SELECTIVE WEAKENING TECHNIQUES FOR RETROFIT OF EXISTING REINFORCED CONCRETE STRUCTURES

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ABSTRACT :

This paper presents the conceptual development and the preliminary analytical-experimental results of a counter-intuitive approach for the seismic retrofit and rehabilitation of older reinforced concrete buildings, referred to as selective weakening (SW). The basis of a SW strategy is to modify the inelastic mechanism towards a more desirable mechanism by first weakening selected regions of the structure for protection against brittle failure mechanism. Subsequently, if necessary, the structure is further upgraded to the desired strength/stiffness/ductility and energy dissipation capacity. Different levels of performance can be achieved, from collapse prevention to damage control. The feasibility of alternative techniques to implement a SW strategy is first conceptually discussed for structural walls, precast hollowcore floors and reinforced concrete frame systems. Focus is then given to the implementation of SW to the retrofit of exterior beam column (bc) joints with substandard details. The mechanics and effectiveness of partial SW of the beam within an exterior bc joint subassembly is numerically investigated using a 3D finite element micro-plane model. Finally, the global behaviour of a prototype frame prior and after a SW retrofit is investigated using non-linear time history analyses.

KEYWORDS: Retrofit, selective weakening, strengthening, beam-column joint, existing r.c. frame

1. SEISMIC VULNERABILITIES AND THE NEED FOR RETROFIT

The significant risks associated with substantial damage and global collapse of existing reinforced concrete (r.c.) moment-resisting frame structures designed prior to the introduction of modern seismic design codes in the mid-1970s are well acknowledged. Recent experiences with large earthquakes near populated centers (Sichuan, China 2008 and Izmit-Kocaeli, Turkey 1999) further highlight the urgent need for economical and effective seismic retrofit techniques for these structures. The vulnerabilities of pre-1970s rc buildings have been identified to be due to the absence of adequate seismic design provisions, capacity design considerations and detailing for ductile behaviour (NZSEE, 2006). Experimental tests of sub assemblages (Aycardi et al., 1994) and rc frames (Calvi et al., 2002) have shown that the excessive damage or failure of beam-column joints, in particular exterior (or corner) joints, can lead to the global collapse of a building. The poor joint behaviour of older construction can be attributed to: the inadequate shear reinforcement in joint region, the poor bond properties of plain round bars reinforcement (commonly used prior to 1970s) and the deficient anchorage details into the joint region (Hakuto et al., 1997). Various retrofit or seismic rehabilitation schemes have been previously proposed and implemented for bc joints and rc frames (ASCE-41, 2007; fib, 2003). The majority of the established methods involve either the strengthening of the joint only or both the joint and column in order to induce plastic hinging in the beams. Alternatively, the demand onto the structure can be reduced by supplementary damping or base-isolation. While most retrofit techniques can theoretically achieve a targeted structural performance, excessive costs, invasiveness and constructability are still main issues for a wider implementation. In this contribution, a counter-intuitive alternative seismic retrofit strategy, referred as "selective weakening"(SW) (Pampanin, 2005a) is presented. After providing an overview of the conceptual development of a retrofit strategy based on a "weakening for strengthening" approach , the implementation of a SW technique for the critical exterior bc joints of rc frames is numerically investigated – pre and post retrofit

2. SELECTIVE WEAKENING AS A RETROFIT STRATEGY

2.1 "Weakening" for strengthening

Many seismic retrofit (or rehabilitation) solutions have been developed in the past few decades following the introduction of new seismic provisions and the availability of advanced materials (e.g. fiber-reinforced polymers, FRP, fiber reinforced concrete and high strength steel). Specific assessment methods, retrofit strategies and performance targets have also been developed and adopted for many developed countries (e.g. FEMA-547, 2006; NZSEE, 2006). Typical retrofit strategies are based on increasing the capacity (strengthening) through the use of various techniques (jacketing, FRPs, adding braces or shear walls). It should be clarified that retrofit strategies are different from retrofit techniques, where the former is the basic approach to achieve an overall retrofit performance objective, such as increasing strength, increasing deformability, reducing deformation demands while the latter is the technical methods to achieve that strategy, for example FRP jacketing (see Figure 2a). Alternative strategies include the reduction of the seismic demand by means of supplementary damping and/or use of base isolation systems. The effects of various retrofit strategies on the structural performance are illustrated in Figure 1 within an Acceleration-Displacement Response Spectrum domain, typical of a capacity spectrum method.

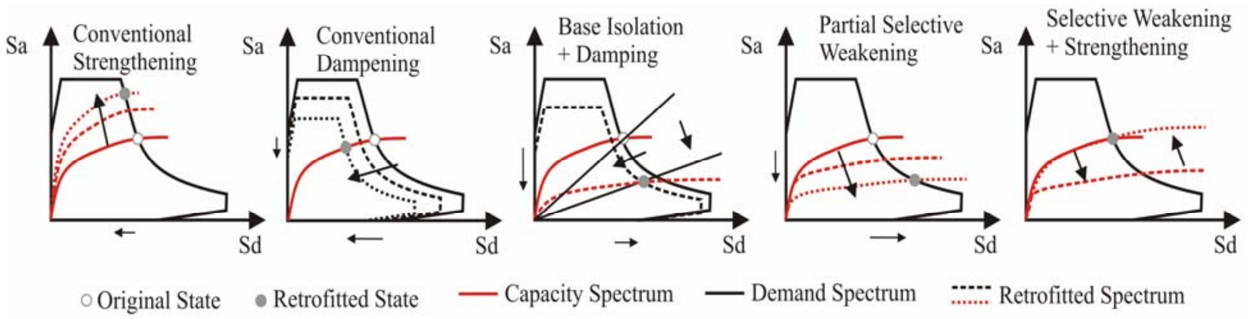
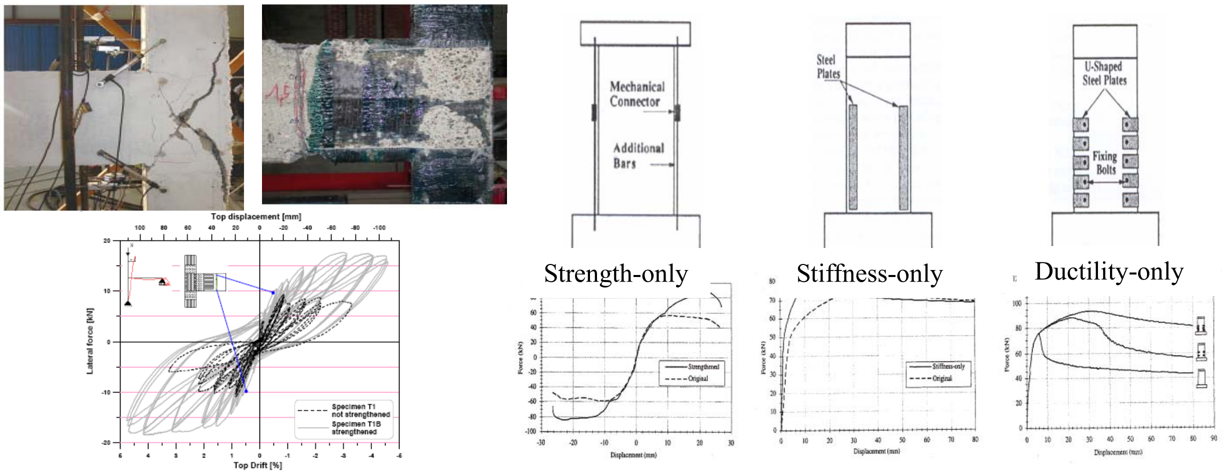


Figure 1: Acceleration-Displacement Response Spectrum (ADRS) illustration of different retrofit philosophies and strategies a) strengthening b) added damping c) base isolation d) partial SW (weakening only) e) full SW (weakening and further enhancement)



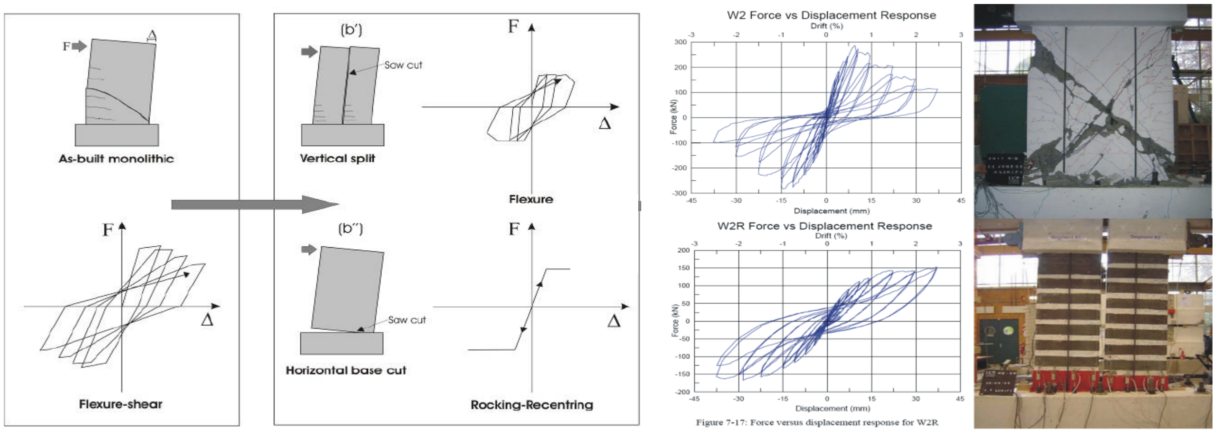
(a) (b)

Figure 2: (a) FRP retrofit technique to improve both strength and ductility capacity of exterior bc joint (Pampanin et al., 2002) (b) Selective retrofit techniques for strength-only, stiffness-only and ductility-only for structural wall (El Nashai and Pinho, 1998)

However, in some scenarios, the ideal retrofit solution could be to selectively improve certain aspects of the structure. This could be due to the presence of multiple brittle and weak elements such as beam-column joints and lapped spliced columns, or overstressed foundation. Elnashai and Pinho(1998) proposed and successfully tested a series of retrofit techniques that selectively targets the upgrade of strength-only, stiffness-only or ductility-only. By adding steel plates or external rods, the flexural and shear capacity, the stiffness and the ductility of the plastic hinge region can be improved without significantly altering other properties of the structure (see Figure 2b). Based on a similar concept, the proposed selective weakening approach aims to improve the global inelastic mechanism of the structure by weakening and then upgrading certain structural (or non-structural) elements. In FEMA-356 (2000), “selective material removal” was suggested as a seismic rehabilitation method, where preliminary suggestions include severing longitudinal reinforcement in the beam in order to induce a weak-beam strong-column mechanism. Conceptually, the retrofit strategy of weakening a structure is illustrated in Figure 1d, where by selectively weakening certain elements, the ductility capacity of a structure may be increased if a brittle failure mechanism (e.g. joint shear failure) is avoided. Pampanin (2005a) outlined the concept of SW strategy and its possible implementation for structural walls, floor diaphragm and rc frames. Viti et. al.(2006) has proposed a similar strength reduction and added supplementary damping as a viable retrofit strategy for essential emergency facilities (hospitals). Via numerical studies of a prototype hospital structure, it was shown that by weakening and dampening a structure, the floor acceleration and inter-storey drift can be better controlled, thus limiting both structural and non-structural damage.

2.2 University of Canterbury research on selective weakening retrofit

Based on the proposed selective weakened approach, which targets the development of jointed ductile (articulated) systems with low-damage, a comprehensive research program has been carried out at the University of Canterbury (UoC) to develop SW retrofit techniques for various retrofit scenarios. By strategically weakening parts of the structure through structural disconnection, improved local and global performance can be achieved by explicitly considering the hierarchy of strength of the individual elements and overall sequence of failure mechanisms. To further complement SW retrofit, further enhancements can be added to the retrofit solution.



(a) (b)

Figure 3: a) Schematic illustration of SW retrofit on shear-failure dominated structural wall b) Lateral force versus top displacement response and photograph of specimen W2 (original) and W2R (selectively weakened and added FRP and steel plates for confinement and ductility enhancement) (Ireland et al., 2007).

Ireland et. al.(2007) has implemented and experimentally investigated the use of SW retrofit for existing, shear-prone structural walls with poor reinforcement details (plain round bar with straight, 40-bar-diameter laps and minimal transverse reinforcement). Cyclic, quasi-static tests on four specimens were carried out: two benchmark walls with substandard detailing (W1 & W2), and two full SW retrofit walls (W1R & W2R). Figure 3a presents the schematic illustration of the partial SW retrofit on the walls, where a vertical split can potentially avert brittle shear-failure of the wall, and a horizontal cut at the base can convert the inelastic mechanism to a rocking-recentering wall mechanism. W1R specimen incorporates a SW at the base and the subsequent addition of post-tensioned tendons and energy dissipaters. W2R incorporates a SW with a vertical cut and subsequent confinement upgrade using FRP. In both retrofit solutions, shear-failure (Figure 2a) was averted while a ductile flexural mechanism based on rocking and dissipative motion at the base connection is activated. Figure 3b shows the comparison between the specimen W2 (top) and W2R (bottom) where the enhanced behaviour of the retrofitted W2R specimen is evident.

The concept of SW retrofit has also been implemented and extended to the retrofit of precast hollowcore floors (Jensen et al., 2007) . Observed collapse during earthquakes (e.g. Northridge, 1994) and experimental investigation of precast hollowcore floor (Matthews et al., 2003) has highlighted the vulnerability of such flooring system in the event of strong earthquakes. Recognising that the rigidity of the monolithic seating connection can lead to undesirable and catastrophic brittle shear-delamination and web-splitting (as observed in HC1 in Figure 4a), the proposed retrofit solution involved drilling holes to create a weakened plane at the seating connection (as in HC4 in Figure 4b). The weakening is also necessary to compensate for the increased confinement (hence flexural strength) from the added seating (bolted 100x50x6 RHS). Overall, the retrofitted HC4 performed very well and no shear failure or premature unseating was observed.

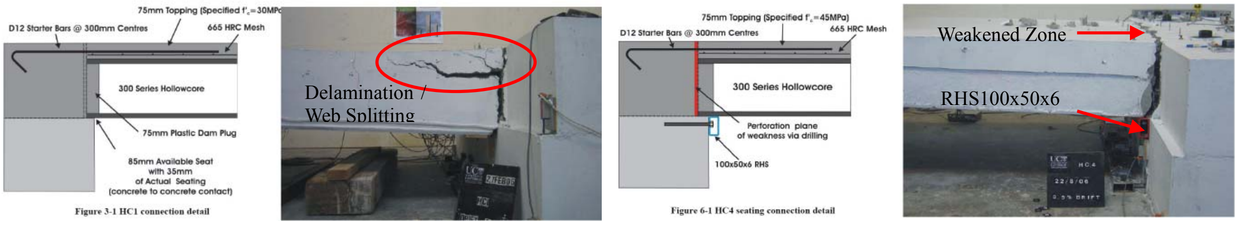
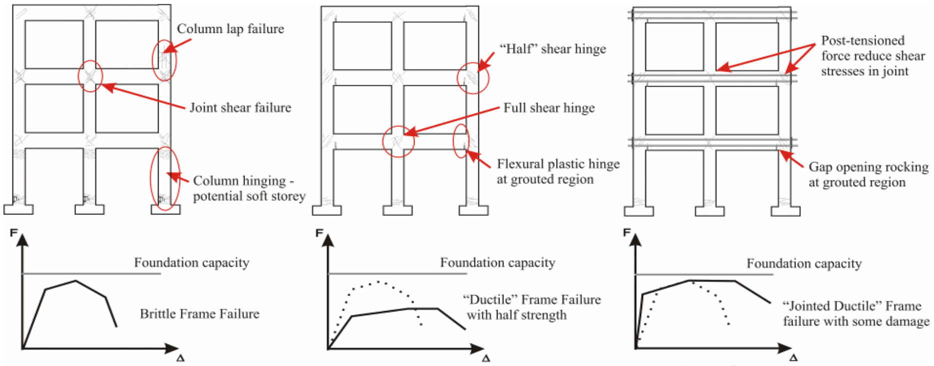


Figure 4: Structural detail and experimental photograph of a) Specimen HC1 (pre-2004 NZ worst case detailing representation) b) Specimen HC2 (selective weakened via drilling and added seating) (Jensen et al., 2007)

3. CONCEPT OF SELECTIVE WEAKENING RETROFIT OF EXTERIOR B.C. JOINT

The concept of weakening for retrofit of rc frames has been previously proposed with reference to the weakening of the beams in order to create a weak-beam strong-column mechanism(FEMA-356, 2000; Pampanin, 2005b; Viti et al., 2006). Herein, the concept of the SW retrofit for rc frame is discussed, with particular focus on the exterior bc joints and the effects on global response and failure mechanism. In the next two sections finite element analyses will be used to validate the concept. Let us consider a typical existing (pre-1970s) rc frame with various critical weaknesses as illustrated in Figure 5a. In most cases, due to economical restraints, particularly when dealing with the need to intervene a large number of buildings, the designer might decide to target a partial retrofit solution capable of guaranteeing the collapse prevention, while accepting a significant level of damage. In such scenarios, a partial SW retrofit, where some (or all) bottom longitudinal rebar at the exterior bc joint can be severed, as shown in Figure 5b, is a more effective solution. The amount of weakening permissible is based on the required beam shear-capacity for gravity loading while full hinging under positive moment can be assumed for lateral loading.



(a) Existing inadequately detailed and poorly designed RC frame

(b) Partial Retrofit: Weakening Only

(c) Full Retrofit : Weakening + Post tensioning

Figure 5: SW retrofit for rc frame: a) existing rc frame b) cutting the bottom longitudinal bars to reduce joint shear stress c) post-tensioning joint and weakened beam-column interface

In addition to the reduction of bc joint positive moment demand due to the weakening of the beam positive moment, a more significant advantage is the prevention of a complete joint shear failure mechanism. The reduction in positive moment demand prevents the formation of a "concrete wedge" as shown in Figure 2a-1, which can lead to the collapse of the column/floor above. By limiting the shear stress into the joint panel, only a uni-directional diagonal crack can form. Considering a minimum acceptable performance level (e.g. collapse prevention), a hybrid mechanism based on the combination of a flexural plastic hinge in the beam under positive moments and a uni-directional joint shear hinge under negative moments is postulated to be far more desirable than a complete joint shear failure or column collapse due to shear/lap splice failure.

By weakening the beams, and the frame as a whole, the total displacement response of the frame is expected to increase significantly (as illustrated in Figure 1d). Therefore, according to a full SW retrofit solution, post-tensioning and/or supplementary dissipation devices can be incorporated into the exterior bc joint retrofit intervention to ensure that a higher target performance level is met. This is conceptually illustrated in Figure 5c. The added post-tensioning and energy dissipation increases the strength and the ductility capacity of the frame, converting the inelastic failure mechanism from joint shear hinging, or column shear-flexural hinging, to a partial rocking mechanism.

4. LOCAL BEHAVIOUR OF PARTIAL SELECTIVE WEAKENING OF EXTERIOR B.C. JOINT

4.1 Macro-plane finite element modeling of exterior beam-column joint

To investigate the seismic response of an exterior bc joint, before and after a selective weakening retrofit, FEM analyses have been carried out using the software MASA. MASA, developed at the University of Stuttgart (Ožbolt et al., 2001), is based on a micro-plane concrete model with relaxed kinematic constraints within a smeared crack approach. Proper modeling of the bond-slip relationship for plain round bars have been recently implemented and successfully validated with experimental results (Eligehausen et al., 2008). Figure 6a, 6b and 6c present the physical properties and the finite element model of a prototype exterior beam-column joint, representative of pre-1970s rc frame construction. More details of the benchmark (as built) model can be found in Eligehausen et al. (2008).

4.2 Partial selective weakening retrofit of exterior bc joint – local sub-assembly behaviour

Figure 7 presents the summary of the preliminary results of the benchmark exterior beam-column joint under cyclic push-pull lateral loading (a series of two cycles are increasing drift to failure) and a varying axial load (N=120kN ±4.63V_c; + for push cycle, V_c = lateral load). First, it can be observed that the failure mode and cracking mechanism are well captured by the as-built FE model when compared to the experimental observations. Second, in terms of force-displacement response, the FE model tends to over-predict the envelope response by approximately 5% (Push) and 17.6% (Pull), indicating the variation of axial load is not properly captured in the model. It can also be observed that the pinching effect is more pronounced in the experimental result, in which further refinement of the bond-slip cyclic behaviour is required.

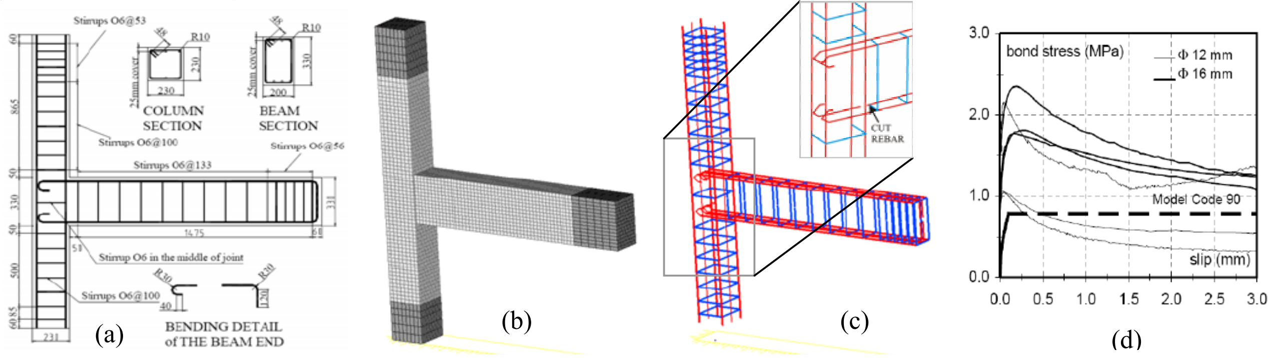
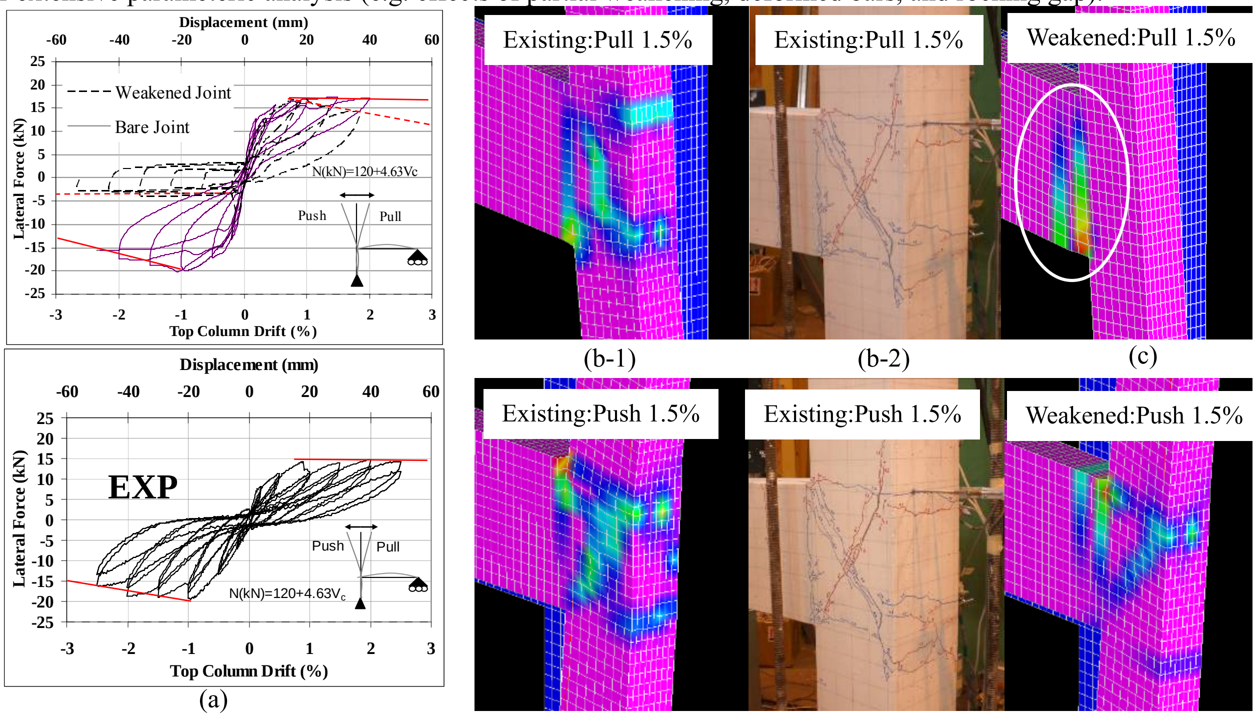


Figure 6: a) Geometry and reinforcement of exterior beam-column joint b) FE Model – discretization of concrete non-linear element c) FE Model – discretization of reinforcement and bond elements (zoom: weakened beam) d) Bond stress-slip monotonic relationship for plain round bars

When a partial selective weakening retrofit is implemented, as shown in Figure 6c, the bottom longitudinal reinforcement is severed with the objective of reducing the shear stress transferred into the joint, hence preventing a full shear failure mechanism, as shown in Figure 2a (top left). In Figure 7c, it can be observed that the partial retrofit objective was achieved as the inelastic mechanism is concentrated within the weakened zone. The key concept is the change of the inelastic mechanism from a brittle, joint shear rotation to a ductile beam flexural hinge. When comparing the force-displacement responses of the weakened specimen to the as-built specimen, it can be seen that the weakened joint, albeit having lower lateral strength, has a higher ductility capacity, owing to the ductile flexural hinging in the beam. In this preliminary analysis, all the bottom longitudinal bars were initially severed but the weakened section was then re-grouted to maintain the same beam depth. A series of experimental tests are on-going to validate the efficiency of the proposed technique as well as the reliability of the FE model, which would be used for extensive parameteric analysis (e.g. effects of partial weakening, deformed bars, and rocking gap).



(b-1) (b-2) (c)

(a)

Figure 7: Seismic performance of existing bc joint and partial SW of bc joint. (a) Lateral force versus top column drift – top: numerical result (MASA); bottom – experimental result – existing bc joint. (b) Predicted and observed failure mode and cracking pattern of existing bc joint. (c) Predicted of failure mode and cracking pattern of partial SW retrofitted bc joint.

4.3 *Effect of partial beam weakening on joint shear*

Figure 8a illustrates a well-accepted joint-shear model for exterior b-c joints. Formulating the joint shear capacity in terms of principle tensile (p_t)and compression stresses (p_c), using the Mohr's circle theory , taking into account horizontal (f_h) and vertical (f_v) stresses, the following equation can be derived for the sub-assembly lateral force (V_c):

$$V_c = \frac{V_{jh}}{\left[\frac{l_c}{jd}(1-\frac{h_c}{2l_b})-1\right]} \qquad (1) \qquad\qquad V_{jh} = b_{je}h_b\sqrt{\left[p_t^2 - p_t(f_v+f_h)+2f_vf_h\right]} \qquad (2)$$

Where l_c = column length, h_c = column depth, l_b = beam length, h_b = beam depth, b_{je} = effective width of the joint. Using this model, a joint shear strength degradation model, based on experimental results (Pampanin et al., 2003), can be adopted to determine the limit states for the joint panel zone (Figure 8b). When weakening the positive moment capacity of the beam, the steel tension force T_s is reduced, thus, the joint shear stress is reduced (or principal tensile stress demand). Based on the preliminary FEM model results (e.g. in Figure 7), the peak capacity and strength degradation branch of the exterior joint with uni-directional shear hinge (after beam positive moment weakening) is higher and less severe as illustrated schematically as Ext. 2 in Figure 8b. Without high bond-induced tensile stress from T_s, the principal tensile stress capacity of the bc joint in the positive moment (anticlockwise at beam interface) is higher. The on-going experimental tests at the University of Canterbury will provide confirmation and quantitative evaluations of this assumption.

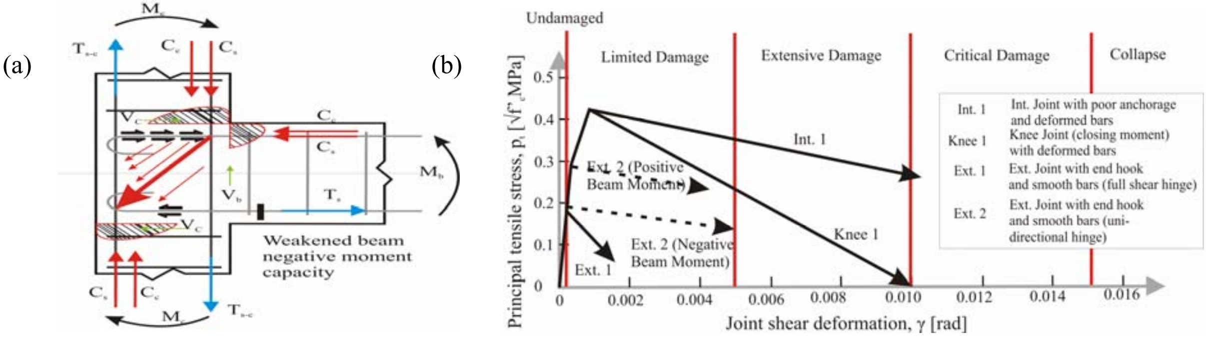


Figure 8: a) Joint shear mechanism of partial selective weakening retrofitted exterior beam-column joint b) Joint degradation model for poorly detailed bc joint with damage limit states

5. GLOBAL BEHAVIOUR OF PARTIAL SELECTIVE WEAKENED OF R.C. FRAME

5.1 *Numerical modelling of existing rc frame and selectively weakened rc frame*

The prototype pre-1970s existing rc frame is a six-storey frame with three bays (4.5m-2.5m-4.5m) and inter-storey height of 3m (except for the ground floor, with 2.75m), typical of residential building stock built in Italy and other Mediterranean countries between the 1950s and 1970s. More information about the prototype frame can be found in (Galli, 2007). Two rotational joint springs, with appropriate hysteresis rules to model cyclic strength degradation, stiffness degradation and pinching hysteresis behaviour are used for the joint panel zone for the existing rc frame. The properties of the spring are calibrated against experimental results of sub-assemblages testing (Pampanin et al., 2003). For the selectively weakened rc frame, the negative moment capacity of the beam is reduced at the exterior bc joint. The rotational joint springs in the exterior joint panel zone are modified and modeled using thin modified Takeda hysteresis (α=0.5, β=0), assuming less severe strength degradation in the uni-directional shear hinge.

Name	Earthquake Event	Year	Mw	Station	Rclosest (km)	Soil Type	Scaling Factor	Scaled PGA (g)	Scaled PGV (cm/s)
FAR FIELD SUITE (WITHOUT DIRECTIVITY EFFECT)									
FF1	Superstition Hils	1987	6.7	Brawley	18.2	D	3.00	0.401	51.6
FF2	Northridge	1994	6.7	Canoga Park – Topanga Clan	15.8	D	1.27	0.452	40.7
FF3	Northridge	1994	6.7	LA – Hollywood Stor FF	25.5	C	2.15	0.496	39.3
FF4	Northridge	1994	6.7	N Hollywood – Coldwater Can	14.6	C	1.50	0.406	33.3
FF5	Loma Prieta	1989	6.9	Capitola	14.5	C	1.19	0.571	43.4
FF6	Landers	1992	7.3	Desert Hot Springs	23.3	D	2.09	0.320	43.7
FF7	Landers	1992	7.3	Yemo Fire Station	24.9	D	1.82	0.382	54.1

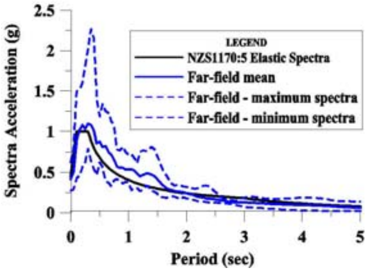


Figure 9: Characteristics of the ground motion records and the scaled acceleration spectra.

5.2 *Analysis assumptions and ground motion used*

The inelastic time history analyses were performed using the finite-element program RUAUMOKO2D (Carr, 2008). A Newmark-beta integration scheme with a Rayleigh damping model proportional to the tangent stiffness was adopted. P-Δ effects were ignored. Lumped mass and lumped plasticity modeling are adopted, where inelastic deformations are limited to discrete inelastic rotational springs in the joints and beams and columns. A suite of historical strong ground motion records without directivity effects were used. All records were taken from the PEER online strong ground motion database (PEER, 2007)). The scaling of the earthquake records followed the recommendations of (NZS1170, 2004) to the design level of earthquake (a probability of exceedance of 10% in 50 years, R=1), corresponding to a peak ground acceleration of 0.4g and deep or soft soil (type D). The earthquake characteristics of the scaled earthquake records and the scaled acceleration spectra are presented in Figure 9.

5.3 Average of the Envelope Responses of the rc frames: pre- and post-retrofit

Figure 10 presents the mean of the peak response values of the non-linear time history analyses. The first row (a-d) is the response of the pre-retrofit (as-built) frame while the second row(e-h) is the response of the partial SW retrofitted frame. The global response (inter-storey drift) of the partial SW retrofit frame clearly shows a remarkable reduction of the soft storey mechanism at the fourth floor level, observed in the as-built frame response. This can be explained by analysing the mean peak rotation of each component at the exterior bc joint connection. Upon weakening the beam, a flexural plastic hinge is induced within the beam (in the negative moment), hence increasing the beam plastic rotation. This will also effectively limit the shear force entering the bc joint connection, therefore, the corresponding rotation demands in the column and joint elements are lower. In relation to the damage limit states presented in Figure 8b, the mean value of 0.01 radians for the retrofitted joint indicates extensive damage while the bare frame joints exceeded 0.018 radians, indicating incipient collapse.

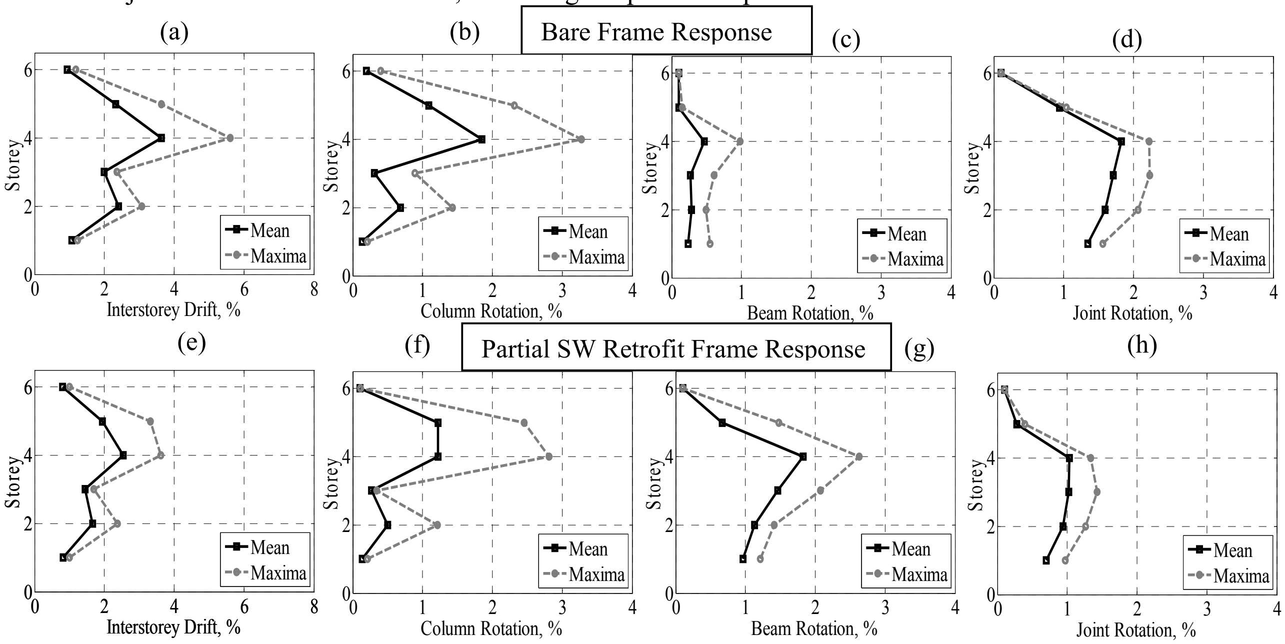


Figure 10: a) Mean of peak inter-storey drift envelopes responses of the existing and retrofitted frames. b-d) mean of peak rotation (%) of: b)column, c)beam and d)joint at the exterior bc joint connection.

6. CONCLUSIONS

A counter-intuitive approach for seismic retrofit, termed ”selective weakening” (SW) has been proposed. The basis of a partial SW strategy is to modify the inelastic mechanism towards a more desirable mechanism by selectively weakening parts of the structure to avoid a brittle failure mechanism. In a full SW strategy, the structure can then be further upgraded to the desired strength/stiffness/ductility and energy dissipation capacity. The concept has been briefly described within an overview of applications of SW for walls and hollowcore floor systems. Then the application of SW to exterior bc joint for the global retrofit of vulnerable existing rc frames is presented conceptually and numerically. The 3D finite element model of a partially weakened exterior bc joint confirmed the increased deformation capacity of a ‘uni-directional joint shear hinge’. While the global drift demand of the SW retrofitted rc frame was only slightly lower, the improved performance is more pronounced in terms of shifting the inelastic deformation demand into beam flexural hinging instead of joint shear rotation. Whilst not shown here, preliminary experimental results undergoing at the University of Canterbury are confirming some of the numerical results presented herein. A series of exterior bc joint sub-assemblages will be tested to investigate the influence of various design parameters and to confirm the numerical analysis results.

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