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Application of Post-Installed Anchors for Seismic Retrofit of RC Beam-Column Joints: Design Method

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ABSTRACT: Many reinforced concrete (RC) structures, built in seismic-prone countries before the introduction of the modern seismic oriented codes and usually designed for gravity loads only, necessitate an upgrade in terms of strength and ductility against lateral loading. In this paper the possibility of using post-installed anchors for seismic retrofit solutions is investigated. Post-installed anchors are usually fast and easy to install and they represent a valuable low-invasive solution to transfer high loads with quite low costs. The retrofit of RC beam-column connections with a diagonal haunch element fastened to the existing structural element using post-installed anchors is proposed. The design method based on experimental and analytical investigations is presented. Particular focus is given to the requirements in terms of load displacement characteristics, i.e. stiffness on the post-installed anchors.

Keywords: Seismic retrofit, RC exterior beam-column joints, post-installed anchors

1 INTRODUCTION

In seismic-prone countries worldwide there is a large amount of buildings that were built before the introduction of modern seismic oriented design codes. Earthquakes during the last decades have shown that these structures designed with substandard detailing need urgently retrofitting and strengthening measures, either to withstand future seismic events with moderate damage, or at least without any collapse. The retrofitting may target the upgrading of the seismic performance in terms or strength and/or ductility. Global strategies may be adopted to enhance the resistance of structures to lateral loads (e.g. insert of shear walls or of steel bracing) or to reduce the effect of the seismic action (e.g. damping systems or base isolation). Local strategies are usually chosen to prevent the brittle failure of structural elements, such as wall and column under shear and to assure a ductile plastic behavior of the structure.

Large earthquakes that occurred in the recent past showed that deficiencies in the detailing of exterior beam-column joints (i.e. lack of transverse reinforcement, poor anchorage of the beam longitudinal bars in the core and use of plain round bars) are usually responsible for the non-ductile brittle failure mode of the beam-column connections that can induce a collapse of the entire moment resisting frame (Figure 1).

Many retrofit solutions have been proposed and investigated in the recent past to improve the seismic response of beam-column connections and more specifically to avoid brittle failure modes such as column or joint shear failure in favour of more ductile plastic mechanisms such as beam flexural hinging. Various retrofitting techniques are available such as concrete jacketing (e.g. Tsonos, 1999), steel jacketing (e.g. Ghobarah et al., 1997), wrapping with fibre reinforced polymer (FRP) sheets (e.g. Akgüzel, 2011), external prestressing (Kam, 2011), 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. 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.

In this study an economical and low invasive technique, the Haunch Retrofit Solution (HRS), proposed by Pampanin et al. (2006) is considered. As explained in Section 2 the simplification of this retrofit solution by using post-installed anchors is proposed. Post-installed anchor systems find extensive application in many different retrofit solutions by attaching new elements to an existing structure. For the design of the anchorages it is necessary to take into account cyclic and impulsive actions and the conditions of the anchorage material, e.g. cracked and low strength concrete. In most of the applications the anchorages are expected to be over-designed in such way that stiff connections between old and new structural elements may be ensured (CEB, 1995). However, a proper design of such anchorages is often neglected and the real demand on the anchorage in terms of strength and ductility is underestimated. In the frame of a research cooperation between the University of Stuttgart and the University of Canterbury (UC) the application of post-installed anchors in different seismic retrofit solutions is investigated.

a) Turkey (1999) – Photo: EERC Library, Berkeley, USA

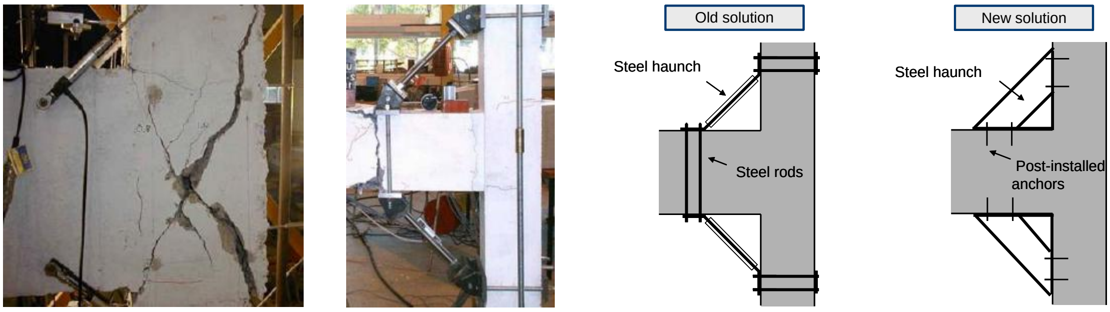
b) L'Aquila, Italy (2009) – Photo: A. Brignola

Figure 1: Typical failures of beam-column joints observed in recent earthquakes

2 RETROFIT CONCEPT

The "Haunch Retrofit Solution" (HRS) (Figure 2b,c) was developed at the UC in order to modify the internal hierarchy of strength of the beam-column connection (Figure 3a) and to induce the formation of a ductile flexural hinge in the beam (Figure 2b) rather than a brittle shear failure in the joint panel (Figure 2a) (Pampanin et al., 2006). Compared to a wrapping of the joint e.g. using fibre reinforced polymers, this solution represents a cheaper and less invasive way to retrofit a beam-column connection. Although both solutions have the same goal, the functioning principles are very different. With wrapping the shear strength of the joint panel is increased, while with the application of the diagonal steel haunches the joint is protected reducing the shear demand.

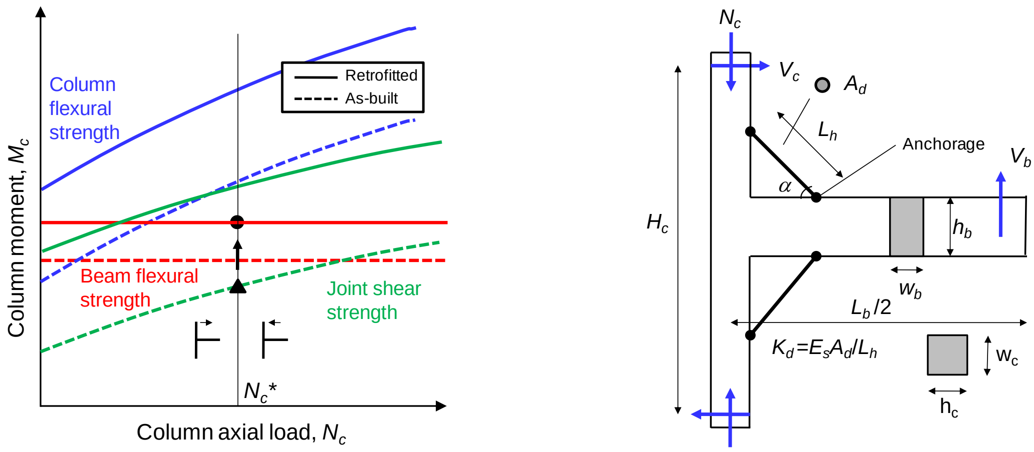
The installation of a metallic haunch would be easier and less invasive if the external threaded rods used to fasten the steel diagonals on the beam and on the column could be substituted by post-installed anchors (Figure 2d). In this way no drilling through the floors and the infill walls of the building would be necessary. The results of a numerical analysis, performed with the finite element code MASA developed at the University of Stuttgart (Ožbolt, 2001), showed that the efficiency of this solution depends mainly on the stiffness of the haunch connection and its slippage on beam and column surface (Eligehausen et al., 2008).



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

Figure 2: Haunch Retrofit Solution for exterior beam column joints (Pampanin et al., 2006); (Genesio and Akgüzel, 2009)

As already mentioned, if properly designed, the retrofit solution is able to modify the internal hierarchy of strength in a M-N domain of the beam-column connection (Figure 3a). In the schematic example shown in Figure 3a, for an assumed column axial load, N_c*, the as-built joint is expected to fail due to joint shear cracking. The retrofit solution should prevent joint and column to fail. The beam flexural strength should be the smallest resistance to achieve a ductile plastic mechanism of the beam-column joint. The design parameters to be chosen to achieve the desired hierarchy of strength are the inclination, α, length, L_h and stiffness, K_d of the haunch (see Figure 3b). If the HRS has to be realised as in Figure 2d another additional parameter is the choice of the anchorage in terms of type and number post-installed anchors.



a) b)

Figure 3: a) Hierarchy of strength of joint before and after retrofit; b) Design parameters of the HRS

3 ANALYTICAL APPROACH

The design of the HRS can be basically carried out following the method proposed by Pampanin et al. (2006). However, the use of post-installed anchors instead of externally clamped threaded rod (compare Figure 2c and Figure 2d) implies some modifications in the design procedure. The efficiency of the HRS is mainly dependent on the stiffness of the diagonal haunches as shown in Pampanin et al. (2006). With increasing stiffness, the axial load in the haunches also increases and the moment in the beam and column decreases. This induces a reduction of the shear stress in the joint panel.

In the case of the solution shown in Figure 2c, assuming that the steel rods are sufficiently prestressed, the axial stiffness, K_d of each steel haunch with length, L_h and cross sectional area, A_d can be easily written as $K_d=E_sA_d/L_h$. If post-installed anchors are used, the calculation of the stiffness of the haunches becomes more complicated, since the tensile and shear stiffness of the anchorages have to be taken into account.

In Figure 4 two limit approaches that can be adopted for the evaluation of the stiffness of the fully fastened haunches are shown. In Figure 4a it is assumed that the concrete elements (beam and column), where the haunches are fastened, are perfectly rigid. In Figure $4b_{1,2}$ beam and column are assumed to be flexible and consequently another distribution of forces in the anchors occurs. In both cases it appears evident that the stiffness of the diagonal haunches under tension ($K_{h,t}$) and compression ($K_{h,c}$) must be different.

The stiffness of the haunch loaded in tension $K_{h,t}$ can be calculated using the approach of Figure 4a according to Equation (1a), assuming that the shear forces are directly transmitted to beam and column.

$$K_{h,t} = 1 / \left(\frac{2 \sin \alpha}{n k_N} + \frac{1}{k_d} \right) \tag{1a}$$

with: k_N = tensile stiffness of a single anchor, n = number of anchors in the group and α = inclination angle between diagonal haunch and beam axis.

Alternatively, if the deformability of beam and column are taken into account as in Figure $4b_2$ the following Equation can be used as first approximation of the tensile stiffness of the haunch:

$$K_{h,t} = 1 / \left(\frac{2}{\sqrt{(n k_N \sin \alpha)^2 + (n k_V \cos \alpha)^2}} + \frac{1}{k_d} \right) \tag{1b}$$

with: k_V = shear stiffness of a single anchor

The compression stiffness can be estimated using Equation (2) for both approaches.

$$K_{h,c} = 1 / \left(\frac{2 \cos \alpha}{n k_V + K_f} + \frac{1}{K_d} \right) \tag{2}$$

with k_f = stiffness contribution due to friction between concrete and steel plate.

In the approach shown in Figure $4b_1$ the frictional contribution is reduced, because of the inflection of beam and column. In this case, compression forces avoid the displacement of the haunch along beam and column occurs in the contact area between the steel haunch and the deformed beam and column. For reason of simplicity the effect of these forces is considered equivalent to the effect of friction in the configuration of Figure 4a.

For the sake of brevity further discussion of the analytical determination of $K_{h,t}$ and $K_{h,c}$ is omitted in this paper. More detailed information can be found in Genesio (2011). It should just be noted that the assumption of the shear and tensile stiffness of the anchors is the greatest uncertainness in the design of the HRS using post-installed anchors, because of the general lack of knowledge in this matter. The design of post-installed anchors according the most advanced design provisions (e.g. CEB, 2011) is basically force oriented and the load-displacement characteristics of anchors are strongly product dependent and it may vary significantly.

The variation of the stiffness of the anchorages should be taken into consideration and lower and upper bound should be evaluated:

- The minimum stiffness of the anchorage should be large enough to ensure the protection of the joint panel from a brittle shear failure;
- The maximum stiffness of the anchorage should not induce an axial loading of the anchorage, which exceeds its strength.

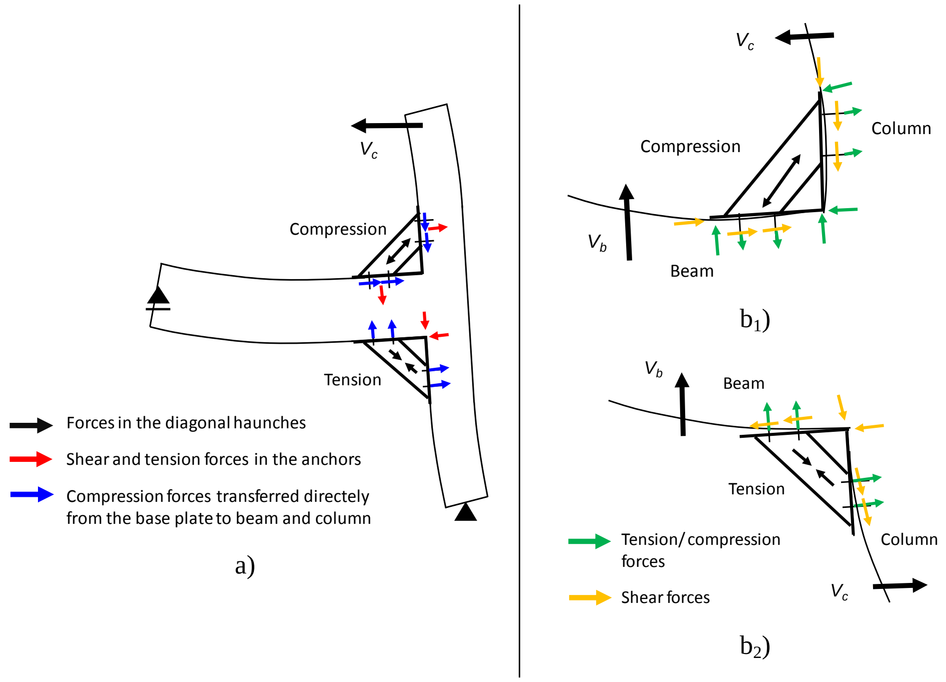


Figure 4: Possible approaches for the calculation of the stiffness of the haunches fastened with post-installed anchors (Genesio, 2011): rigid (a) and flexible ($b_{1,2}$) RC beam and column

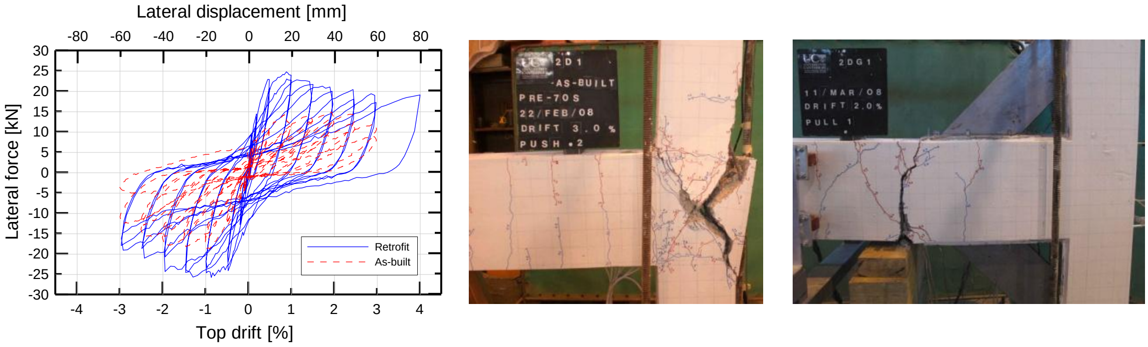
The strength design of the anchorage can be carried out according to the CC-Method (CEB, 2011). The anchorage has to carry loads very close to a plastic hinge (Figure 2b,d). Since according to the existing design codes, post-installed anchors should not be used in such location, the anchorage should be designed with high redundancy. However, it may be difficult to install an effective large anchor group in a thin structural member such as 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. In order to investigate the feasibility of the new solution, experimental tests were carried out. More detailed information about the design approach to be followed for the design of the HRS using post-installed anchors can be found in Genesio (2011).

In the following sections the performed experimental validation is briefly presented and discussed (Section 4). At last some design recommendations for the retrofit of beam-column joints with fully fastened haunches are introduced (Section 5).

4 EXPERIMENTAL VALIDATION

The proposed retrofit solution was experimentally validated and different cases were investigated with tests carried out at the University of Canterbury (Genesio and Akgüzel, 2009) and at the Bhabha Atomic Research Centre in Mumbai (Genesio and Sharma, 2010), as part of a collaborative research project. In all the tests briefly discussed below epoxy based bonded anchors arrange in a group with 6 anchors were used. In this section only some qualitatively results are presented, which show the feasibility of the proposed retrofit solution.

As first step a feasibility study on 2/3 scale specimens was carried out (Figure 5). Two beam-column joints were tested before and after retrofit. Both joint were characterised by typical pre 1970s reinforcement detailing. Plain round bars and 180°-hooks for their anchorage in the joint panel were used. No shear reinforcement in the core was provided. The applicability of post-installed anchors for the HRS was confirmed. The joint panel was successfully protected remaining uncracked during the entire test and no visible displacement of the anchorages could be observed. More information about the feasibility tests can be found in Genesio and Akgüzel (2009) and Genesio et al. (2010). The anchorage with post-installed anchors was over designed in respect to the forces expected.

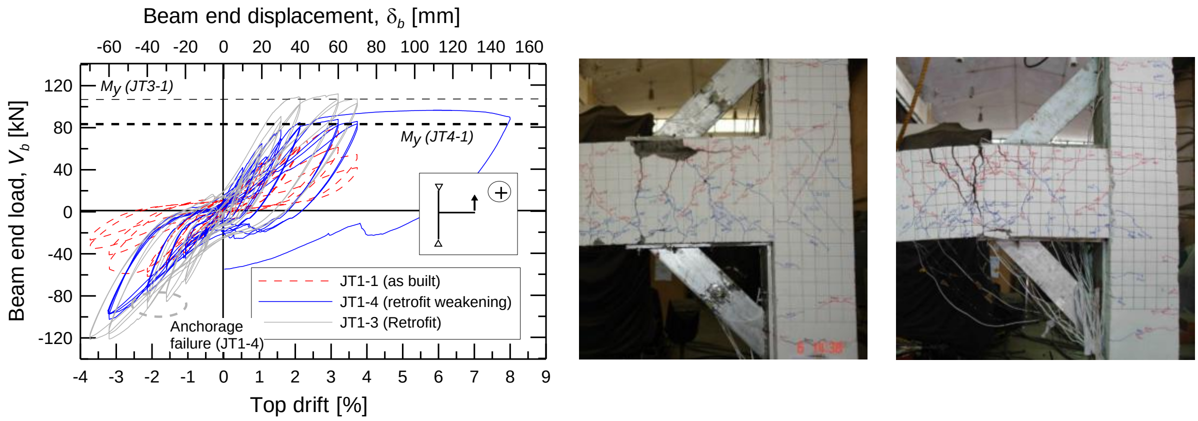


a) b) c)

Figure 5. Feasibility study of joint retrofit with fully fastened haunch (Test 2DG1): a) Hysteretic behaviour; b) Joint shear hinge in the as-build specimen; c) Beam flexural hinge in the retrofitted specimen (Genesio and Akgüzel, 2009)

Further tests were carried out on full scale specimen with deformed bars, but without hoops in the joint (Genesio and Sharma, 2010). As explained in the previews section an excessive tensile stiffness of the anchorage may induce an excessive tensile loading of the anchorage. This situation was reproduced in the test JT1-3 (Figure 6a,b). The hysteretic behaviour of the retrofitted specimen was only slightly influenced by the loss of strength of the anchorage in negative loading direction (Figure 6a), but the joint could not be fully protected and some shear cracks occurred in the core (Figure 6b). The failure of the top beam anchorage can be clearly seen in Figure 6b.

A possible solution to this problem was proposed with the test JT1-4, where the principles of selective weakening were applied (Kam and Pampanin, 2010; Kam, 2011). The flexural strength of the beam was reduced by cutting some of the longitudinal reinforcing bars. In this way the demand in the haunch and in the anchorage were significantly reduced. The ultimate strength of specimen JT1-4 was slightly lower than the one of the test JT1-3, but a very ductile behaviour up to 8.0% drift was observed (Figure 6a).



a) b) c)

Figure 6. a) Comparison between as-built specimen and two different retrofit schemas (Genesio and Sharma, 2010); b) Cracking pattern of specimen JT1-4; c) Cracking pattern of specimen JT1-3

More tests were carried out using different type of anchors and also simulating the effect on the beam-column connection of a total failure of the anchorage. They are described in Genesio and Sharma (2010) and Genesio et al. (2010).

In Table 1 the analysis of the maximum tensile ($F_{h,t,max}$) and corresponding compressive ($F_{h,c}$) forces measured in the haunches are shown. The ratio between compressive and tensile forces is equal to the ratio between compressive and tensile stiffness and using Equation (1a) and (2) the stiffness of the anchorages and of the anchors can be calculated (k_N and k_V). The calculated values of k_N indicate axial stiffness for single anchors varying between 19 and 71 kN/mm (n = 6). k_N would vary between 19 and 52 kN/mm if calculated using Equation (1b). These values are all in the range that may be expected for a M12 bonded anchor (Genesio, 2011). It is worth noting that the highest axial stiffness was calculated for the test JT1-3, where a partial failure of the anchorage was observed (see Figure 6b). The value $F_{h,t,max}$ = 170 KN exceeded the calculated tensile strength of the anchorage of approx. 25%.

The contributions of the anchors (k_V) and the friction (K_f) on the shear stiffness of the haunches cannot be uncoupled. Associating the contribution of friction to each anchor, k_V would vary between approximately 28 and 127 kN/mm. Most of the calculated k_V values are much higher than what could be reasonably expected for M12 bonded anchors that were used in the tests (10 to 20 kN/mm according to Genesio, 2011). This difference is due to the effect of friction and beam and column deformation according to Figure 4b$_1$, which is further discussed in Genesio (2011).

It should be noted that the tests indicated 1.58 as average ratio $K_{h,c}/K_{h,t,max}$ with a small coefficient of variation of 11.6%.

Table 1: Experimental comparison between $K_{h,c}$ and $K_{h,t}$

Test	$F_{h,t,max}$ [kN]	$F_{h,c}$ [kN]	$K_{h,c}/K_{h,t,max}$ [-]	$K_{h,t}$* [kN/mm]	$K_{h,c}$* [kN/mm]	k_N [kN/mm]	k_V+K_f / n [kN/mm]
2DG1	40 / 50#	60 / 65#	1.50 / 1.30#	75 / 140	113 / 182	19 / 38	30 / 52
2DG2**	15* / 40	20* / 60	- / 1.50	- / 100	- / 150	- / 27	- / 42
JT1-2	135 / 120	235 / 200	1.75 / 1.67	150 / 100	263 / 167	47 / 28	110 / 54
JT1-3	135 / 170	240 / 195	1.78 / 1.15	160 / 200	285 / 230	51 / 71	127 / 88
JT1-4	95 / 80	120 / 115	1.26 / 1.44	90 / 70	113 / 100	25 / 19	33 / 28
		Average:	**1.58**				
		cov:	**11.6%**				

#: positive / negative loading direction; *: not reliable values; *: values calculated using Equations (1a) and (2) related to the maximum loading of the haunch; **: Anchorage with n = 4

5 DESIGN RECOMMENDATIONS

As shown in the previous sections the determination of the anchor stiffness under tension and shear loading is the greatest uncertainness for the design of the HRS using post-installed anchors. After the assumption of those values the design model proposed by Pampanin et al. (2006) can be applied. The anchor stiffness is reported in the technical approval documents of pre-qualified post-installed anchors, according to ETAG 001 (1997) in Europe or AC308 (2009) and AC193 (2010) in USA. It should be noted that evaluation report of ICC-ES (International Code Council-Evaluation Service), e.g., according AC193 (2010) for mechanical anchors do not provide any information about shear stiffness of anchors. In the USA bonded anchors are ruled by AC308 (2009), but for them no stiffness values are provided. Approvals according to ETAG 001 (1997) generally provide values of shear and tensile stiffness in cracked and uncracked concrete and for short and long term loading. As proposed in Section 3 lower and upper bound of the anchorage stiffness should be determined. For a conservative design it is suggested to use the following values for the anchor stiffness:

- Upper bound: stiffness under short term loading in cracked concrete; and
- Lower bound: stiffness under long term loading in cracked concrete.

According to the experimental tests discussed in Section 4, it is also suggested to assume the compressive stiffness of the haunch as 1.5 of the tensile stiffness. In this way only the tensile stiffness of anchors is required and no assumption on shear and frictional stiffness (which is generally unknown) are necessary. Further details concerning the design of the HRS with post-installed anchors can be found in Genesio (2011).

6 CONCLUSIONS

An application of post-installed anchors for the refinement and simplification of a retrofit solution for

RC beam-column joints, based on the use of metallic diagonal haunches, was presented. The main required modifications of the design model proposed by Pampanin et al. (2006) for a safe and economical use of post-installed anchors in the HRS were explained. The feasibility of the new solutions was experimentally validated.

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