EXPERIMENTAL VALIDATION OF A LOW-INVASIVE SEISMIC RETROFIT SOLUTION FOR EXISTING UNDER-DESIGNED RC FRAMES

Stefano PAMPANIN[1] Constantin CHRISTOPOULOS [2]

[1] Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand
[2] Department of Civil Engineering, University of Toronto, Canada

Keywords: existing buildings, non-seismically designed, shear hinging, beam-column joints, non-invasive, seismic retrofit

Abstract The feasibility and efficiency of a low-invasive seismic retrofit solution for existing reinforced concrete frame systems, designed before the introduction of modern seismic-oriented design codes in the mid 1970s are herein experimentally investigated. A diagonal metallic haunch system is introduced at the beam-column connections to protect the joint panel zone from extensive damage and brittle shear mechanism while inverting the hierarchy of strength within the beam-column subassemblies and forming a plastic hinge in the beam. The experimental results from cyclic quasi-static tests on 2/3 scaled beam-column subassemblies in as-built and retrofitted configurations provided validated the conceptual design and practical implementation of the overall retrofit strategy.

1 INTRODUCTION

Recent experimental-analytical investigations on the seismic performance of existing reinforced concrete frame buildings, designed for gravity loads only, as typical of most seismic-prone countries before the introduction of adequate seismic design code provisions in the mid-1970s (Aycardi et al., 1994; Beres et al., 1996, Hakuto et al., 2000, Park, 2002; Pampanin et al., 2002; Calvi et al., 2002a,b) have confirmed the expected inherent weaknesses of these systems that had also been observed in past earthquake events. As a consequence of the poor reinforcement detailing, the absence of capacity design philosophy and the use of end-hooked plain round reinforcing bars, brittle failure mechanisms are expected either at local (e.g. shear failure in the joints or columns and beams) or global level (e.g. soft storey mechanism). An appropriate retrofit strategy, which is capable of providing adequate protection to the joint region while modifying the hierarchy of strengths between the different components of the beam-column connections according to a capacity design philosophy, is therefore required.

Alternative strengthening/retrofit solutions have been studied in the past and adopted in practical applications, ranging from conventional techniques (i.e. braces, jacketing or infills, Sugano, 1996) to more recent approaches including base isolation, supplemental damping devices or advanced non-metallic materials as Fiber Reinforced Polymers, FRP, (*fib* 2001) or Shape Memory Alloys, SMA (Dolce et al. 2000). Most of these retrofit techniques have evolved in viable upgrades to these structures. However, issues of cost, invasiveness, and practical implementation still remain the most challenging aspects of retrofitting non-seismically designed RC frames.

In this contribution the experimental validation of a simple, low-invasive and inexpensive retrofit solution, which relies on diagonal metallic haunches to protect the panel zone and favor a more desired hierarchy of strength, is presented. Results from quasi-static cyclic tests on three exterior beam-column subassemblies, 2/3 scaled, comprising of one as-built specimen and two retrofitted ones are reported as a confirmation of the applicability of the overall retrofit solution, from design strategy to practical implementation.

2 SEISMIC BEHAVIOR OF POORLY DESIGNED RC FRAMES

2.1 Vulnerability of the panel zone region

Within a recent experimental and analytical research program on the seismic vulnerability of existing reinforced concrete frame buildings designed for gravity loads only, as typical in Italy before the introduction of seismic-oriented codes in the mid-1970s (Pampanin et al., 2002; Calvi et al, 2002a,b), particular attention was given to the vulnerability of the panel zone region. Peculiar brittle damage mechanisms at both the beam-to-column subassembly level and at the global frame level were observed, due to the total absence of joint transverse reinforcement and the use of end-hooked plain round bars for the longitudinal reinforcement (see Fig. 1).

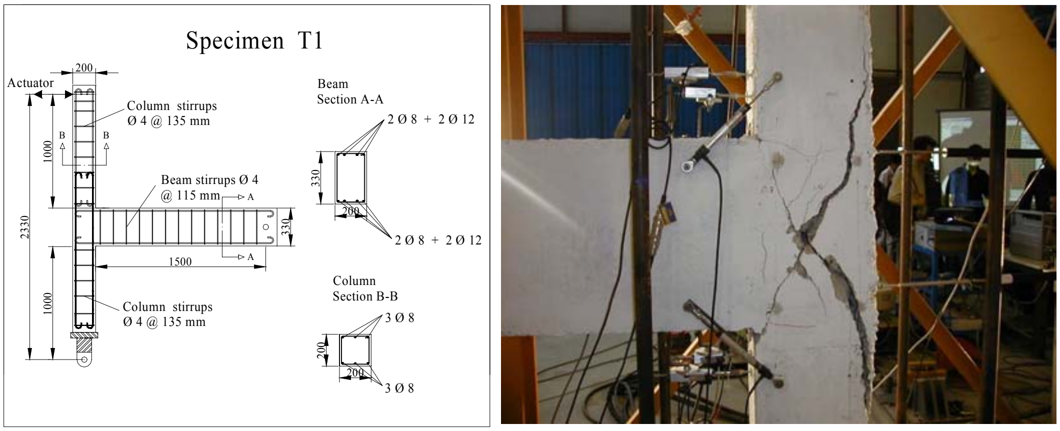

Figure 1. Exterior T-joint Specimen T1 and Joint Damage (Pampanin et al., 2002)

Different damage or failure modes are expected to occur in beam-column joints (Priestley et al., 1997; Pampanin et al, 2002) depending on the typology (exterior or interior joint) and of the adopted structural details (i.e. presence of transverse reinforcement in the joint; use of plain round or deformed bars; alternative bar anchorage solutions). In absence of transverse reinforcement in the joint region, the post-cracking behavior depends solely on the efficiency of the compression strut mechanism to transfer the shear within the joint. Thus, while rapid joint strength degradation after joint diagonal cracking is expected in exterior joints (Fig. 2a), a hardening behavior after first diagonal cracking can be developed in interior joint. Furthermore, when hinging in the columns occurs, significant displacement ductility can be developed at a subassembly level. At the global level, however, the response of the system can be seriously impaired if a soft-storey mechanism is caused by the hinging in the columns. In Figure 2 the experimental force-deflection response of an exterior joint (joint shear damage and beam hinging) and of an interior joint (column flexural damage) are shown. The joint shear stress is generally expressed in terms of either the nominal shear stress (v_{jn}) or the principal compression/tensile stresses (p_c , p_t). Although current codes tend to limit the nominal shear stress v_{jn} expressed as a function of the concrete tensile strength, $k_1\sqrt{f'_c}$, or the concrete compressive strength, $k_2 f'_c$, where k_1 and k_2 are empirical constants, it is commonly recognised that principal stresses, by taking into account the contribution of the actual axial compression stress (f_a) acting in the column, are better indicators of the stress state and consequently of the damage level in the joint region. Strength degradation curves for different joint typologies (exterior knee or interior tee-joint) and different structural detailing (i.e. plain round or deformed bars, anchorage solutions) based on principal tensile stresses-shear strain deformations have been suggested in the literature.

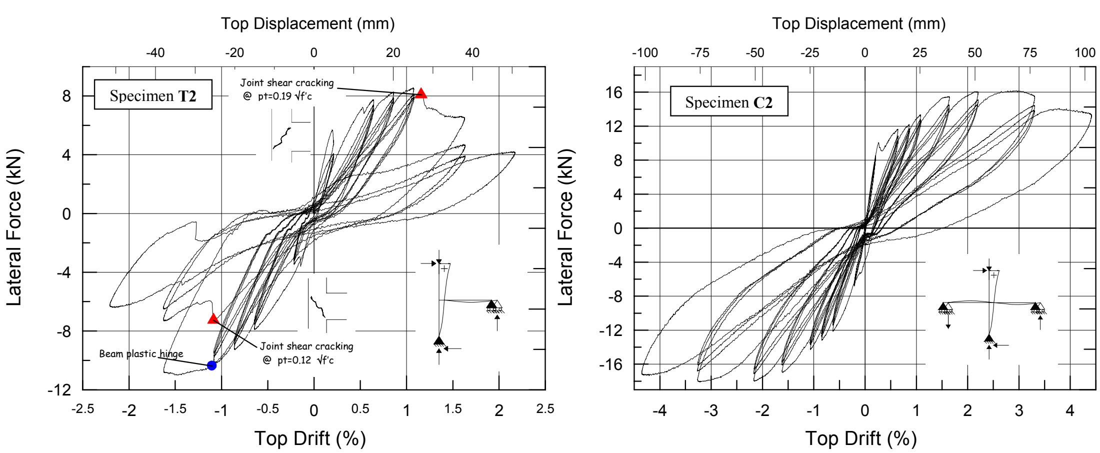

Figure 2. Experimental Hysteretic Response of Exterior Tee-joint(T2) and Interior Cruciform Joint(C2) (Pampanin et al., 2002)

2.2 Shear hinge mechanism and effect on global response

A critical discussion on the effects of damage and failure of beam-column joints in the seismic assessment of frame systems has been given in (Calvi *et al*, 2003). Based on experimental evidences and numerical investigations, the concept of a shear hinge mechanism has been proposed as an alternative mechanism to flexural plastic hinging in beams or columns. The concentration of shear deformation in the joint region, through the activation of a shear hinge, can reduce the deformation demand on adjacent structural members, postponing the occurrence of undesirable soft-storey mechanisms which can lead to a collapse of the whole structure.

The drawback of this apparent favourable effect on the global response is the increase in shear deformations in the joint region that can lead to possible strength degradation (depending on the detailing) and loss of vertical load-bearing capacity. Based on this detailed assessment of the local damage and corresponding global mechanisms, a more realistic seismic rehabilitation strategy can be defined.

A simplified analytical model to describe the joint non-linear behaviour (shear hinge mechanism) has been presented in (Pampanin et al., 2003). According to a concentrated plasticity approach, the model consists of a rotational spring able to describe the variation of principle tensile stresses at mid-depth of the joint panel zone. Satisfactory analytical-experimental comparisons were obtained using the proposed model and adopted to define limit states based on joint shear deformation.

3 HAUNCH RETROFIT SOLUTION

3.1 Conceptual behaviour and design methodology

An alternative low-invasive retrofit solution for existing under-designed RC frame systems has been recently proposed by Pampanin and Christopoulos (2003) as an extension of retrofit solutions developed for steel moment resisting frames following the significant number of weld fractures observed after the Northridge earthquake (Gross et al., 1999, Christopoulos and Filiatrault, 2000).

As illustrated in Figure 3 for an exterior Tee-joint, the proposed haunch retrofit aims to protect the panel zone region from excessive shear stress demand by re-directing the stress-flow around the joint region and inducing a plastic hinge in the beam. By properly selecting the geometry (location and angle) and stiffness of the haunch elements, the moment at the face of the column can be controlled and consequently the joint panel zone can be protected from undesirable brittle failure mechanisms. Furthermore, a more desirable hierarchy of strength can be achieved by inducing a plastic hinge in the beam section where the haunch is connected. Capacity design considerations must also be followed in order to guarantee that no shear failure in the structural elements occur, while a proper hierarchy of strength is maintained leading to a weak-beam strong column inelastic mechanism.

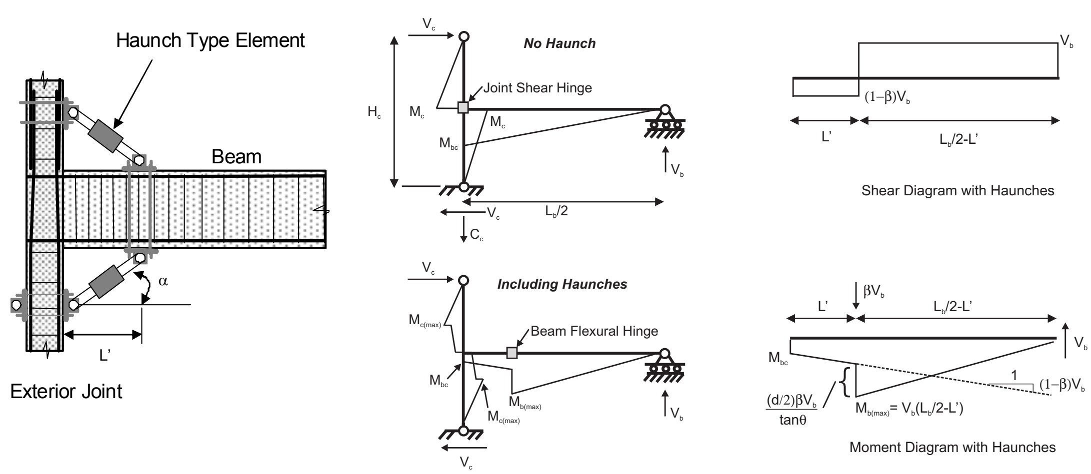

Figure 3. Proposed Haunch Retrofit Configuration for Exterior Joints; Modifications to the Internal Forces Diagrams

Details on the conceptual behaviour and design procedure have been presented in Pampanin and Christopoulos (2003) along with preliminary numerical investigations and feasibility studies referred to comparative performance of beam-column joints as well as a multi-storey frame in the as-built and in the retrofited configuration.

4 VALIDATION OF THE PROPOSED RETROFIT SOLUTION

4.1 Experimental program

A series of experimental tests on existing beam-column joints, either interior or exterior, in a 2-D or 3-D configuration (i.e. uni-axial and bi-axial tests), for different alternatives for the haunch elements (i.e. elastic, yielding or friction device) is currently underway in the Structural Laboratory of the University of Canterbury, in New Zealand in cooperation with the University of Toronto, in Canada to validate the proposed retrofit solution.

The preliminary results of the quasi-static cyclic tests on three exterior 2-D beam-column joints, representative of an as-built (benchmark) configuration (Specimen THDP2) and two alternative retrofit solutions (elastic haunch, specimen THR1 and a yielding haunch, specimen THR2) are herein presented.

4.2 Benchmark Test: as-built configuration

The beam-column joint as-built specimen TDP2 (Tee-joint, deep beam and plain round bars) used as benchmark for the retrofit intervention, had similar characteristics as the specimens T1 described in previous paragraph that were tested at the University of Pavia in Italy except for the presence of one horizontal stirrup in the joint and a bigger column section (230x230mm). The test setup as well as details on the beam and column dimensions and reinforcement (similar for all three specimens) are shown in Fig. 4. The reinforcing steel consisted of grade 300 plain round bars and the concrete compression strength, f'c, was 25 MPa at the day of testing for all the three specimens.

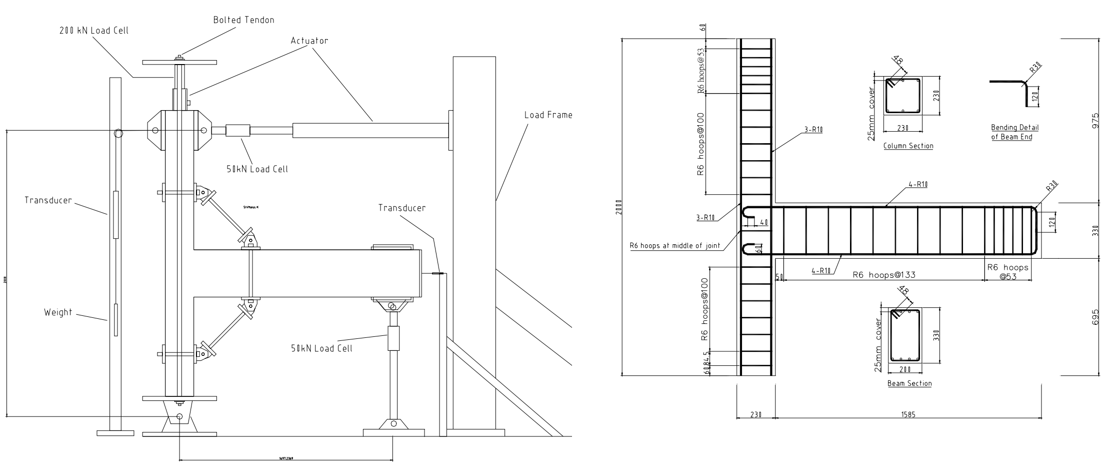

Figure 4. General Test Set-up and Details of the Beam-Column Joints Specimens

The as-built specimen TDP2 was subjected to a cyclic quasi-static testing protocol with increasing column drift level (two cycles per level) up to 4%. As expected, the benchmark specimen experienced first shear cracking in the joint region at around 0.5% drift. As the drift level was increased extensive damage to the joint area occurred confirming the weakness of the beam-column joint panel zone that had been observed in previous tests. In Fig. 5 pictures of the damage in the joint of specimen TDP2 at drift levels of 0.5%, 1.5% and after the end of test (4%) are shown. The excessive damage to the joint region is evident while no cracking is observed in the beams and columns, indicating that a shear hinge mechanism developed in the joint without, flexural hinges forming in the adjacent elements.

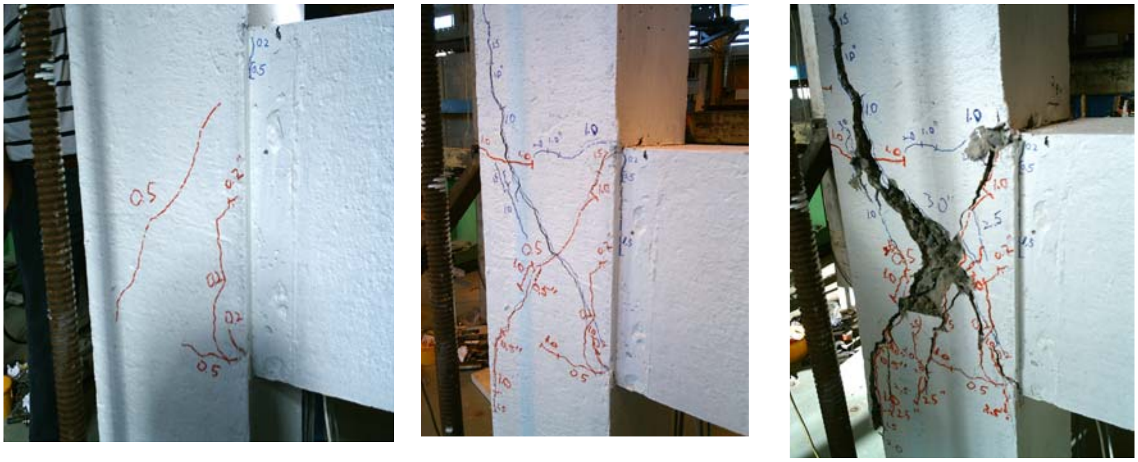

Figure 5. Damage in the Joint Region of the As-built Specimen TDP2.

at Drift Levels 0.5%, 1.5% and at the end of testing

In Fig. 6 the force-drift response of the TDP2 benchmark specimen is shown. The response of the system shows strength deterioration beyond drifts of 1.5% as well as marked pinching of the hysteretic curves. The gradual loss of strength is due to the formation of shear hinge mechanism in the beam-column joint. Unlike the results of tests carried out at the University of Pavia, where a sudden drop of system strength was observed after the formation of the shear hinge mechanism (see Fig. 2), the TDP2 specimen displayed a more gradual loss of strength with increasing drift due to the presence of one stirrup in the joint panel zone region as well as, to a lesser extent, to the adoption of a less demanding testing protocol (two cycles instead of three per drift level).

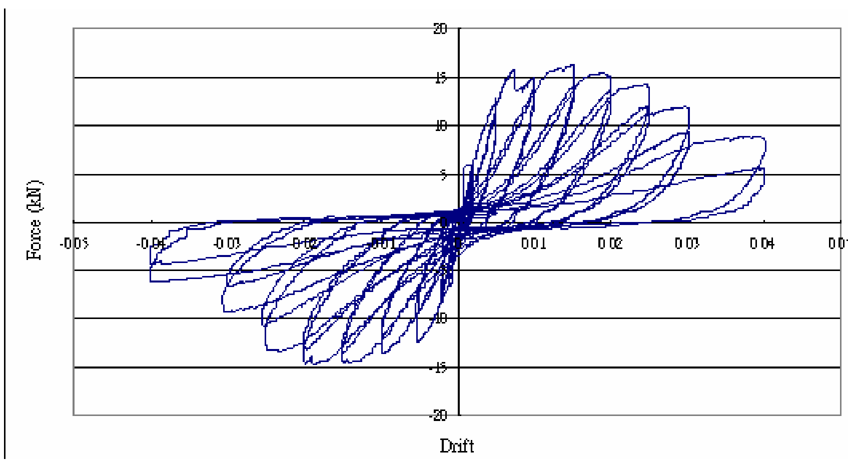

Figure 6. Force Displacement Response of THR1 Benchmark Specimen under Cyclic Loading.

4.3 Design of the haunch system

The haunch system was designed according to the procedure presented in Pampanin and Christopoulos (2003) in order to protect the joint region from excessive damage while enforcing a plastic hinge to occur in the beam away from the column interface (relocation). As mentioned, beam and column members must be protected from excessive shear demand and brittle failure by controlling the haunch design parameters.

The haunch system consisted of axially loaded elastic elements that can be sized to yield at a predetermined load (fuse) and a hinge support connected to the concrete elements as illustrated in Fig. 7. The stiffness and fuse strength were achieved by machining down a deformed bar for a design length and then inserting it into a steel grouted tube adopted as anti-buckling system. Steel plates were used to connect the haunch elements to the bare specimen using fasteners (anchor rods) as well as external rods partially prestressed to guarantee proper anchorage of the whole haunch system (Figure 8).

Figure 7: Haunch Element.

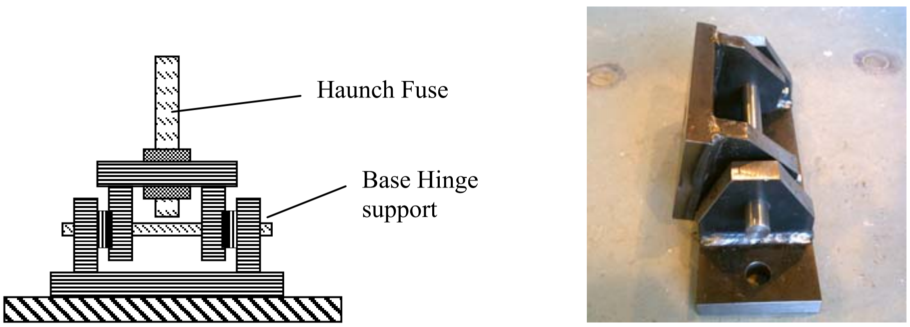

Figure 8: Hinge Support for the Haunch System

4.4 Response of system with haunch elements

The same testing protocol used for the benchmark specimen TDP2 tests was applied to the retrofitted systems THR1 and THR2. Results of the elastic haunch solution (THR1) are here presented.

In Fig. 9 a picture of the retrofitted specimen with haunches designed to remain elastic at a drift of 2.5% is shown. As anticipated, no shear damage occurred in the joint panel zone region, while flexural hinging of the beam was observed. The formation and progressive widening of a main flexural crack in the beam at the haunch-to-beam connection confirmed the migration of the section of maximum moment from the face of the column to the beam-haunch connection point. Note that the single crack hinge is typical of beams reinforced with smooth bars since the lack of bond between the longitudinal reinforcement and the concrete does not allow for the propagation of plasticity and the formation of a proper plastic hinge region.

In Fig. 10 the force-drift response of the retrofitted system is shown along with the force-drift response of the non-retrofitted specimen. As a result of the haunch retrofit, a significant increase in the system lateral strength was observed. Furthermore, unlike the non-retrofitted specimen, under cyclic loading of increasing displacement amplitude the retrofited system exhibited stable hysteretic response with good energy dissipation and little strength degradation. This is due to the relocation of the plastic hinge away form the column interface which provides the longitudinal beam bars with proper anchorage/development length as confirmed by the limited pinching in the hysteresis.

Figure 9: Comparison of Observed Damage in the Retrofitted (THR1, left) and As-built (TDP2, right) Specimens

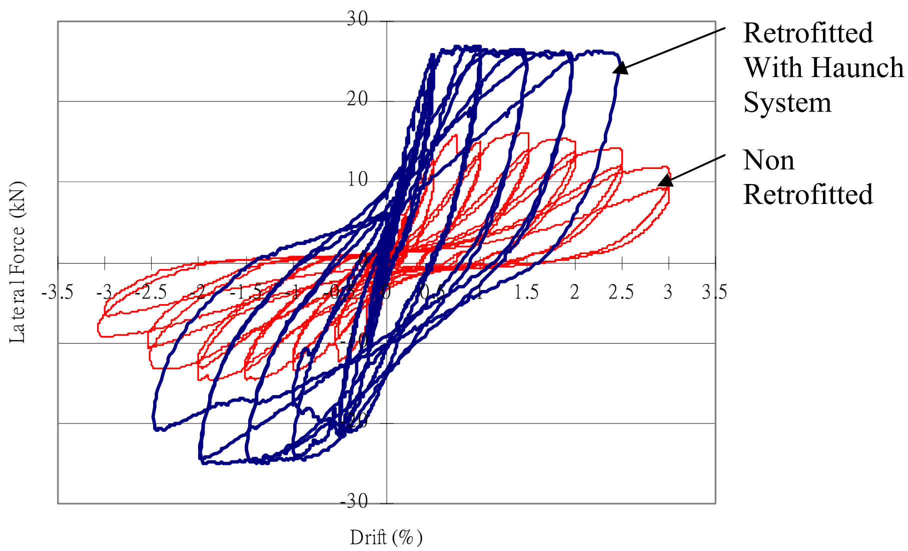

Figure 10: Comparison of Force Displacement Response of Retrofitted (THR1) and as-built (TDP2) Specimens

3 CONCLUSIONS

A simple and viable retrofit strategy for existing reinforced concrete buildings designed mostly for gravity loads, prior to the introduction of modern seismic code provisions has been presented. The feasibility of the proposed solution, which consists of introducing haunch type elements locally in the vicinity of beam-to-column connections, had been investigated numerically as a means to significantly enhance the seismic performance of these buildings. A simplified design approach, to control the hierarchy of strength within beam-column subassemblies, reducing the damage in exterior joints as well as avoiding soft storey mechanisms, was adopted.

An experimental program was initiated at the University of Canterbury in New Zealand to experimentally verify the effectiveness of the proposed technique to significantly improve the seismic response of non-seismically designed RC frames.

Results from a control benchmark test were first presented where the deficiencies related with the joint panel zone shear damage were confirmed. The design and practical implementation of a simple haunch element consisting of a threaded steel bar fastened to hinged plates that are connected to the beams and columns was then carried. Two retrofitted specimens were then subjected to the same loading protocol and displayed a substantially enhanced response when compared to the non-retrofitted specimens by eliminating damage to the joint and forming a plastic hinge in the beam at the location of the beam-haunch connection. This resulted in an increase in the system lateral strength, a stable hysteretic behaviour and enhanced energy dissipation capacity.

Further studies on the application of this retrofit technique to other types of non-seismically designed RC frames (i.e. shallow and wide beam, flat slabs) and on the practical definition of alternative elastic or dissipating haunch elements are needed. Experimental investigations on the local behaviour of the haunch system including appropriate fastening solutions to the existing frame are currently underway. Finally, investigations on the multiple aspects of the global response (3-D bi-axial, larger super-assemblage with floor systems) of systems retrofited with the proposed technique are also being carried out.

ACKNOWLEDGMENTS

The partial financial support of the NZ Foundation of Science and Technology with the FRST-Research Program "Retrofit Solutions for NZ" is acknowledged. The assistance of the University of Canterbury postgraduate student Mr. Te Hsiu Chen during the experimental phases of the project is also appreciated. The Financial support of the National Science and Engineering Research Council of Canada is also greatly appreciated.

REFERENCES

Aycardi, L., E., Mander, J., B. and Reinhorn, A., M. Seismic Resistance of Reinforced Concrete Frame Structures Designed Only for Gravity Loads: Experimental Performance of Subassemblages, ACI Structural Journal, Vol. 91, No.5, 552-563, 1994

Beres, A., Pessiki, S., White, R., Gergely, P. Implications of Experimental on the Seismic Behaviour of Gravity Load Designed RC Beam-Column Connections, Earthquake Spectra, Vol. 12, No.2, May, pp. 185-198, 1996

Calvi, G.M., Magenes, G., Pampanin, S. Experimental Test on a Three Storey R.C. Frame Designed for Gravity Only, 12th European Conference on Earthquake Engineering, London, paper n. 727, 2002a

Calvi G.M., Magenes G. and Pampanin S. Relevance of Beam-Column Damage and Collapse in RC Frame Assessment. Journal of Earthquake Engineering, Special Issue sup6(2), 2002b

Christopoulos, C. and Filiatrault, A., Non-invasive passive energy dissipating devices for the retrofit of steel structures, Proceedings of the International Conference on the behaviour of steel structures in seismic areas - STESSA 2000, Montreal, Canada, pp.387-394, 2000

Dolce, M., Cardone, D., Marnetto, R., Implementation and testing of passive control devices based on shape memory alloys. Earthquake Engineering & Structural Dynamics, 29, 7, 945-968, 2000.

fib Federation International du Beton, Externally bonded FRP reinforcement for RC structures, Bulletin n.14, Lausanne, 2001

Gross, J.L, M.D. Engelhardt, C-M. Uang, Kasai K., Iwankin N.R., Modification of Existing Welded Steel Moment Frame Connections for Seismic Resistance American Institute of Steel Construction, 1999

Hakuto, S., Park, R. and Tanaka, H. Seismic load tests on interior and exterior beam-column joints with substandard reinforcing details. ACI Structural Journal, V. 97, N.1, 11-25, 2000

Pampanin, S., Calvi, G.M. and Moratti, M. Seismic Behaviour of R.C. Beam-Column Joints Designed for Gravity Loads, 12th European Conference on Earthquake Engineering, London, paper n. 726, 2002

Pampanin, S., Magenes, G. and Carr, A., Modelling of Shear Hinge Mechanism in poorly Detailed RC Beam-Column Joints, Proceedings of the fib Symposium Concrete Structures in Seismic Regions, Athens, paper n. 171, 2003

Park, R., A Summary of Results of Simulated Seismic Load Tests on Reinforced Concrete Beam-Column Joints, Beams and Columns with Substandard Reinforcing Details. Journal of Earthquake Engineering, Vol. 6, No. 2, 1-27, 2002

Priestley, M.J.N., Displacement-based seismic assessment of reinforced concrete buildings", Journal of Earthquake Engineering, Vol. 1, No. 1, 157-192, 1997

Sugano, S. State of the art in Techniques for Rehabilitation of Buildings, Proceedings of the 11th World Conference on Earthquake Engineering, Acapulco, Mexico, Paper no. 2175, 1996.