high shear forces are generated in the joint core (Paulay and Priestley, 1992; Hakuto et al, 2000). Fig 4 shows the mechanics of an exterior joint when subjected to seismic forces. The lateral seismic loading on a frame leads to bending moments and shear forces that can be simulated in the joint as shown in Fig 4 (a). Here the length of the beam L_b is half of the bay width and L_c is the storey height. The horizontal shear, vertical shear and principal tensile stresses can be calculated by considering the equilibrium of the joint. (Paulay and Priestley, 1992; Tsonos, 2007)



(b) Horizontal and vertical joint shear

(a) External actions and forces in beams and columns (c) Principal stresses in joint

Fig. 4 Mechanics of exterior joint under seismic actions

A system of diagonal compression strut and tension tie is developed in the concrete core to transmit the joint shear forces. Some of the internal forces, particularly those generated in the concrete will combine to develop a diagonal strut (Paulay and Priestley, 1992; Hakuto et al, 2000). Other forces transmitted to the joint core from beam and column bars by means of bond, necessitate a truss mechanism. The strength of the diagonal strut controls the joint strength before cracking. The transverse reinforcement in the joint helps confine the concrete diagonal strut in the joint core thereby contributing to increased joint strength after the first diagonal cracking. If the joint shear forces are large, diagonal cracking in the joint core occurs followed by the crushing of concrete in joint core. The joint reinforcement alone is not sufficient to avoid undesirable pinching in hysteretic loops at this stage (Murty et al., 2003). Standards (ACI 318, 2008; NZS 3101, 1995; EC8, 1998) recommend keeping the stresses in the joint below permissible limits. ACI 318 (2008) and EC8 (1998) specify this limit based on the tensile strength of concrete by specifying the value of maximum permissible horizontal joint shear stress as $k\sqrt{f_c'}$, where, f'_c is the cylinder compressive strength of concrete and k is a parameter that depends on the confinement provided by the members framing into the joint. NZS 3101 (1995) recommends that the horizontal shear stress shall not exceed a value of 0.2 f'_c. Other authors recommended that principal stresses that consider the contribution of axial forces also, provide better criteria for the damage in the joint (Priestley, 1997; Pampanin et al, 2003). The values are suggested as $k\sqrt{f'_c}$, where, f'_c is the cylinder compressive strength of concrete and k is a parameter that depends on the type of joint, type of reinforcement and end anchorage details of the beam longitudinal bars in the core. Priestley (1997) suggested the critical principal tensile stress values for exterior and corner beam-column joints with deformed bars with bent-in and bent-out type end anchorages and Pampanin (2003) proposed more recently the same for exterior beam-column joints with plain round bars and end hooks. Once, the joints are analyzed based on the formulations given above, the decision on whether a joint needs retrofitting or not, and to what extent, can be made. Many researchers proposed more sophisticated models to assess the joint shear capacity including the influence of several parameters such as the joint slenderness ratio (height of the beam / height of the column). Experimental and numerical investigations are ongoing in order to refine the approach by Priestley (1997) and to include the influence of different parameters (Genesio et al., 2010-1).

SEISMIC RETROFIT STRATEGIES FOR RC BEAM-COLUMN JOINTS

Various retrofit techniques have been investigated by different researchers throughout the world to enhance the seismic behavior of reinforced concrete joints. A few of them are discussed below.

Concrete Jacketing

Concrete jacketing is a conventional and popular method for strengthening of frame members such as concrete beams and columns. Codes such as IS 13935:1993 (2002) have been recommending this approach for strengthening frame members of the structures. Few researchers have attempted to apply the technique for retrofitting reinforced concrete beam-column joints. The reinforced concrete jacketing of a joint has to be performed in such a way that all the members connected at the joint collaborate together (Tsonos, 2000). Strengthening involves encasing the original beam-column joint and certain critical regions of the columns with a cement grout jacket reinforced with additional ties in the joint region and the columns. For an adequate bond between original and new concrete and possibly for the welding of new reinforcement to the existing reinforcement, the concrete cover must be chipped away (Tsonos, 2000). Additional horizontal ties and vertical reinforcement are placed in the joint region in order to provide adequate joint shear strength by passing the new horizontal ties through drilled holes. It is necessary that sufficient thickness of the jacket be provided in order that the large number of reinforcement bars required can be installed. Tsonos (2000) tested seven exterior reinforced concrete sub-assemblages that were subjected to severe earthquake damage. The specimens were repaired and strengthened by concrete jacketing and the strengthened specimens were tested again. He found that the repaired and strengthened specimens exhibited higher strength, higher stiffness and better energy dissipation capacity than the original specimens. Dhakal et al (2003) tested a full scale interior beam-column joint that was first subjected to cycling load history to induce damage (Fig. 5 (a)) and was then strengthened using RC jacket (Fig. 5 (b)) and then again tested (Fig. 5 (c)). A much improved seismic response was obtained for the strengthened specimen. Shannag et al (2002) tested five 1/3-scale interior beam column joints having old detailing, under cyclic lateral loading. The specimens were then repaired using high performance fibre reinforced concrete (HPFRC) jacket, all around the joint column regions, and tested again up to failure. Higher load levels, more ductile behaviour, substantial energy dissipation and slower stiffness degradation were observed. Failure modes were modified from brittle shear in the joint to ductile beam failure through plastic hinge formation.

All these tests showed that concrete jacketing is indeed an effective method to improve the seismic behaviour of the non-ductile detailed joints. However, it can be noted that the actual implementation of this scheme is quite cumbersome and requires high amount of labour and time, though the material cost is relatively low. Moreover, applying such a scheme in a real structure where beams and slabs are framing into the joint from all directions may be very complicated. Though, it must also be noted that the biggest advantage of this scheme is that it can be used to repair and strengthen the joints that had already suffered some damage during previous earthquakes. Technically, the biggest drawback of the scheme is that it considerably changes the dynamic characteristics of the original structure since it increases the stiffness significantly. Therefore, not only the strength side of the equation is modified, but also the demand side and therefore, the retrofitting design becomes iterative where after each design of the jacket, another analysis using the current proposed dimensions, need to be performed and a comparison of demand and capacity need to be done at every step.

(a) Original Joint (b) RC Jacketing (c) Strengthened Joint

Fig. 5 Original and RC Jacketed beam-column joint tested by Dhakal et al (2003)

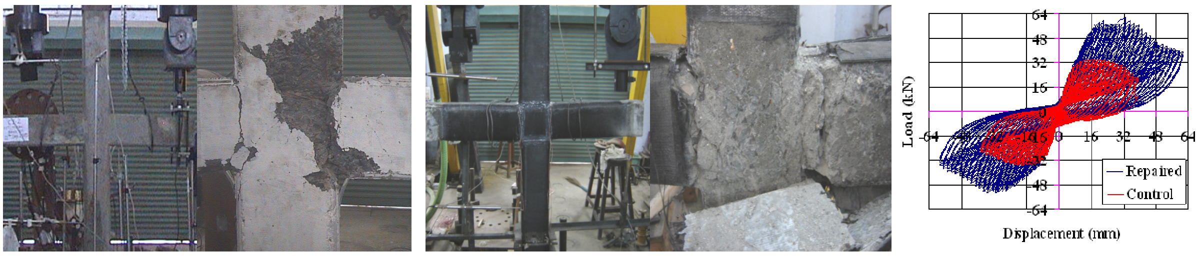
FRP Wrapping

Significant research has been carried out for understanding and promoting the use of fibre reinforced polymers (FRP) for seismic retrofitting of RC structures. The reason for such an interest among researchers and practitioners is in various advantages that this technique offers over other conventional methods such as concrete jacketing. A few of the advantages can be listed as: very high specific strength (strength to weight ratio), high corrosion resistance, almost no increase in member size, limited invasion (but only after the application) and tailorability. The biggest disadvantages of FRP are generally the high material cost and poor fire resistance of adhesive. Furthermore, high qualification of the installers is required in order to assure an effective wrapping. However, it can be argued that the cost factor can be negated if an economical design is performed and keeping in mind that though the material cost is high but labour cost and construction time is much lower than conventional techniques such as RC jacketing.

The efficiency and convenience of the technique has been demonstrated by the wide use of this retrofitting technique for various structures (Sharma et al, 2005) and the growing popularity is proven by the fact that several codes/guidelines worldwide recommend the use of this technique for seismic strengthening of the structures such as ACI 440 2R (2008), and FIB-Bulletin 14 (2001) are examples of such guidelines. Although, the use of FRP for the confinement of columns (Saatcioglu, 2003) and the retrofitting on infill masonry walls (Saatcioglu, 2006) are well documented, the studies on beam-column joints are relatively few.

Ghobarah and Said (2002) tested four joints without transverse reinforcement in the core, and designed according to strong-beam weak-column concept. The specimens were strengthened using FRP with and without mechanical anchorage. The joints with no anchorage failed in joint shear whereas those with anchorage failed by flexural hinging of the beam emphasizing the importance of proper anchoring of FRP. Antonopoulos and Triantafillou (2003) carried out 18 tests on joints without transverse reinforcement, strengthened in shear with various FRP schemes. FRP ratio, presence of anchoring and the presence of transverse reinforcement in the joint were among the major parameters studied. All the tested joints displayed partial or complete debonding of FRP followed by joint shear failure. Ghobarah and El-Amoury (2005) investigated the performance of beam-column joints that had inadequate anchorage for beam bottom bars combined in some cases with no transverse reinforcement in the joint. The specimens failed according to different modes, including debonding of FRP in specimen with no mechanical anchorage. Mukherjee and Joshi (2005) presented results of tests carried out on 13 interior beam-column joints. The parameters studied were: inadequate anchorage, FRP ratio; the type of FRP fibres and FRP retrofit scheme. All the retrofitted specimens failed by flexural hinging at the beam-joint interface. The test results clearly showed the effectiveness of the FRP system regardless of FRP schemes, and indicated that specimens strengthened using CFRP exhibited stiffer behaviour than GFRP strengthened specimens. Although, all the joints had no transverse reinforcement and no FRP was placed within the joint core to address this deficiency, the retrofitted specimens displayed a quite improved behaviour, which was surprising (Bousselham, 2010). Al-Salloum and Almusallam (2007) tested interior beam-column joints retrofitted using CFRP, with and without mechanical anchorage. They showed that in both cases, shear failure of the joint was delayed although the specimens with no anchorage experienced shear failure, preceded by debonding whereas specimens with anchorage failed by beam flexural hinging. Karayannis and Sirkelis (2008) performed a series of tests on exterior joints repaired and strengthened with epoxy resin injections and CFRP. The test results showed that the CFRP contribution to the shear capacity depends on whether the strengthened joint is reinforced in shear with steel reinforcement. Pantelides et al. (2008) conducted tests on eight interior joints and the experimental results clearly showed the effectiveness of the FRP system regardless of FRP type.

Rai (2007) tested interior joints without transverse reinforcement under cyclic loads till significant damage (Fig. 6 (a)) in joint. The joints were repaired and retrofitted with epoxy injections and carbon fibres. After repair of the joint, slots were made in the column to insert laminates applied on the top and bottom face of the beam, wraps were applied on the front and back face of the columns and then the beams and columns along with the joint were wrapped with carbon fibres (Sharma et al 2006). Thus, significant amount of material was used for strengthening. The retrofitted joint (Fig. 6 (b)) displayed much higher resistance, higher energy dissipation and almost the same stiffness as original joints. Also, the failure was shifted from the joint core to the beam flexure (Fig. 6 (b)).



(a) Control Joint (b) Retrofitted Joint

Fig. 6 Joint testing and failure mode for joints tested by Rai (2007)

Pampanin et al (2007) tested a 3D exterior joint with reinforcement made by plain round bars with the anchorage of beam reinforcement in the form of end hooks in the joint core without any transverse reinforcement (Fig. 7). The retrofitting scheme using GFRP was designed with an aim at controlling the hierarchy of strength within the beam-column joint system by protecting the panel zone and relocating the plastic hinge in the beam. It was reported that very promising confirmations on the efficiency of the adopted retrofit strategy and solution were provided.

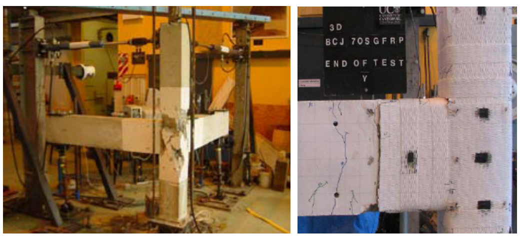
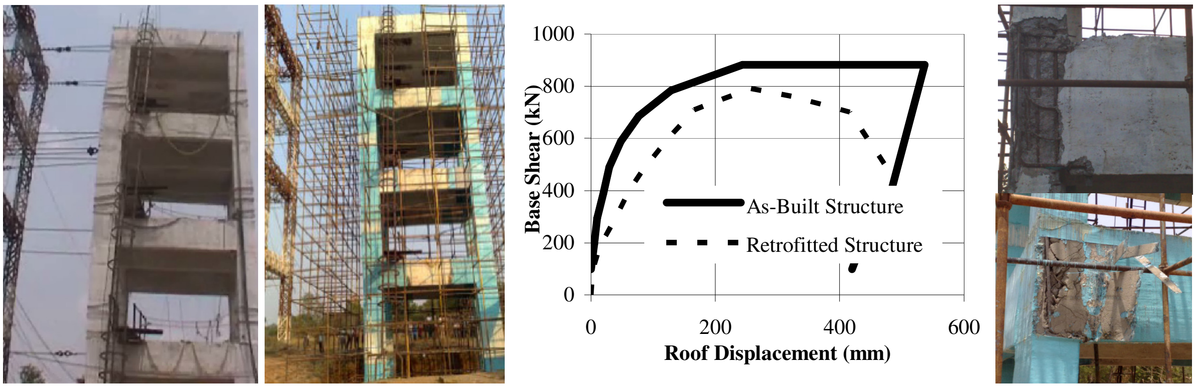


Fig. 7 Experiment on as-built and retrofitted 3D joints by Pampanin et al (2007)

Based on the above-discussed tests, it can be concluded that FRP retrofit, in general can be quite effective for retrofitting of the joints, even if they have suffered some damage. Both the strength and the energy dissipation of FRP retrofitted joints increase, though not proportionally, with the number of FRP layers. Mechanical anchorage increases the effectiveness of FRP rehabilitation technique and the effectiveness of FRP increases as the transverse reinforcement in the joint decreases. However, in case of FRP wrapping, the authors feel that the biggest drawback of the system is susceptible to workmanship and uneven surfaces. Recently, a full-scale RC structure (Fig. 8 (a)) that was earlier tested under pushover loads till failure (Sharma et al, 2010) was repaired and retrofitted using a combination of CFRP and GFRP and re-tested (Fig. 8 (b)). The FRP design criterion was set as to bring back the structure to almost at same level as original structure. A higher criterion could not be set due to economical considerations. It was found that the structure could reach 90% of the base shear as was recorded for original structure (Fig. 8 (c)), but the stiffness of the retrofitted structure was reduced and delamination was quite pronounced due to surface unevenness in locations that are critical but difficult to reach in practice, whereas in case of laboratory testing, the quality control and approachability is much better. Although, in general the joint behaviour was improved due to prevention of spalling of concrete (Fig. 8 (d)), the failure could not be prevented. Moreover, it was noticed that while doing research at member level or joint level, economy is not a constraint and generally much higher amount of FRP than necessary is provided, which cannot be the case while performing retrofitting at structural level.



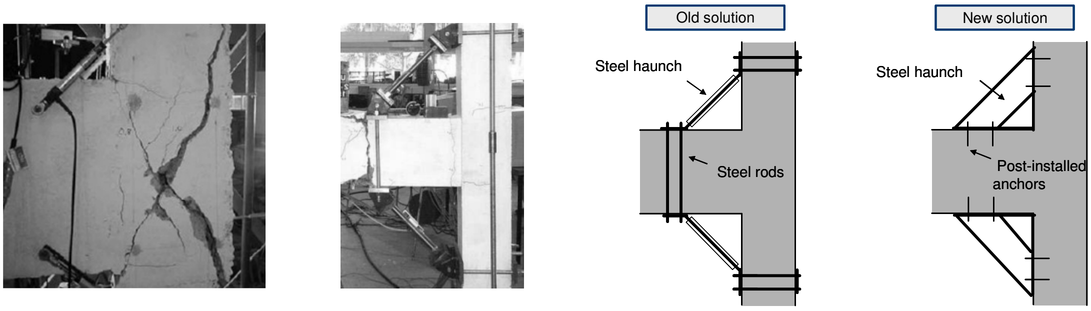
(a) As built (b) Retrofitted (c) Pushover Curves (d) Joint Failures

Fig. 8 Full scale structure being tested under pushover loads

Haunch Retrofit Solution

A seismic retrofit strategy for pre-1970s exterior beam-column RC joints designed for gravity loads only has been recently numerically and experimentally investigated by the authors of this paper. The "Haunch Retrofit Solution" (Fig. 9 (b),(c)) was developed at the University of Canterbury in order to modify the internal hierarchy of strength and to induce the formation of a ductile flexural hinge in the beam (Fig. 9 (b)) rather than a brittle shear failure in the joint panel (Fig. 9 (a)) (Pampanin et al., 2006). It represents an extension of a retrofit solution developed for steel moment resisting frames, following a high amount of weld fractures observed after the Northridge earthquake (Yu et al., 1997), in order to relocate the plastic hinge away from the welded connection between beam and column. Compared to a FRP wrapping of the joint (Fig. 6), this solution represents a cheaper and less invasive way to retrofit a beam-column connection. Although these solutions have the same goal, the functioning principles are very different. With GFRP wrapping the shear strength of the joint panel is increased, while with the application of the diagonal haunches the joint is protected reducing the shear demand. The design of the haunch can be performed using the formulations proposed by Pampanin et al (2006). The installation of a metallic haunch would be easier and less invasive if the external threaded rods used to fasten the steel diagonals on the beam and column could be substituted by post-installed anchors (Fig. 9 (d)).

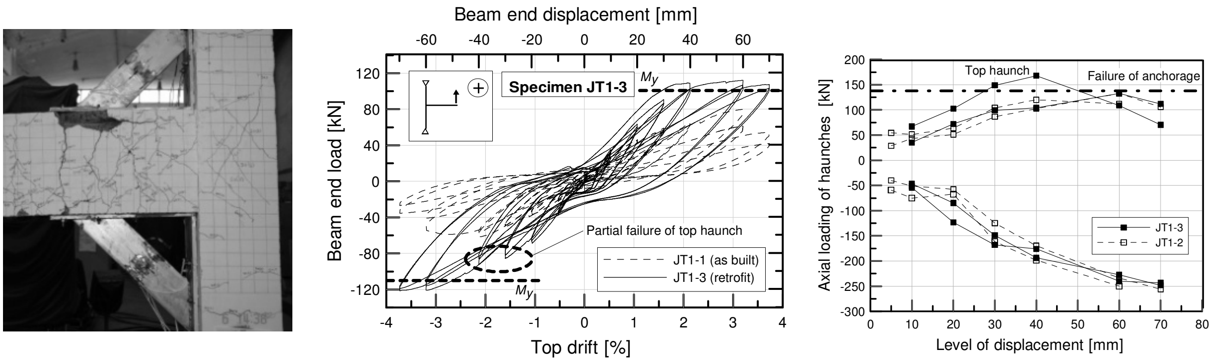
It was numerically showed that the efficiency of this solution depends mainly on the stiffness of the haunch connection and its slippage on beam/column surface (Eligehausen et al., 2008). The design of anchorage can be carried out according to the CC-Method (Eligehausen et al., 2006). The anchorage has to carry loads very close to a plastic hinge (Fig. 9 (b)) and since according to the existing design codes, post-installed anchors should not be used in such location, it should be designed with high redundancy. However, it may be difficult to install an effective large anchor group in a thin structural member such as a beam or column. The highly demanding load-history, to which the anchors are subjected, consists of cyclic combined tension and shear in cracked concrete, with need of precise information not only of their resistance, but also of their load-displacement behaviour up to failure.



(a) As-built Joint (b) Haunch Retrofit (c) Externally clamped (d) Fully fastened

Fig. 9 Haunch Retrofit Solution for exterior beam column joints (Pampanin et al., 2006); (Genesio and Akgüzel, 2009)

In order to investigate the feasibility of the new solution, experimental tests were carried out in the laboratory of the University of Canterbury (Genesio and Akgüzel, 2009). Further tests were carried on at BARC, Mumbai (Genesio and Sharma, 2010) in order to modify the design model of the "Haunch retrofit solution" proposed by Pampanin et al. (2006) and to adapt it to the implementation of post-installed anchors. In Fig. 10 the results of one of the tests carried out by Genesio and Sharma (2010) are shown. The retrofit was designed in order to evaluate the effect of a partial failure of the anchorage of the haunch on the overall performance of the joint. The partial failure of the anchorage can be seen in the top part of the beam (Fig. 10 (a)) and it is reflected in the hysteretic behaviour of the specimen with a reduction of stiffness in the negative direction (Fig. 10 (b)). The analysis of the axial forces in the haunches confirmed that the strength of the top haunch was exceeded (Fig. 10 (b)). However, the retrofit was successful, since the behaviour of the specimen was enhanced and the flexural hinging of the beam induced a ductile behaviour of the beam-column connection. More details about the experimental investigations on the retrofit solution with fully fastened haunches can be found in Genesio and Sharma (2010) and Genesio et al. (2010-2).



a) b) c)

Fig. 10 a) Cracking pattern of retrofitted specimen; b) Comparison between hysteretic behaviour of as-built and retrofitted specimen; c) Axial forces measured in the haunches

Thus, for the haunch retrofit solution, it can be said that it is a very practical solution based on the principle of redistribution of forces around the joint so that the plastic hinge is relocated from joint to the beam. As such, the retrofit does not strengthen the beam or the column or the joint but only redirects the load path. With fully fastened system, there is no need for drilling the holes through the slab or walls, and the haunch can be totally hidden in the walls. The invasiveness of the method and the cost implications are the least of all the methods discussed here, making it a very practically viable solution. However, the limitation of the solution may be underlined as the fact that this system is inappropriate, though technically possible, to retrofit the joints that are already damaged due to prior earthquakes. In the case of weak column-strong beam configuration, the relocated hinge may go to the column instead of beam. In such a case the design of the retrofit solution should be modified accordingly, e.g. changing the length and inclination of the haunches. Moreover, design of anchorage has to be carried out very carefully to avoid the anchorage failure prior to beam hinging.

CONCLUSIONS

Seismic retrofitting of RC beam-column connections has proved to be a highly challenging topic in front of researchers for past few years. Although, many different techniques have been tried, tested and developed, every technique has its own strengths and limitations. Concrete jacketing can be used to add the transverse reinforcement to the joint and increase the size so that the stress is reduced and the method has been found suitable for retrofitting the joints even if they are pre-damaged. However, it leads to an increase in size, significant change in stiffness, needs lot of care to make sure that the old and new concrete work together, requires lot of time and labour and is quite invasive. FRP wrapping on the other hand is very light, has a high corrosion resistance, limited invasiveness and also can be used to strengthen pre-damaged joints. However, high material cost and susceptibility to workmanship and uneven surfaces are a matter of concern. Haunch retrofit solution offers a very practical, easy to apply in practice, cheap and efficient system for retrofitting the joints by the concept of redistribution of forces and moments, however, the system may not be totally suitable for retrofitting the pre-damaged joints and extra care in design is needed to strengthen weak column strong beam configuration.

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