Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 364

EXPERIMENTAL INVESTIGATION OF TWO NOVEL FRP RETROFIT SCHEMES FOR STRENGTHENING STEEL COLUMNS

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ABSTRACT

Fiber reinforced polymers (FRP) are increasingly being used to retrofit structural members due to their low weight-to-strength ratio and corrosion resistance. Results from an experimental program conducted to evaluate two recently proposed techniques for retrofitting I-shape steel columns are presented. The first retrofit technique involves the construction of a steel-concrete column, which is subsequently wrapped with resin impregnated FRP sheets with the fibers oriented in transverse direction to confine the concrete. The second retrofit technique utilizes a glass FRP (GFRP) composite tube that is placed around the column and filled with concrete. The GFRP tube acts as a stay-in-place form and provides uniform confinement. Slenderness ratios of the retrofitted specimens are selected such that they cover a range of stub to intermediate long columns. Experimental results show significant increase in load carrying capacity and ultimate displacement of the retrofitted columns due to composite action behaviour. The second proposed retrofit technique, using a GFRP tube, provides increased confinement uniformly which results in greater enhancement in the axial behavior of the retrofitted specimens. Confinement efficiency decreased by increasing the specimen length as failure occurred due to overall buckling of the columns.

Introduction

A significant amount of critical infrastructure requires immediate retrofitting or replacement. For example, the current and future performance of many bridges around the world is under question as a result of corrosion deterioration and due to increased traffic loads not considered in the original design. Fiber Reinforced Polymer (FRP) products have been widely utilized in repair and retrofit of structures recently due to their unique properties including corrosion resistance and low weight to strength ratio. The higher initial cost of FRP materials compared to conventional construction materials is offset by significant savings in labour costs

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due to ease of application.

To date most FRP retrofit applications have been limited to reinforced concrete (RC) structures. More recently applications of FRP in repair and retrofit of steel structural members have been investigated with the majority of these studies focusing on the retrofit of steel beams and bridge girders (Liu et al. 2001, Patnaik and Bauer 2004, El Damatty et al. 2005, Photiou et al. 2006, Shaat and Fam 2006). Limited studies on strengthening steel columns using FRP have been reported on. Most of the retrofitted steel columns were hollow structural steel section (HSS) wrapped with FRP sheets to enhance their axial behaviour by preventing local buckling (Shaat and Fam 2006, Teng and Hu 2007). Traditional methods of strengthening steel columns included steel or concrete jacketing. The former labour intense technique is performed by welding steel plates to the columns, which significantly increases the dead load of the structure. The latter technique involves heavy formwork, significant steel reinforcement consumption and is also labour intensive.

This paper proposes two retrofit techniques for strengthening I-shape steel columns and evaluates their performance through an experimental program. The first proposed retrofit technique involves construction of a steel-concrete composite column by filling the voids between the column flanges with concrete. The composite section is subsequently wrapped with FRP sheets as shown in Fig 1.a. The FRP wraps consist of unidirectional fibers oriented in circumferential direction to provide confinement to the concrete core. The FRP protects the steel and concrete against corrosion. Also, the FRP and concrete delay local buckling of the steel web and flanges.

The second proposed retrofit technique utilizes a GFRP tube placed around the steel column and filled with concrete. The two most common types of FRP composites currently used in the construction industry are glass and carbon FRPs with the former being more economical. Although a solid GFRP tube was used to construct the specimens in this study, in the field applications the FRP jacket can be manufactured by bonding slotted FRP pipes together using epoxy glue as shown in Fig 1.b (Liu et. al. 2005). The GFRP tube consists of unidirectional fibers oriented in circumferential direction to confine the concrete. Additional advantages of this proposed retrofit technique are the improved concrete confinement and the GFRP tube acting as stay-in-place formwork for concrete.

The objective of the two proposed retrofit techniques is to enhance the behaviour of steel columns under axial loading by increasing their load carrying capacity, stiffness and ultimate displacement. The proposed retrofit techniques are evaluated through an experimental program covering a range of stub to intermediate long columns. The influence of column slenderness on axial behaviour is investigated in this study.

Experimental Program

A total of ten columns were tested in the experimental program, four were used as control specimens and the remaining six were retrofitted using the two retrofit techniques proposed in this study. The selected column heights were 0.5, 1.0 and 1.5 m, covering a range of stub to intermediate long columns. The steel column section was W150×14, which ensured cross

(a) (b)

Figure 1. Schematic representations of the proposed retrofit schemes utilizing (a) resin impregnated FRP sheets (b) GFRP tube (epoxy glues slotted pipes).

(a) (b)

Figure 2. Steps involved in the proposed retrofit procedures utilizing (a) resin impregnated FRP sheets (b) GFRP tube.

sectional yielding prior to the onset of local or overall buckling for short columns.

Applying the first retrofit scheme, wood forms were first placed around the columns and filled with concrete. After concrete partially cured and solidified, the forms were removed and the columns were wrapped with a single GFRP layer to prevent galvanic corrosion, which can occur between steel and the subsequent carbon FRP (CFRP) layers when in direct contact (Shaat and Fam, 2006). Two CFRP layers were then subsequently applied. Both glass and carbon FRP sheets were unidirectional fabrics with the fiber reinforcement oriented in circumferential direction. Dry fiber sheets were impregnated with an epoxy resin forming a wet lay-up system before being applied to the specimens. The thickness of one layer of GFRP and CFRP composite laminate after curing were 1.3 and 1.0mm, respectively. A 250mm overlap was developed to ensure that debonding would not occur in the FRP wraps prior to achieving their ultimate strength. Prior to testing, specimens were fully cured at room temperature for a minimum of 28 days from the date of pouring concrete. Fig. 2.a shows the manufacturing procedure for the steel columns retrofitted based on the first retrofit technique.

For the second proposed retrofit technique, GFRP pipes were first placed around the steel columns and subsequently filled with concrete. The wall thickness and inside diameter of the GFRP pipe were 3.2 and 211mm, respectively. Fig. 2.b shows the retrofit procedure for the second proposed retrofit technique.

Material properties of the glass and carbon FRP composite laminates and the GFRP tube utilized in retrofitting of the steel columns are presented in Table 1. The average yield and ultimate strength of steel, obtained from tensile coupon tests, were 411 and 526 MPa,

Table 1. Material properties of the GFRP and CFRP composite laminates and the GFRP tube (as provided by the manufacturer)

	GFRP laminate	CFRP laminate	GFRP tube
Circumferential Tensile Strength (MPa)	575	876	275
Circumferential Tensile Modulus (GPa)	26.1	575	15.9
Longitudinal Compressive Strength (MPa)	------	------	138
Longitudinal Compressive Modulus (GPa)	------	------	10.3

Table 2. Test matrix

Test No.	ID.	Retrofit scheme No.	Height (m)
1	C-0.5 (1)	------	0.5
2	C-0.5 (2)	------	0.5
3	C-0.5 (3)	------	0.5
4	C-1.5	------	1.5
5	R1-0.5	1	0.5
6	R1-1.0	1	1.0
7	R1-1.5	1	1.5
8	R2-0.5	2	0.5
9	R2-1.0	2	1.0
19	R2-1.5	2	1.5

respectively. The average compressive strength of concrete after 28 days was 47.3 MPa.

The test matrix is presented in Table 2. In the table, “C” identification code denotes the control specimens and “R1” and “R2” indicates the specimens retrofitted based on retrofit technique 1 (using resin impregnated FRP sheets) and retrofit technique 2 (using the GFRP tube). The number following the hyphen indicates height of the specimen in meters and the digit in the parenthesis shows the test number for the specimens of the same type.

Test Setup and Instrumentation

The specimens were tested under axial loading in a self reacting frame. The load was uniformly applied over the composite section using a 5000 kN actuator running under displacement control with a rate of 0.1mm/min. The top and bottom swivels simulate hinge boundary conditions at the ends. Linear potential transducers (LPTs) were used to measure axial and lateral displacement of the columns. Strain gauges were mounted longitudinally and laterally along the length of each specimen at mid-height and quarter-height from each end of the columns to measure strain values in the FRP jacket in both axial and circumferential direction. Fig.3 shows the test setup and photograph of a gauged specimen prior to testing.

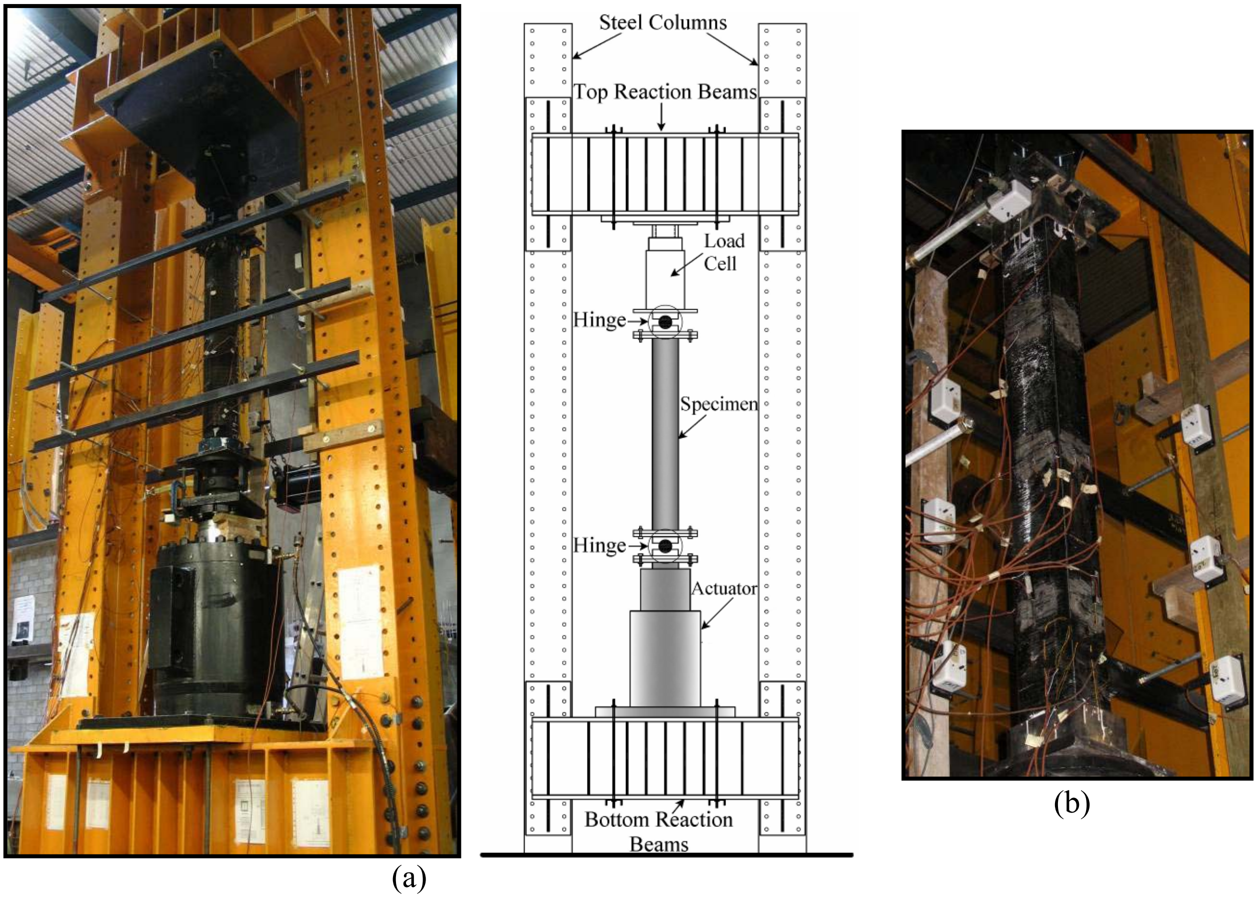


Figure 3. (a) Test setup for compression test of columns (b) gauged specimen

Test Results

The axial load-displacement behavior of the tested specimens is shown in Fig. 4. In order to highlight confinement and composite action between the three constituent materials in enhancing axial behavior of the retrofitted columns, separate contributions of the steel column and the unconfined concrete are analytically obtained and superimposed, denoted as "Steel+Unconfined concrete" in Fig. 4. Comparing the axial load-displacement diagrams of the retrofitted columns and the Steel+Unconfined concrete shows the effect of confinement on the axial behavior of the retrofitted columns. From Fig.4, it can be observed that confinement and composite action between the constituent materials result in considerable increase in the ultimate capacity and ultimate displacement of the retrofitted specimens. However, it has negligible effect on the elastic axial stiffness. This enhancement is more significant for the specimens retrofitted using the FRP tubes.

The increased strength, stiffness and ultimate axial strain of the tested specimens, the maximum lateral strain developed in the FRP jacket, and the compressive strength of the confined concrete (f'_{cc}) evaluated from the test results are tabulated in Table 3. From this table it can be seen that a maximum increase of 73% and 14% are obtained for the compressive strength of the confined concrete for the specimens retrofitted using the first and second proposed retrofit

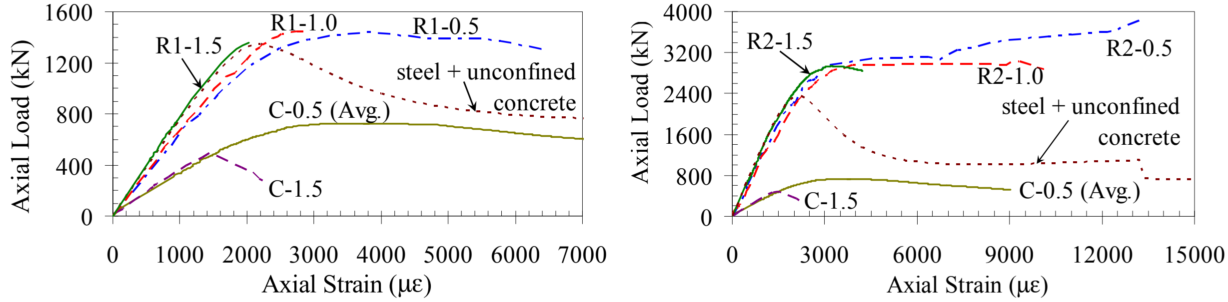


Figure 4. Axial load versus average axial strain measured over the full height of the specimens

Table 3. Experimental results

Specimen ID	Ultimate Strength	Stiffness	Ultimate Axial Strain	Max. Lateral Strain in the FRP Jacket	f'_{cc}	
	(kN)	(kN/mm)	(με)	(με)	(MPa)	Increase (Ratio)
C-0.5 (Avg.)	726	793	1,830	------	------	------
C-1.5	497	264	1,255	------	------	------
R1-0.5	1,440	1673	3,899	5,631	54.0	1.14
R1-1.0	1,447	800	2,834	1,754	54.3	1.14
R1-1.5	1,354	562	1,823	823	47.6	1.01
R2-0.5	3,821	3,244	13,215	14,391	82.0	1.73
R2-1.0	3,041	1,589	9,723	1,866	61.6	1.30
R2-1.5	2,935	1,049	3,294	1,684	58.5	1.24

techniques, respectively. It is also observed that the maximum lateral strain developed in the FRP jacket and consequently the confinement is severely reduced by the increased specimen height. The enhancement in the compressive strength of the confined concrete reduces from 14% to 1% and 73% to 24% for the specimens retrofitted based on the first and second proposed retrofit techniques, respectively, by increasing the height of the columns from 0.5 m to 1.0 m.

Fig. 5 shows the strain ratio versus axial strain relationship for the refitted specimens. The strain ratio (v) is defined as the absolute value of the average lateral strain divided by the average axial strain. An increase in the strain ratio indicates more pronounced confinement. As can be seen from this figure, there is a slight increase in the strain ratio until failure for the R1 specimens indicating minor confinement for these retrofitted columns. For the R2 retrofitted specimens, the strain ratio increases slowly in the elastic range and it is approximately equal to the Poison's ratio of the FRP jacket (v_{yx}≈0.11) in this region. However, it increases rapidly beyond the elastic limit and continues to increase until failure, indicating significant confinement over concrete for these retrofitted columns.

Fig. 6 shows the lateral deflection curves for the retrofitted specimens R1-1.5 and R2-1.5 where, n is the ratio of the axial load divided by the ultimate load. As can be seen from this figure, the mid-span lateral deflection is insignificant until the load reaches about 95% and 97% of its maximum value for the R1 and R2 retrofitted specimens, respectively. At these levels of

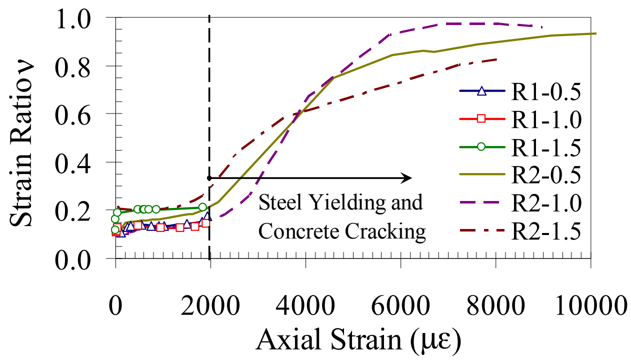
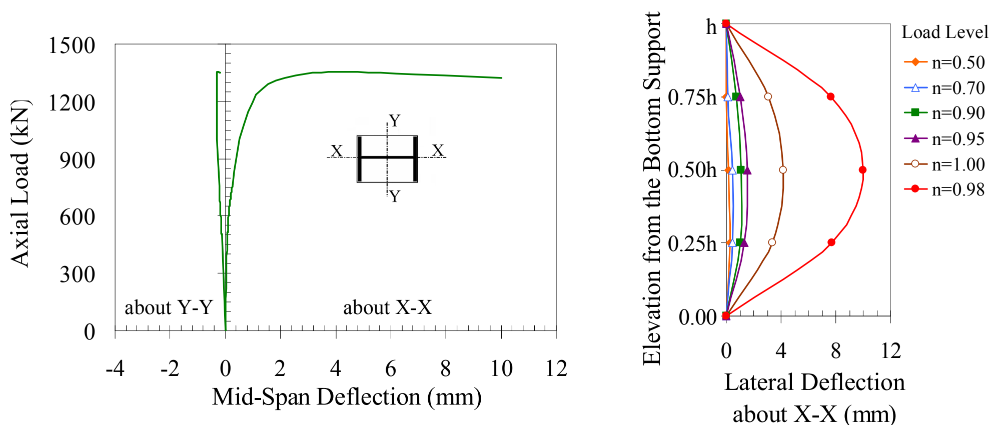
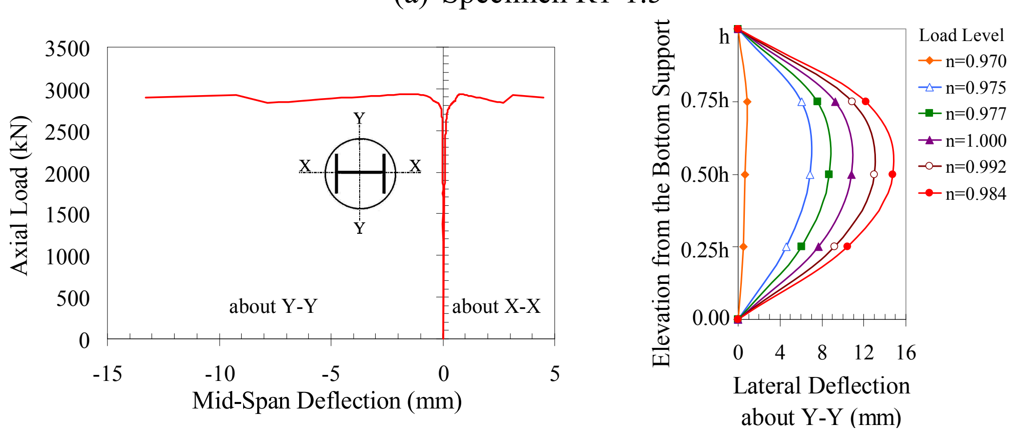


Figure 5. Comparison of strain ratio versus axial strain diagrams for the retrofitted specimens



(a) Specimen R1-1.5

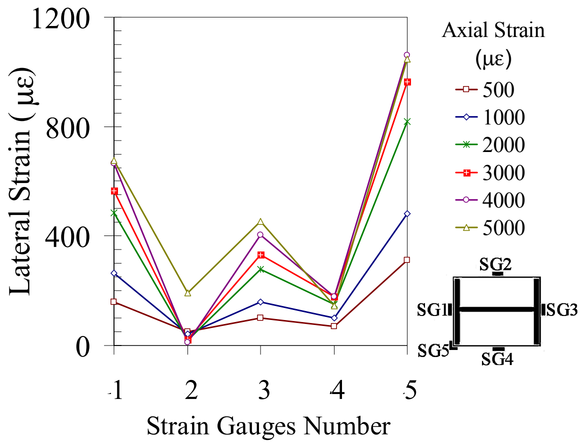


(b) Specimen R2-1.5

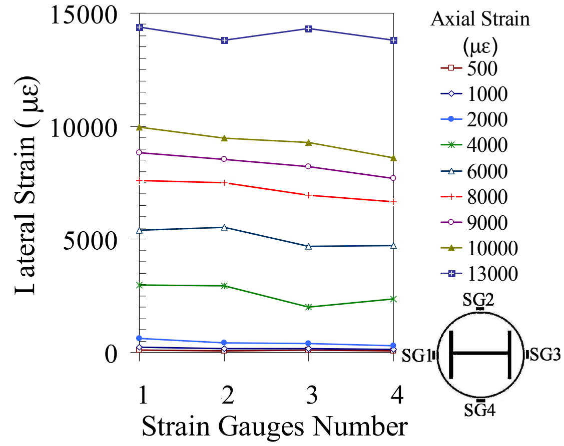
Figure 6. Lateral deflection curves

axial load, the lateral deflection begins to increase significantly.

Confinement efficiency is highly dependent on the uniformity of confinement (Ozbakkaloglu and Oehlers 2008). Fig. 7 shows the distribution of lateral strains for different axial strain levels over the perimeter of the retrofitted specimens R1-0.5 and R2-0.5 as an example. For the R1 retrofitted columns, the lateral strain profile is fairly uniforms up to 500 με



(a) Specimen R1-0.5



(b) Specimen R2-0.5

Figure 7. Distribution of lateral strains

Figure 8. Failure modes of the tested columns

axial strain. Further compression of columns beyond this level of axial strain will results in a highly nonuniform distribution of lateral strains. The tubular retrofitted columns, R2s, show relatively uniform lateral strain distribution below 2000 με axial strain. The specimen R2-0.5 maintained this uniform distribution until failure. However, for the specimens R2-1.0 and R2-1.5 the lateral strain distribution was distorted past 2000 με axial strain level, mainly due to development of flexural strain as a result of overall buckling of the columns.

Photographs of the failed specimens are presented in Fig. 8. Failure of the control steel columns was due to local buckling of flanges and web for specimens C-0.5 (1) and elastic overall buckling of the column for specimens C-1.5. Failure of all the three R1 retrofitted specimens was associated with overall buckling. From the axial strain readings at the point of failure it was found that the overall buckling occurred in the inelastic range for specimen R1-0.5 and in the elastic range for specimens R1-1.0 and R1-1.5. Failure of specimen R2-0.5 was caused by rupture of the FRP tube followed by crushing and spalling of concrete. Specimens R2-1.0 and R2-1.5 failed due to inelastic overall buckling.

Conclusions

Two novel retrofit techniques for strengthening I-shape steel columns were introduced and evaluated in this paper through an experimental program. Experimental results confirm the effectiveness of the confinement mechanism and composite action between the constituent materials in enhancing axial capacity and failure displacement of the retrofitted specimens. Axial elastic stiffness was not considerably affected by confinement. Retrofit technique 2 was found to provide greater enhancement to the axial behaviour.

Evaluation of the strain ratio and lateral strain distribution along the perimeter of the retrofitted specimens also revealed a more uniform and effective confinement was provided by retrofit technique 2. The maximum lateral strain developed in the FRP jacketed, and consequently the confinement, was severely reduced by increase of specimen height. Three different modes of failure including cross sectional failure, elastic and inelastic overall buckling were observed for the retrofitted specimens based on their slenderness ratio.

Acknowledgments

This study was carried out as part of ongoing research at McMaster University Centre for Effective Design of Structures funded through Ontario Research and Development Challenge Fund of the Ministry of Research and Innovation. Funding was also provided by Natural Sciences and Engineering Research Council of Canada (NSERC). The authors would like to gratefully acknowledge Fyfe.Co.LLC for providing the FRP materials utilized in the first proposed retrofit technique. Contribution of Walters Inc. in construction of the setup is also gratefully appreciated.

References

El-Damatty, A. A., M. Abushagur and M. A. Youssef, 2005. Rehabilitation of composite steel bridges using GFRP plates, *Applies Composite Materials* 12, 309–325.

Liu, X., P. Silva and A. Nanni, 2001. Rehabilitation of steel bridge members with FRP composite materials, *CCC2001 conference*, *Composites in Construction*, Porto, Portugal, 613-617.

Liu, X., A. Nanni and P. F. Silva, 2005. Rehabilitation of compression steel members using FRP pipes filled with non-expansive and expansive light-weight concrete, Advances in Structural Engineering 8(2), 129-142.

Ozbakkaloglu, T. and D.J. Oehlers, 2008. Manufacture and testing of a novel FRP tube confinement system, Engineering Structures 30, 2448–2459.

Patnaik, A. K., and C. L. Bauer, 2004. Strengthening of steel beams with carbon fiber laminates, *Advanced Composite Materials in Bridges and Structures*, Calgary, Alberta.

Photiou, N. K., L. C. Hollaway and M. K. Chryssanthopoulos, 2006. Strengthening of an artificially degraded steel beam utilizing a carbon/glass composite system, *Construction and Building Materials* 20, 11–21.

Shaat, A. and A. Fam A., 2006. Rehabilitation of damages steel-concrete composite beams using high modulus CFRP sheets, *7th International Conference on Short and Medium Span Bridges*, Montreal, Canada 4, 1-11.

Shaat, A. and A. Fam A., 2006. Axial loading tests on short and long hollow structural steel columns retrofitted using carbon fibre reinforced polymers, *Canadian Journal of Civil Engineering* 33: 458–470.

Teng, J.G. and Y. M. Hu, 2007. Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression, *Journal of Construction and Building Materials* 21: 827–838.