EFFECTS OF VARIATION OF AXIAL LOAD AND BI-DIRECTIONAL LOADING ON THE FRP RETROFIT OF EXISTING B-C JOINTS

U. Akguzel[1] and S. Pampanin[2]

[1] *PhD Candidate, Department of Civil Engineering, University of Canterbury, Christchurch, NZ*
[2] *Senior Lecturer, Department of Civil Engineering, University of Canterbury, Christchurch, NZ*
Email: uze10@student.canterbury.ac.nz, stefano.pampanin@canterbury.ac.nz

ABSTRACT :

Most of the experimental studies on the seismic assessment and retrofit of existing, poorly detailed, beam-column joints have typically concentrated on the 2-dimensional (2D) response, based on uni-directional cyclic loading testing protocol under constant axial load. However, in order to obtain a more realistic understanding of the behavior of deficient exterior beam-column joints prior and after retrofit intervention, consideration of the 3-dimensional (3D) response under a) bi-directional and b) varying axial loads are necessary.
In this contribution, these two effects on the assessment and retrofit of exterior beam-column joints using GFRP composite materials are discussed. A series of 2/3 scale, 2D and 3D exterior (corner) beam-column joint subassemblies representative of pre-1970s construction practice were tested quasi-statically. Performance-based retrofit approach has been adopted in order to achieve the desired ductile failure mode by modifying the hierarchy of strength within the beam-column joint system. A critical comparison of the existing and retrofitted joints with regard to the observed damage and the global hysteresis behavior are shown, emphasizing the effects of axial load variation and bi-directional loading.
The experimental results provided satisfactory confirmations of the efficiency of the proposed retrofit solution, aimed at protecting the panel zone region, while activating a flexural behavior in the beam in order to achieve a more desired weak beam-strong column global inelastic mechanism.

KEYWORDS: Reinforced Concrete, Rehabilitation, Fiber reinforced polymers, Biaxial tests

1. INTRODUCTION

The technique of using FRP systems for structural enhancement mitigates several disadvantages inherent in the conventional strengthening methods and hence is gaining preference over traditional strengthening methods such as concrete jacketing, steel plate bonding and sprayed concrete. FRPs offer excellent corrosion resistance to environmental agents as well as strength-to-weight ratios when compared to conventional construction materials.
Various researchers have conducted tests on different layout of FRP fabric and sheets bonded to R.C. beam-column connections (Aycardi et al., 1994; Gergely et al., 2000; Hakuto et al., 2000; Prota et al., 2001; Ghobarah and Said, 2001; El-Amoury and Ghobarah, 2002; Park, 2002; Antonopoulos and Triantafillou, 2003; Calvi et al., 2002; Pampanin et al., 2004; Pampanin et al., 2007a). The tests unanimously indicated the effectiveness of the strengthening procedure by achieving significant improvements in the strength, stiffness and ductility of the retrofitted joints.
Recent earthquakes have demonstrated the higher vulnerability of existing exterior corner beam-column joints under a real bi-dimensional lateral cyclic loading. Nevertheless, aforementioned studies as well as design guidelines (e.g. *fib*, 2003, 2006; ACI 440, 2001; AIJ, 1997) related to the seismic assessment and FRP retrofit of existing RC buildings, have concentrated on the in-plane (2D) response of the strengthened specimen under uni-directional cyclic loading conditions. Limited information is available on the 3D response of exterior beam-column joints, either before or after FRP retrofitting (e.g. Hertanto, 2006; Pampanin et al., 2007b; Engindeniz et al., 2007).
In this contribution, the feasibility and efficiency of a retrofitting intervention based on GFRP composites is presented based on tests carried out at the University of Canterbury under uni-directional and bi-directional quasi-static cyclic loading on four exterior beam-column joint specimens, designed prior to the 1970s

construction practice, before and after retrofit using GFRP sheets. Two 2D and two 3D configuration are used to investigate the effects of bi-directional loading. In addition the effects of the variation of axial load, due to the lateral sway of the frame system, have also been properly reproduced during the test.

2. PERFORMANCE OF POORLY DETAILED BEAM-COLUMN JOINTS

2.1. General

Experimental studies on old type of beam-column joints report that joint panel degradation can cause the partial or total collapse of the building before any significant damage take place in either beams or columns. Different damage and failure mechanisms can be expected depending on the typology of joints (interior vs. exterior) and on the structural detailing adopted (i.e. plain round or deformed bars, anchorage solutions, total lack or presence of a minimum amount of transverse reinforcement) (Pampanin et al, 2004). In particular, brittle local failure mechanisms, likely to impair the overall system loading bearing capacity leading to global collapse modes, have been observed in exterior beam-column connection with lack of adequate transverse reinforcement in the joint, due to the intrinsic lack of alternative and reliable sources of shear transfer mechanism within the panel zone region after first diagonal cracking. Ad-hoc retrofit strategies are therefore required, being capable of providing adequate protection to the joint region, while modifying the strength hierarchy between the different components of the beam-column connections according to a capacity design philosophy.

2.2 Additional Effects due to Bi-directional Loading and Varying Axial Load

The extensive damage observed during the recent earthquakes emphasized the significant vulnerability of poorly detailed corner (exterior) beam-column joints when compared to other joint types. A further reduction in the joint shear strength capacity of exterior corner joint can be due to two critical effects: (1) the simultaneous bi-directional loading causing similar strength reduction as observed in biaxially loaded columns; (2) the variation of axial load due to the frame sway mechanism under lateral loading leading to a premature (either in terms of lateral force or of interstorey drift) damage in the joint or column. Underestimating or overlooking such effects may greatly effect the efficiency of a retrofit intervention. In addition, the effects of variation of axial load on poorly detailed joint is mostly disregarded in current assessment procedures.
It should be noted that, while well detailed and designed specimens are not expected to be substantially modified by the variation of the axial load during the later sway, thus supporting the implementation of simplified testing protocol based on a constant axial load, when dealing with poorly detailed subassemblies, the effects on the damage level and mechanisms could be significant. Incorrect and non-conservative assessment of the sequence of events can result, leading to inadequate design of the retrofit intervention. Consequently, it would be possible to activate, after a retrofit intervention, a global failure mechanism (i.e. due to the formation of a soft storey) which would have not occurred in the as-built configuration.

3. EXPERIMENTAL PROGRAM

3.1. Specimen Details and Material Properties

Two as-built specimens, representing pre-1970s construction detailing (i.e. plain round with end hook anchorage, and minimum or total lack of transverse reinforcement in the joint), and two retrofitted specimens using externally bonded Glass Fiber Reinforced Polymer (GFRP) sheets have been quasi-statically tested under uni- and bi-directional cyclic testing protocols. Figure 1 shows the geometry and reinforcement details of the 3D as-built and retrofitted specimens. The properties of the 2D specimens (2DB and 2DR) are equivalent to those of the x-direction face. Material and the uni-directional glass fibres properties are given in Table 1 and Table 2, respectively.

3.2. Test Set-up and Loading Procedure

Figure 2 illustrates the test set-up and loading protocol adopted. Beam and column elements were extended between points of contra-flexure (assumed to be at mid-span in the beams and at mid-height in the columns) where pin connections were introduced. Simple supports at the beam ends were obtained connecting pin-end steel members to the strong floor. column axial load was varied as a function of the lateral force, as it would occur due to the frame lateral sway, except for the specimen 3DR. The relationship between the lateral force F and the variation of axial load N $(N = N_{gravity} \pm \alpha F)$ is a function of the geometry of the building (i.e. number of bays and storeys) and can be derived by simple hand calculations or pushover analyses of the prototype frame.

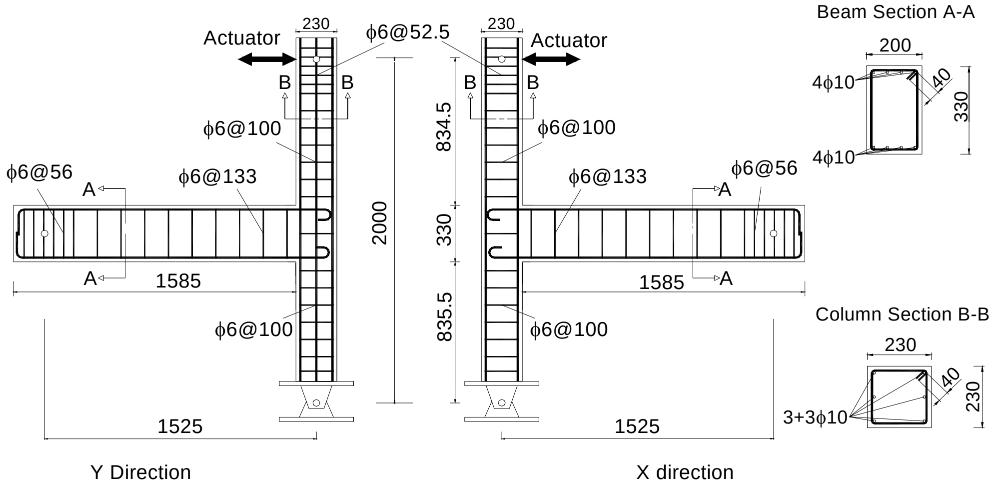


Fig. 1. Geometry and reinforcement details of the 3D exterior (corner) joint specimens

Table 1. Material properties

Specimen	Concrete	Reinforcement		
		Longitudinal		Transverse
		Beam Bars No. 10	Column Bars No.10	No.6
	f_c`(MPa)	f_y (MPa)	f_y (MPa)	f_y (MPa)
2DB	25.0	388	385	344
2DR	31.2	388	385	388
3DB	24.8	388	385	344
3DR	30.1	388	385	388

Table 2. Properties of the uni-directional glass fibres (GFRP SikaWrap -100G)

Areal Weight (g/m^2)	Fiber Density (g/cm^2)	Fabric Thickness (mm)	Tensile Strength (MPa)	Elastic Modulus (MPa)	Ultimate Strain (%)
935 ± 47	2.56	0.36	2,300	76,000	2.8

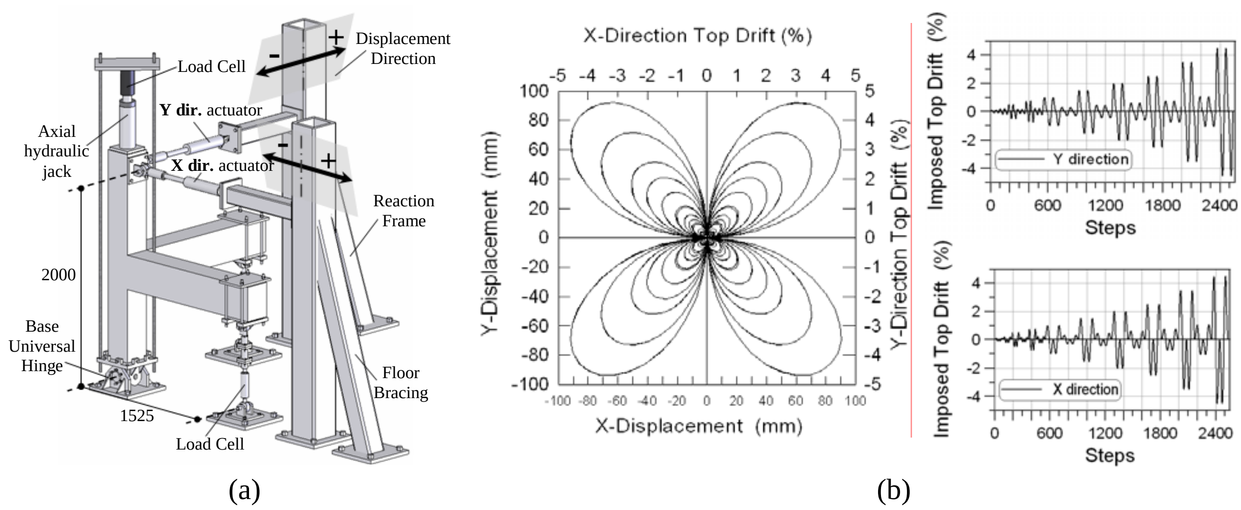
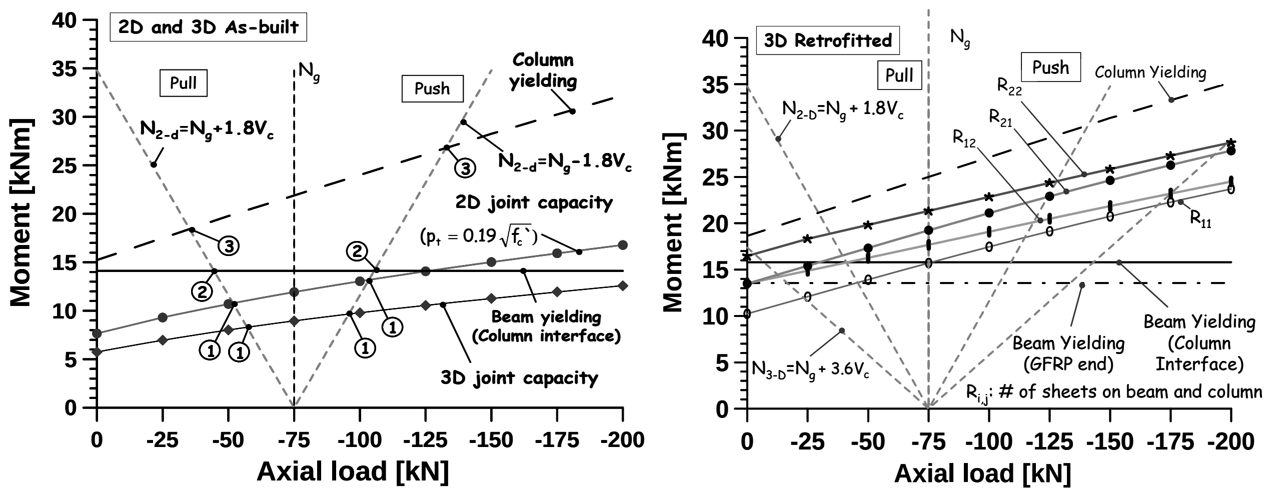


Fig. 2. (a) Test set-up; (b) Four-cloves displacement loading protocol for uni- and bi-directional testing

4. FRP STRENGTHENING INTERVENTION

Appropriate rehabilitation techniques can be applied by rearranging the sequence of events within the joint to bring them up to-capacity design provisions. For this purpose, recently proposed simple procedure can be employed to evaluate the expected sequence of events through the comparison of internal hierarchy of strengths within a beam-column-joint system (Pampanin et al., 2007a) through the construction of capacity and demand curves within a *M-N* (moment-axial load) performance domain. Figure 3(a) shows, as an example, the M-N performance domain adopted to predict the sequence of events and the level of damage in the joint panel zone expected for the as-built 2DB and 3DB specimens. The capacity of beam, column and joint panel zone are evaluated for given limit states. For the joint panel zone, cracking and extensive damage are considered and expressed as function of principle tensile stresses. A principle tensile stress of $0.19\sqrt{f_c`}$ can be assumed as a limit corresponding to the first cracking in a joint with end-hooked plain round bars after which a significant strength degradation is expected. As shown in the same figure, demand curves should account for the variation of axial load due to the effects of lateral forces in a frame system (for either opening and closing of the joint).
The retrofit solution was designed based on the M-N performance domain of Figure 3(b), where the expected effects of alternative retrofit solution are shown. The generic retrofit scheme Rij refers to a configuration with i number of GFRP layers in the beam and j number of GFRP layers in the column (on each side). The main target of the intervention was to protect the panel zone region from excessive damage and invert the hierarchy of strength enforcing the development of a plastic hinge in the beam. The details of the analytical procedure adopted for the evaluation of the FRP strengthening contribution to the joint shear capacity can be found in Pampanin et al., (2007a).



(a) (b)

Fig. 3. M-N Performance Domain: Evaluation of hierarchy of strengths and sequence of events; (a) the as-built specimens; (b) as-built 3D specimen with alternative retrofit configurations

A “R11” (i.e., one layer in the beam and one layer on each side of the column) retrofit scheme was adopted as a “minimum” retrofit solution according to the schematic layout given in Figure 4. One vertical layer of Uni-directional glass fiber laminates (Table 2) is used on two sides of the column in order to increase the column flexural capacity as well as the joint shear strength. In addition, one U-shape or L-shape horizontal laminate, wrapped around the exterior face of the specimen at the joint level, was used to increase the joint shear strength as well as to prevent the expulsion of the concrete wedge observed in the as-built configurations.

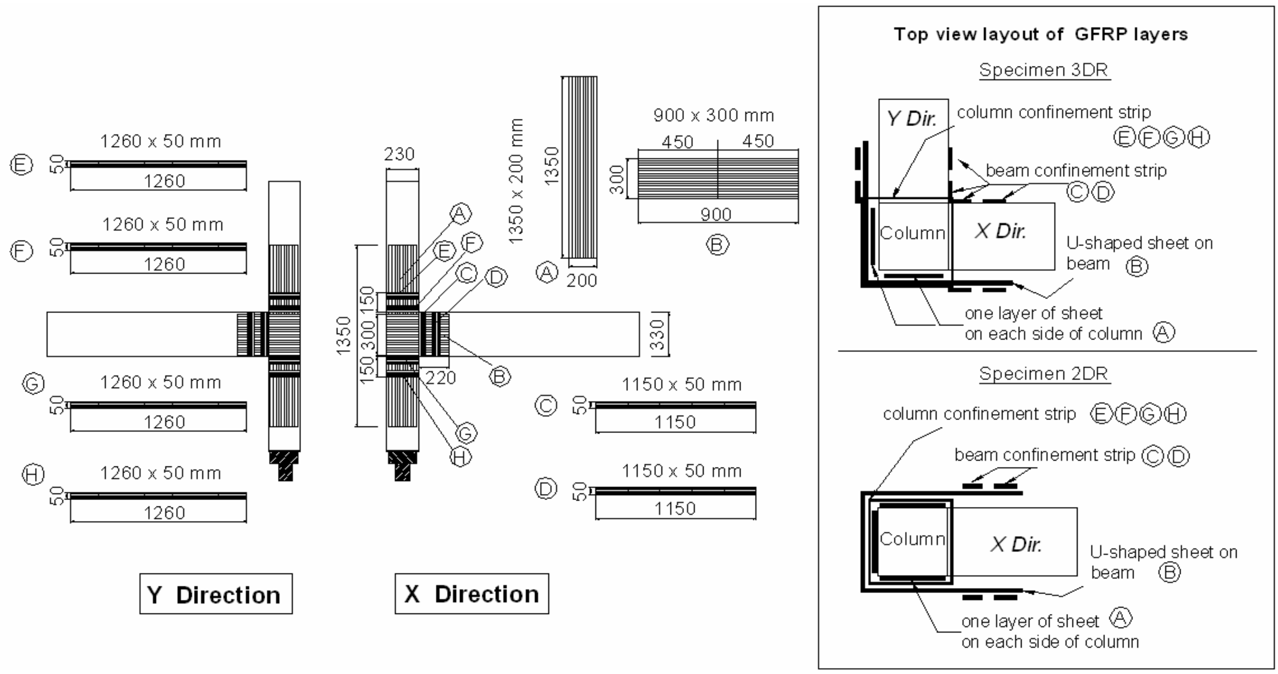


Fig. 4. GFRP retrofit configuration for the 2D and 3D corner joint specimens

5. TEST RESULTS and DISCUSSION

5.1. As-Built Specimens

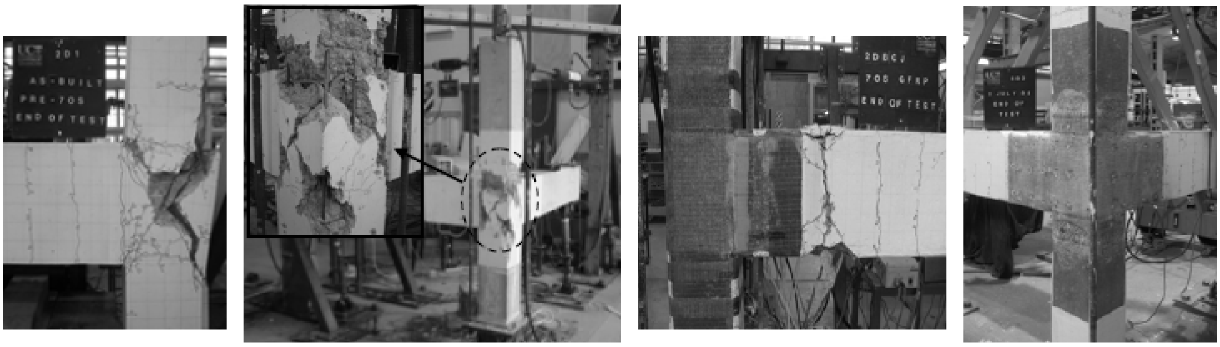
The 2D specimen (2DB) showed a particular brittle hybrid failure mechanism given by joint shear damage combined with slippage of beam longitudinal (plain round) bars within the joint region with concentrated compressive force at the end-hook anchorage. Load bearing capacity started to decrease after 1.5 % and 2% drift levels in each directions respectively following the widening of existing cracks vertically at the outer face of the column. Finally, extensive concrete wedge mechanism occurred resulting in spalling at the outer face of the column after 3% drift level. At 4% drift level specimen had already lost its bearing capacity around 75% in each direction.

The 3D specimen (3DB) exhibited a more complex three-dimensional concrete wedge mechanism (Figure 5b) due to the bi-directional loading regime confirming the damage observed in recent earthquakes. Similar to the two-dimensional response, the first diagonal joint crack occurred at 1% of drift. A reduction in the overall load capacity of 33 % and 15% in the positive and negative directions, respectively, was observed. Extensive joint damage and more strength degradation were observed compared to the 2D equivalent counterpart in spite of the partial confinement effect provided by the orthogonal beam. Summary of test results are given in Table 3.

Table 3. Summary of test results

Specimen	Maximum Lateral Force, P_{max} (kN)				Yield drift* (%)				Displacement Ductility (μ=$\Delta u/\Delta y$)			
	x dir		y dir		x dir		y dir		x dir		y dir	
	Pull	Push	Pull	Push	Pull	Push	Pull	Push	Pull	Push	Pull	Push
2DB	16.2	-14.7	-	-	0.5	-0.6	-	-	5	4	-	-
2DR	23.9	-26.6	-	-	1.4	-1.1	-	-	3	4	-	-
3DB	9.13	-13.9	11.0	-12.2	0.6	-0.4	0.5	-0.5	3	5	5	4
3DR	20.6	-23.3	19.8	-24.5	1.3	-0.4	1.2	-0.6	3	8	3	5

* The yield displacement is calculated from an equivalent elasto-plastic system, based on equal-area (energy) rule.



(a)

a) b) c) d)

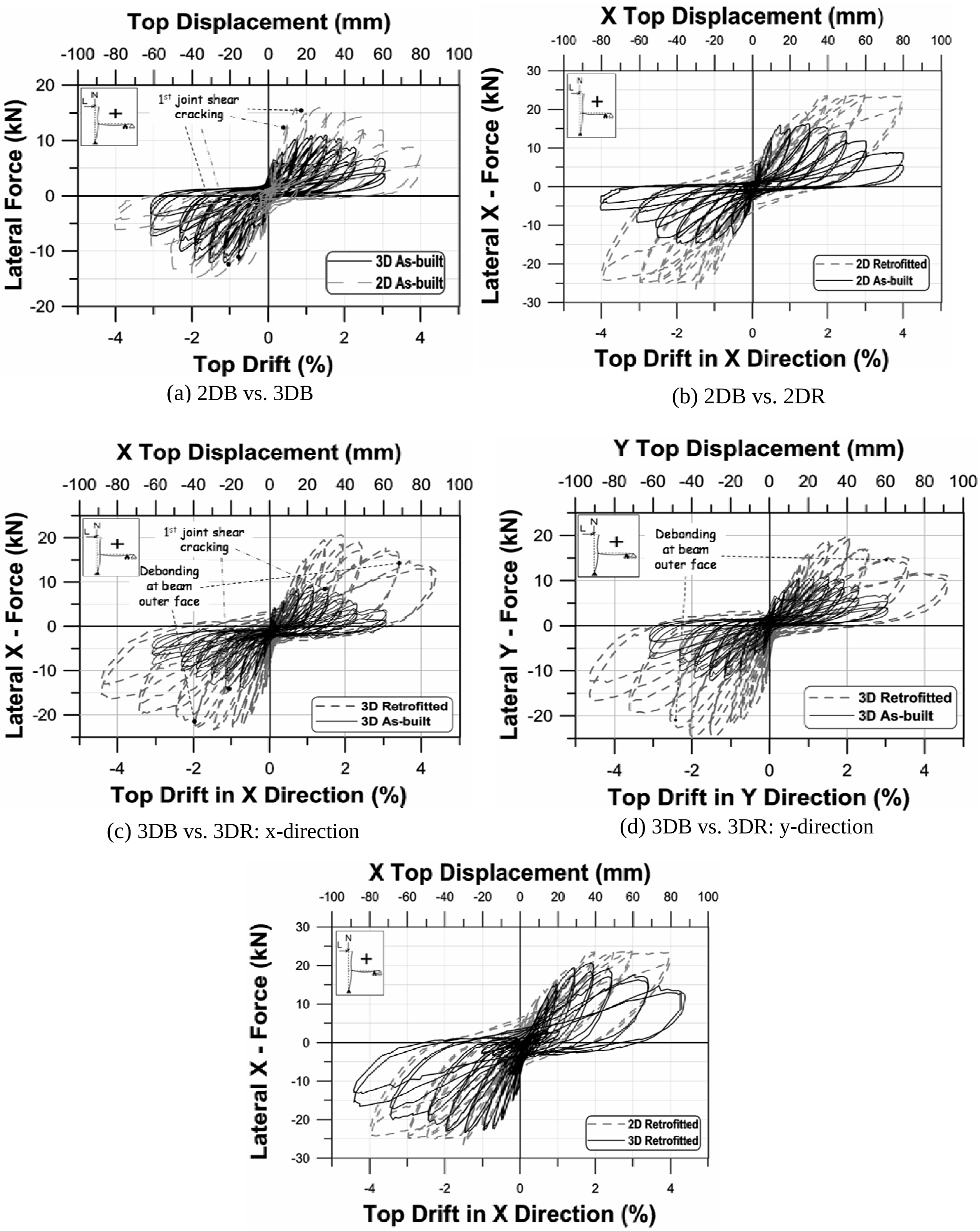
Fig. 5. Failure pattern of tests specimens at the end of the tests:
(a) As-built 2DB; (b) As-built 3DB; (c) Retrofitted 2DR; (d) Retrofitted 3DR

5.2. Retrofitted Specimens

The specimen 2DR has shown significant improvements in comparison to the as-built specimens. A part from some hairline cracks occurred in the column faces and beam-column joint intersection, no debonding, damage in the joint or delamination of the GFRP sheet were observed. The GFRP provided a favorable confinement effects in the column and beam such that plastic hinge region was located away from the joint in the beam section at the end of the GFRP (Figure 5c). Stable hysteresis behavior without any degradation of bearing capacity was achieved until the end of the experiment as shown in Figure 6.
The performance of the retrofitted specimen 3DR was in general satisfactory and in line with the expected targeted “minimum” performance level. The panel zone was protected from excessive damage. First minor delamination was observed in y direction at 1% drift level (20kN). After 2% of drift level debonding propagated along the beam into the joint. Along with the strength degradation, some minor cracking and separation of the GFRP on the outer face of the column were also observed in the following cycles. At the subsequent cycles to 2.5% strength degradation occurred due to the increased separation crack at the inner side of the joint as well as to the debonding of the FRP laminate at the outer faces of the beam. Most of the inelastic behavior concentrated in the beam via flexural cracking at the end of the GFRP laminate as well as at the inner face of the joint at the column interface similarly to what occurred in the as-built configuration (Figure 5d). Although post-test investigation revealed that a slight shear damage occurred in the panel zone underneath the FRP layers, the joint panel remained mostly intact due to the confinement effect of GFRP confinement.

6. CONCLUSIONS

Limits and drawbacks of standard plane assessment and retrofit procedure for exterior b-c joints using GFRP composite materials based on a standard 2D plane frame behavior assumptions and constant axial load assumption have been discussed. In particular the effects of varying axial load and of bi-directional loading have been investigated by comparison the response and observed damage of four specimens in an as-built and retrofitted configuration, tested under uni- and bi-directional loading regime. ing.
It is emphasized that in order to obtain the actual `sequence of events` prior and after the retrofit design actual demand curves, accounting for the variation of axial load on the corner joints due to the sway mechanism of the structure, should be used. In addition to that, an overall strength reduction for corner joints due to bi-directional loading should be taken into consideration. The results of an ongoing experimental program provided satisfactory confirmations of the efficiency of the proposed retrofit solutions for existing poorly detailed frame buildings. Overall and most importantly, the targeted performance after retrofit, consisting of preventing the joint from excessive damage while relying on the flexural inelastic deformation capability of the beam, was achieved. The results of quasi-static tests on exterior 3D (corner) poorly detailed beam-column joints, subject to a bi-directional (four cloves) displacement loading protocol before and after a retrofit intervention using GFRP sheets, provided very valuable confirmations of the efficiency of the adopted retrofit strategy and solution.



(a) 2DB vs. 3DB

(b) 2DB vs. 2DR

(c) 3DB vs. 3DR: x-direction

(d) 3DB vs. 3DR: y-direction

(e) 2DR vs. 3DR: x-direction

Fig. 6. Comparison of global hysteresis responses: As-built (2DB and 3DB) vs. retrofitted specimens (2DR and 3DR)

7. ACKNOWLEDGEMENTS

The financial support provided by the NZ Foundation for Research, Science and Technology (FRST) through the Research Program "Retrofit Solutions for NZ" is gratefully acknowledged. The material support and technical assistance provided by Sika-NZ and BBR-Contech are also kindly appreciated.

REFERENCES

Aycardi, L., E., Mander, J., B. and Reinhorn, A.M. (1994). "Seismic Resistance of R.C. Frame Structures Designed Only for Gravity Loads: Experimental Performance of Subassemblages." ACI Struct. J., 91(5), 552-563.

AIJ, Architectural Institute of Japan (1997). Design Guidelines for Earthquake-Resistant R.C. Buildings Based on Inelastic Displacement Concept (draft, in Japanese).

American Concrete Institute, ACI Committee 440, (2001). "Guide for the Design and Construction of Externally bonded FRP systems for strengthening concrete Structures".

Antonopoulos, C. P. and Triantafillou, T. C. 2003. Experimental investigation of FRP-strengthened RC beam-column joints. Journal of Composites for Construction, ASCE, 7(1): 39-49.

Calvi, G.M., Magenes, G. & Pampanin, S. 2002a. Relevance of Beam-Column Damage and Collapse in RC Frame Assessment. Journal of Earthquake Engineering, Special Issue 1, 75-100

El-Amoury and Ghobarah, A. Seismic rehabilitation of beam-column joints using GFRP sheets, Engineering Structures, 24: 1397-1407.

Engindeniz, M., Kahn, L. and Zureick A.-H., (2007). "Bidirectional loading of pre-1970 RC corner beam-column joints before and after rehabilitation with CFRP composites." 6th National Conference on Earth-quake Engineering, October, Istanbul.

Federation International du Beton (fib). (2003). "Seismic assessment and retrofit of reinforced concrete build-ings" Bulletin No. 24, Lausanne.

Federation International du Beton (fib). (2006). "Retrofitting of concrete structures by externally bonded FRPs with emphasis on seismic applications" fib Bulletin No.35, Lausanne.

Hakuto, S., Park, R. and Tanaka, H. (2000). "Seismic Load Tests on Interior and Exterior Beam-Column Joints with Substandard Reinforcing Details." *ACI Struct. J.*, 97(1), 11-25.

Hertanto, E. (2006). "Seismic Assessment of pre-1970s Reinforced Concrete Beam-Column Joint Subassem-blies", M.E. Dissertation, Department of Civil Engineering, University of Canterbury, Christchurch, New Zealand.

Gergely, J., Pantelides, C. P. and Reaveley, L.D. (2000). "Shear Strengthening of RC T-Joints Using CFRP composites", J. Compos. Constr., 4(2), 56-64.

Ghobarah, A. and Said, A., 2001. Seismic rehabilitation of beam-column joints using FRP laminates, Journal of Earthquake Engineering, Vol. 5, n. 1, p. 113-129.

Park, R., 2002. 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

Pampanin, S., Bolognini, D., Pavese, A., Magenes,. G., Calvi. 2004. Multi-level seismic rehabilitation of existing frame systems and subassemblies using FRP composites, CICE, Adelaide.

Pampanin, S., Bolognini, D., Pavese, (2007a). "Performance-based Seismic Retrofit Strategy for Existing Reinforced Concrete Frame Systems using FRP composites", ASCE Journal of Composites for Construction, Invited Paper for Special Issue on "Recent International Advances in FRP Research and Application in Construction", Vol. 11, No. 2, March/April 2007, pp. 211-226.

Pampanin, S., Akguzel, U., Attanasi, G., (2007b). "Seismic Upgrading of 3-D Exterior R.C. Beam Column Joints Subjected To Bi-Directional Cyclic Loading Using GFP Composites." 8th FRPRCS, Intl. Conference on FRP for Reinforced Concrete Structures, University of Patrass, Greece, July.

Prota, A., Nanni, A., Manfredi, G., and Cosenza, E. (2004). "Selective upgrade of under-designed r.c. concrete beam-column joints using CFRP." ACI Struct. J., 101, 5, 2004, pp. 699-707.