GLASS FIBRE REINFORCED POLYMER BARS IN CONCRETE COMPRESSION MEMBERS

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ABSTRACT

The use of Glass Fibre-Reinforced Polymer (GFRP) composite materials as reinforcement for concrete structures to overcome corrosion problems has been growing. Past Canadian applications are dominated by bridge decks and car parks where de-icing salts are used. Other applications include coastal structures and structures aiming for improved durability. Our research aimed to examine the practicality of using GFRP bars as reinforcement in concrete compression members. Twenty-four concrete columns reinforced with either steel or GFRP were loaded in compression until failure, with ultimate compressive strengths and horizontal displacements of the bars recorded. The results indicate that the use of GFRP bars as reinforcement in concrete compression members is technically viable, with GFRP reinforced columns yielding almost the same capacity as those reinforced with equal areas of steel. Incorporation of extra GFRP stirrups was found to improve the capacity in bending of the longitudinal GFRP reinforcement. Cost comparisons have also been completed to ensure the use of GFRP reinforcement is economically viable. The research concluded that reinforcing concrete columns with GFRP bars is an attractive option when life span and/or durability are of high priority. The research was followed by the first design and construction of reinforced concrete compression members utilising GFRP in Australia. This was done at the Dundas Point Boardwalk on the Swan River in Applecross, Western Australia, completed in 2014. Ongoing research will initiate in 2015 at UWA to investigate GFRP subject to combined bending and axial stressing.

KEYWORDS

Reinforcement, compression, capacity, displacement, concrete, sustainability, innovation.

INTRODUCTION

Background and Motivations

Fibre Reinforced Polymers (FRP) are composite materials used to strengthen concrete structures. They are made of fibres of a particular material selected, embedded in a polymeric resin. The most common fibres used in FRPs are glass, carbon or aramid. FRPs can come in woven sheets, which attach to the outside of reinforced concrete structures to offer strengthening, usually for remediation purposes. FRPs are less commonly produced as reinforcing bars, instead of steel reinforcement.

Advantages of FRP bars include; having high tensile strength, being corrosion resistant, nonmagnetic and lightweight with low thermal and electrical conductivity. This suite of characteristics is useful in many situations. FRP bars are well suited for use in corrosive environments, in structures required to have a very long design life, in hospitals near MRI machines, for example, and provide easy workability because they are so lightweight.

Disadvantages of FRP bars include; no yielding before failure, low transverse strength, low modulus of elasticity and possible durability issues of glass fibres in alkaline environments. These characteristics need to be understood with guidelines to manage risk associated with these properties in concrete.

In 2001, the American Concrete Institute (ACI) released their first standard detailing recommendations of the use of FRP bars in reinforced concrete (RC). "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars" (1) is the most current standard and was published in February 2006. ACI Committee 440 has chosen not to offer recommendations on the use of FRP bars in compression members due to the lack of experimental data.

Objectives

This study aims to further the knowledge of Glass Fibre Reinforced Polymer (GFRP) bars used to internally reinforce concrete compressive members. An experimental program using concrete columns reinforced with GFRP bars was designed to examine the effect GFRP bars has on the compressive strength and failure mode of the columns, and gain data on the displacements of the reinforcing bars themselves. A steel reinforced set of columns of matching size was used for comparison. The overall target was to determine if the use of GFRP bars is practical, and to give accurate guidelines as to what precautions, if any, should be taken when using GFRPs in reinforced concrete compressive members.

Corrosion tests were performed on steel bars and GFRP bars in several different saline solutions to determine if GFRP bars were subject to corrosion in a similar way to steel. The solutions included, distilled water, sea water and three salt water solutions varying in strength (10%, 20% and 32% weight ratio of salt to water). The two steel and GFRP bar types were immersed in the solutions for an extended period and weight loss due to corrosion measured.

GFRP LITERATURE REVIEW

GFRP Bars

Compression members reinforced with GFRP bars are limited to the research laboratories as not enough information has been recorded to allow guidelines or standards to be compiled. The testing of GFRP no. 15 (15mm diameter) bars under compression found that the ultimate compressive strength is approximately equal to 50% of the ultimate tensile strength, and the modulus of elasticity in compression can be considered approximately equal to the modulus of elasticity in tension (3). Alsayed, Al-Salloum, et al. (2) tested full size concrete columns under concentric compression to investigate the effect of replacing steel reinforcement with equal amounts of GFRP reinforcement. The axial capacity of the GFRP reinforced columns was 13% less than the steel reinforced equivalent.

GFRP Ties

Previous literature has evaluated the use of GFRP ties in place of steel ties to assess their effect on the compressive capacity and mode of failure on reinforced concrete columns. Research around GFRP ligatures is dominated by stirrup spacing, which evidently plays a part in the failure mode of compressive members.

Alsayed, Al-Salloum, et al. (2) used GFRP ties in their concentrically loaded columns and deduced that it reduced the axial capacity by only 10% compared to columns reinforced with traditional steel ties. Furthermore, they concluded that the replacement of the steel ties with GFRP ties had no influence on the load-deformation of the column up to approximately 80% of ultimate capacity.

EXPERIMENTAL DESIGN

Column Parameters

The reinforced column sample design had to be of such a size and strength to satisfy certain criteria. The columns need to be:

- long enough to be considered ‘full size’
- short enough to fit comfortably into the testing machine
- deemed to be slender under conditions set out in AS 3600 (4)
- capable of withstanding no more than 2000kN
- designed in accordance with AS 3600 (4)
- and to have ties of appropriate shape and size to be manufactured

Using the Rectangular Stress Block method and modeling columns of different dimensions, reinforcement arrangements and concrete strengths in analysis software to gain an estimate of the column capacities, the dimensions of the sample columns were defined as 160mm x 160mm x 1500mm. It was also decided that four longitudinal bars would be used to reinforce the columns. In addition, two batches of concrete were to be considered. The batches were to have strengths in the range of 40MPa and 60MPa.

Calculations were carried out on all reinforcement arrangements to ensure columns satisfied all conditions of AS 3600 (4) Section 10.

A circular tie of 100mm in diameter was selected. This gave cover to tie reinforcement of 30mm and cover of 45mm to the longitudinal reinforcement.

Reinforcing Materials

GFRP Reinforcement

The ordered materials included 9.53mm diameter GFRP bars in 3 metre lengths and 100mm diameter circular ties using 6.35mm diameter GFRP bars.

The properties of the GFRP bars considered for use in this research are presented in Table 1 below.

Table 1 GFRP Bar Properties.

Bar Size (inches)	Nominal Diameter (mm)	Guaranteed Tensile Strength (MPa)	Modulus of Elasticity (GPa)
#2	6.35	840	43
#3	9.53	750	43
#4	12.70	685	43

Steel Reinforcement

The University of Western Australia Structures Laboratory supplied the steel reinforcing bars used in the columns. All bars used were N-bars and their properties can be seen in Table 2 below.

Table 2 Steel Bar Properties.

Nominal Diameter (mm)	Guaranteed Tensile Strength (MPa)	Modulus of Elasticity (GPa)
6	500	200
10	500	200
12	500	200

It was decided that 6mm wide cuts of 100mm diameter steel pipe would be used as a substitute for steel ligatures. The ties are needed only to provide restraint to the longitudinal reinforcing bars.

Reinforcement Arrangement

There are four different reinforcing arrangements tested in this experiment. They were carefully chosen to give results so that the following points could be investigated.

- How GFRP reinforced columns compare to steel columns when loaded in a manner to create theoretical tensile capacity in the reinforcing.
- How GFRP reinforced columns compare to steel columns with the same nominal volume of reinforcing.
- The effect of tie spacing on the capacity and failure mode of GFRP reinforced columns.

Naming Convention

As there are four reinforcement arrangements and two concrete batches, there are eight different column types considered. Their naming convention is detailed in Table 3.

Table 3 Column Naming Convention.

Column Name	Longitudinal Reinforcement	Tie Spacing	Concrete Ordered
FRP Max 50	9.53mm GFRP	Maximum (150mm)	50 MPa
FRP Min 50	9.53mm GFRP	Minimum (75mm)	50 MPa
10mm Steel 50	10mm Steel	Maximum (150mm)	50 MPa
12mm Steel 50	12mm Steel	Maximum (150mm)	50 MPa
FRP Max 65	9.53mm GFRP	Maximum (150mm)	65 MPa
FRP Min 65	9.53mm GFRP	Minimum (75mm)	65 MPa
10mm Steel 65	10mm Steel	Maximum (150mm)	65 MPa
12mm Steel 65	12mm Steel	Maximum (150mm)	65 MPa

Three columns of each column type were cast. For example the FRP Max 50 columns where named FRP Max 50 (1), FRP Max 50 (2) and FRP Max 50 (3). This means that each group can be easily referred to and each individual column has a distinct name.

METHODS AND PROCEDURES

Concrete Cylinder Compression Tests

The concrete cylinders cast and prepared were tested in compression using the Baldwin machine at the University of Western Australia Concrete Laboratory. The Baldwin machine is a hydraulically operated machine where load is applied by the upwards displacement of the steel table. The load was increased until failure occurred so that a maximum load could be recorded and the failure mode noted. The load and table displacement were recorded with a computer program.

Column Compression Tests

The 24 reinforced concrete columns were tested in compression using the Amsler machine at the University of Western Australia Structures Laboratory. The Amsler machine is a hydraulic operated apparatus. The machine works by displacing the top steel plate downwards to apply load and is capable of delivering up to 2000kN of load.

A steel plate is used to create a slightly eccentric load. This was done to differentiate from the tension and compression sides of the column. The 160mm by 160mm steel plate was designed to be able to line up with each side of the column and the welded semi-circular bar would be precisely 4mm off centre. This ensured that the same eccentricity was placed on each column to provide consistent results.

Strain gauges were attached to the centre of the tension side of the longitudinal reinforcing bars and waterproofed prior to casting the columns. The strain gauges were connected to an amplifier using quarter bridge cables.

The column was loaded at a rate of approximately 5kN per second until failure of the column occurred.
The results of reinforcement displacement, column load and table displacement were recorded into a computer program via a series of data points. These data points can then be used in conjunction with the defects noted and failure modes exhibited to analyse the performance of the reinforcement.

Figure 1 Left: Column in Amsler Machine. Centre: Steel Plate. Right: Ruptured GFRP Bar and Tie.

Corrosion Tests

Corrosion testing was carried out on both steel reinforcement and GFRP reinforcement. Samples of each bar were submerged in distilled water, sea water and three salt water solutions. The measurements of the salt water solutions prepared are shown in Table 4.

Table 4 Salt Water Solutions.

Salt Solution No.	Weight of Salt (g)	Weight of Water (g)	Percentage of Salt in Solution (%)
1	15.2	150	10.1
2	29.7	150	19.8
3	48.6	150	32.4

The samples were weighed prior to testing. The samples were left for 45 days. The bars were then inspected for rust before being thoroughly cleaned and weighed again to measure weight loss.

RESULTS AND DISCUSSION

Concrete Strength

Two batches of concrete were required to cast the 24 columns. Readymix concrete was necessary to ensure the same concrete properties were obtained for each of the specimens, therefore giving reliable results. The slump of both mixtures was ordered at 80mm. As 0.8 cubic metres of each batch was needed, it was clear that mixing the concrete by hand would not be time or cost effective.

The concrete columns were to be cured for 14 days. This meant that an estimation of the standard 28 day strength had to be made so as to receive the strength wanted at 14 days.

The concrete for testing was prepared by casting four, 100mm diameter, 200mm long cylindrical samples for each batch. These were tested in compression after 14 days, the same curing time as the concrete columns.

Table 5 Concrete Batch Strengths.

Concrete Batch No.	Slump (mm)	Load – Average (kN)	Stress – Average (MPa)	Stress – Estimated for 14 days (MPa)	Stress – Ordered (MPa)
1	55	335.886	42.766	44	50
2	115	296.604	37.765	57	65

Column Compression Tests

FRP Max Columns

Table 6 summarises the load and displacement data for all FRP reinforced columns with maximum tie spacing.

Table 6 Average FRP Max Data.

Column – Average	Max Load – Average (kN)	Max Stress – Average (MPa)	Displacement – Average (µm)
FRP Max 50	920.1	35.9	1730.2
FRP Max 65	768.0	30.0	1265.0

With an average 5MPa reduction in 14 day compressive (by cylinder test) column concrete strength came an average 6MPa drop in compressive capacity of the columns. The column testing results are consistent with the low strength results obtained from cylinder testing of the concrete ordered as 65MPa. 465µm less displacement was exhibited in columns cast from concrete batch 2 when compared to concrete batch 1. It is assumed that a smaller load would yield a smaller displacement of reinforcement. The large drop in maximum load suggests that more restraint is necessary for the GFRP bars to be most effective. Either small tie spacing or higher strength concrete must be provided to give this restraint.

FRP Min Columns

The summarised data from the FRP Min columns is displayed in Table 7.

Table 7 Average FRP Min Data.

Column – Average	Max Load – Average (kN)	Max Stress – Average (MPa)	Displacement – Average (µm)
FRP Min 50	989.0	38.6	1539.5
FRP Min 65	917.3	35.8	1656.1

The 5MPa decrease in concrete strength only yielded a 3MPa reduction in the column capacity. It can also be seen that the displacement was increased by 115µm. This goes against the thought that with higher load comes higher displacement. Whilst the average displacement has risen it is only by approximately 7%. This is not a large increase and could be due to factors relating to the proximity of failure with relation to the proximity of strain gauges.

The decrease in load capacity of the column from concrete batch 1 to concrete batch 2 was expected and in line with the reductions seen in the steel reinforced columns. This indicates that the use of smaller tie spacing has provided the restraint necessary to protect the GFRP bars from premature failure. These results could lead to maximum tie spacing requirements for compression members reinforced with GFRP bars being adopted as at approximately half that of the maximum tie spacing for steel reinforced columns.

10mm Steel Columns

The average loads and capacity of the 10mm Steel columns, along with the average reinforcement displacements are presented in Table 8.

Table 8 Average 10mm Steel Data.

Column – Average	Max Load – Average (kN)	Max Stress – Average (MPa)	Displacement – Average (μm)
10mm Steel 50	958.5	37.4	1676.0
10mm Steel 65	919.4	35.9	1553.8

For the 10mm Steel columns, a 5MPa drop in concrete strength resulted in a 1.5Mpa drop in column capacity and a 120μm reduction in reinforcement displacement. The reduction in load is as expected and solely due to the reduction in concrete strength. All 10mm Steel columns failed with rupture of tension or compression side reinforcement. This indicates that the displacements should be similar (as was the case) for both sets of columns. The locations of failure are similar between columns cast from concrete batch 1 and columns from concrete batch 2. This suggests that the reinforcement displacement should be similar. The 7% reduction in displacement may be attributable to the lower concrete strength providing less resistance to the longitudinal reinforcement. This results in a small decrease in column compressive capacity and of the reinforcement displacement.

12mm Steel Columns

The average data recorded through compression testing of the 12mm Steel columns is shown in Table 9.

Table 9 Average 12mm Steel Data.

Column – Average	Max Load – Average (kN)	Max Stress – Average (MPa)	Displacement – Average (μm)
12mm Steel 50	1101.3	43.0	1745.6
12mm Steel 65	1027.0	40.1	1395.6

The reduction in concrete strength yielded a decrease in column capacity and a decrease in reinforcement displacement, as expected. It is noted that the 12mm Steel 50 columns reached the characteristic strength of the concrete before failure occurred, whilst the 12mm Steel 65 columns slightly exceeded the characteristic strength of the concrete. This suggests that the reinforcement allowed the concrete to reach its full potential before failure occurred. This decrease in load is expected as a direct result of lower concrete strength.

The reinforcement displacement suffers a large decrease with decrease in concrete strength. This is because the 12mm Steel 65 columns failed due to concrete crushing before the stresses within the reinforcement were large enough for them to fail. This explains why the displacement of the reinforcement in these columns was not higher, because they did not fail.

Failure Modes

The main failure modes observed were rupture of compression bars, rupture of tension bars, rupture of both compression and tension bars, or failure due to concrete crushing. Table 10 presents a summary of the failure modes exhibited by the columns.

Table 10 Failure Mode Summary.

Column	Compression Side Bar Rupture	Tension Side Bar Rupture	Both Side Bar Rupture	Concrete Crushing
Concrete Batch 1	4	2	4	1
Concrete Batch 2	1	8	0	3
Total	**5**	**10**	**4**	**4**

GFRP Reinforced	4	6	1	0
Steel Reinforced	1	4	3	4

There is one column omitted from these results because the test was performed incorrectly.

FRP Min 50 (2) was the only column to have a rupture within a tie. This rupture was assessed to have been caused by the rupture of the compressive bars at the connection to the tie. The force exerted from the compressive bar failure is assessed as having caused the tie to rupture as well.

It was expected that most failures would be as a result of rupturing of the tension bars. This was the case in ten of the 23 columns. This is because the majority of the compressive loads were taken by the concrete and the reinforcing bars were only in place to combat any tension within the columns.

Compression bar rupture was expected in some cases as the bars on the compression side are bent due to the eccentricity of the load. The tensile strength of the reinforcement can be exceeded due to this, and in five cases, compression bar failure occurred. Even though the bars on the compression side of the column failed, their failure mode was in tension.

Concrete Crushing was observed in four columns, all with 12mm steel reinforcing. It occurred in the three 12mm Steel 65 columns because the compressive strength of the column exceeded the compressive strength of the concrete alone, therefore causing the concrete to crush preferentially. This was also the case with 12mm Steel 50 (2).

Overall Column Comparison

Theoretically, the GFRP column cross sections were similar in compressive capacity to the cross sections of the 12mm Steel columns. This is due to the higher tensile strength of the GFRP reinforcement. Using the Rectangular Stress Block method and assuming 40MPa concrete, a capacity of 1100kN was predicted for both GFRP reinforced columns and the 12mm reinforced steel columns. This prediction was not supported by analysis software, which predicted an ultimate load capacity of 900kN for the GFRP columns and of 1100kN for the 12mm Steel columns. It is clear that the calculations used by the software places higher emphasis on the Modulus of Elasticity than does the Rectangular Stress Block method.

Analysis software and the Rectangular Stress Block method predicted the same outcome for the 12mm Steel Columns. This was again the case with the 10mm Steel columns with both predicting failure at 1000kN. The comparison between the 10mm Steel columns and the FRP Max columns is important as it showed the effects of direct replacement (equal volumes) of steel with GFRP bars.

Testing has shown that whilst theoretically the cross sections are the same for the 12mm Steel and the GFRP reinforced columns, they do not yield the same load in practice. In addition it was found that the direct replacement of steel with the same area of GFRP does not achieve the same ultimate capacity, unless closer tie spacing is adopted.

Due to the very similar statistics shown in Table 11 concerning the FRP Min and 10mm Steel columns, a two sample, unequal variance T test was carried out using all data recorded. This test assesses the probability, with 95% confidence, of a group of data being from populations with the same mean value and can be accurately carried out as each data point is independent of the others. The null hypothesis being tested is that 'The two sample populations have an equal mean.'

Table 11 Column Statistics.

Column Type	Mean (kN)	Standard Deviation (kN)	Coefficient of Variance (%)
FRP Max	844.0375	78.48	9.30
FRP Min	953.1645	44.805	4.70
10mm Steel	938.9547	30.669	3.27
12mm Steel	1064.129	70.932	6.67

The T test is performed using complex functions of the mean and standard deviation of both sets of data. The T test indicated a 65% chance that the null hypothesis is correct. That is, there is significant support for a conclusion that very similar performance of the sample groups can be expected. This provides statistical support for the conclusion that the FRP Min columns have very similar capacity to the 10mm Steel columns, which had the same area of longitudinal reinforcement. The similarities in capacities and displacements within the columns can be seen in Figure 2 below.

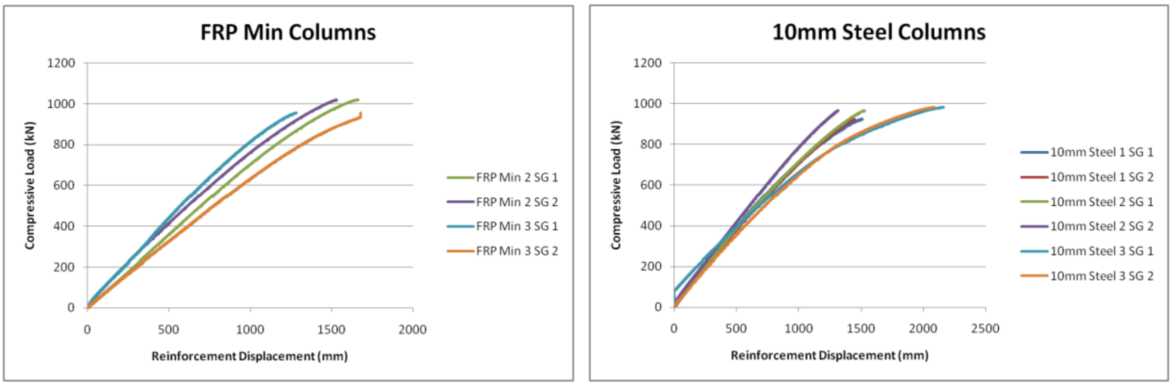

Figure 2 Load vs Reinforcement Displacement for 50MPa Columns.

Corrosion Test

The results of GFRP bars and steel bars submerged in various solutions for testing of mass loss due to corrosion can be seen in Table 12. This includes the weight before testing was undertaken, the weight after 45 days being submerged, and the total mass loss due to corrosion.

Table 12 Corrosion Test.

	GFRP Bars			Steel Bars		
Testing Solution	Weight at Day 0 (g)	Weight at Day 45 (g)	Weight Loss (g)	Weight at Day 0 (g)	Weight at Day 45 (g)	Weight Loss (g)
Distilled Water	20.5	20.5	0	109.1	109.1	0
Sea Water	22.3	22.3	0	109.8	108.9	0.9
Salt Solution 1 (10.1%)	20.9	20.9	0	161.2	160.2	1.0
Salt Solution 2 (19.8%)	21.0	21.0	0	157.2	155.9	1.3
Salt Solution 3 (32.4%)	19.9	19.9	0	109.4	107.3	2.1

As expected, no mass loss was recorded for the GFRP bars. One of the key properties that makes GFRP bars so appealing as reinforcement for concrete structures is its corrosion resistance.

There is no corrosion taking place on the steel bar in distilled water as there is no dissolved oxygen in distilled water. Rusting occurred in all four other tests for steel. In all of the salt solutions there was water and oxygen present, the two materials needed for rusting to occur. The variation of salt clearly helped to speed up the reaction as the chloride ions help to speed up the transfer of electrons from the anode to the cathode. It can be seen that with increasing levels of salt, the speed at which corrosion takes place increases. This is an expected result as there are more chloride ions free to aid in the transfer of electrons.

The sea water solution was used to simulate exposed steel near the ocean. This still exhibited a 0.9g loss for steel over a short 45 day period. Whilst this is less than 1% of the material, when these results are extrapolated over a long period of time, significant damage can be expected to the reinforcement and the structure it is reinforcing.

Whilst these results do not provide an accurate rate of corrosion or percentage loss of mass, they provide an accurate comparison between steel bars and GFRP bars when subject to salt water. Steel will corrode while GFRP bars will not.

COST COMPARISON

The material costs are summarised in Table 13. They present the costs incurred for individual materials and the cost of reinforcement for an entire column with maximum tie spacing. Prices are inclusive of GST.

Table 13 Material Cost Comparison.

Item	GFRP Cost	Steel Cost (UWA Structures Laboratory)	Steel Cost (Steel Fabricator)
Longitudinal Bars	$1.65 per m	$1.40 per m	$5.28 per m
Ties	$2.31 per tie	$1.70 per tie	$6.60 per tie
Total Reinforcement	$33.00	$25.40	$97.68

The costs for the GFRP reinforcement were obtained from an official quotation provided by a GFRP distributor in Australia. The steel costs were provided via verbal quote from the University of Western Australia Structures Laboratory. A West Australian Steel Fabricator was also invited to quote on the materials and their cost can also be seen in Table 13.

The material costs of the reinforcement for one column with maximum tie spacing is $7.60 more when using GFRP reinforcement compared to steel reinforcement. The majority of this ($6.10) was incurred from the manufacture of the ties. The increase in time for production and labour costs are, due to the small diameter, are the reasons for the high price.

It took eight hours to form the twelve GFRP reinforcement cages. This included the use of 48 longitudinal bars and 174 ties. By comparison, it took ten hours to form the twelve steel reinforcement cages, which included 48 longitudinal bars but only 120 ties. The lightweight material allowed for significantly faster construction. It is expected that this could be realised in the construction industry and has the promise of saving large amounts of time and labour due to the ease of working with GFRP reinforcement.

Even with a 30% mark-up on material cost, the 20% reduction in labour time and costs would create equivalence. This is before consideration of maintenance and design life, which is the basic compelling reason for adoption of a GFRP reinforced option.

CONCLUSIONS

The objective of this study was to further the knowledge of concrete compression members reinforced with GFRP bars. The research performed was aimed at determining the compressive capacity, reinforcement displacement and failure modes of the members. In addition, the study aimed to further the development of future construction guidelines and standards through presenting recommendations for the use of GFRP bars in compression members. The results of laboratory tests lead to the conclusion that use of GFRP reinforcement in compression members instead of traditional steel reinforcement is technically and financially viable (subject to full scale check). Although the direct replacement of steel reinforcement with GFRP reinforcement does yield a marginally lower compressive capacity, the GFRP reinforced columns are, provided that ligatures are used at 75mm centres rather than 150mm centres, of comparable capacity to steel reinforced columns with similar area of main reinforcement.

It is evident that with the direct replacement of steel with GFRP, the failure mode of the column is more explosive. This is assessed as due to the low modulus of elasticity of the GFRP bars. Tie spacing is an important design factor when using GFRP reinforcement in compressive members. Experimental work has shown that the compressive capacity significantly increased as the tie spacing decreased.

The corrosion tests performed prove that GFRP bars are not subject to the same type of corrosion displayed by steel. A compelling case could be made for their use in jetty structures where environmental conditions are harsh and the major design condition is bending and axial stress.

With the low level of research devoted to GFRP reinforcing in concrete compression members, combined with the results of this study relating to ductility of the reinforcement, failure mode of the member and warning before failure, it is suggested that somewhat higher safety factors be employed when designing GFRP reinforced members.

Cost comparison indicates that the use of GFRP bars can be quite cost effective. Whilst the GFRP materials do incur an increased start-up cost, the decrease in labour time and cost, due to the low weight material being easy to work with, is compensatory. The significant decrease in maintenance costs will make this product a valuable material in the long term as the effects of corrosion with associated structural degradation can be confidently expected to be absent.

It is concluded from an overview of the results obtained in this experimental investigation, that the use of GFRP reinforcement in concrete compression members is a technically adequate alternative to the use of steel. Design of structures using GFRP will need to be cognisant of the need for closer ligature spacing to achieve parity with steel. The use of GFRP reinforcing bars is not isolated to but will be most beneficial in environments of high corrosion to lower the lifetime cost of the structures.

Dundas Point Boardwalk

The research performed in 2012 led to the first implementation of GFRP reinforced concrete compression members in Australia. The Dundas Point Boardwalk in Applecross was upgraded utilising GFRP bars in the concrete columns to replace the previous corroded concrete encased steel columns. It is now expected that the columns will have a serviceable life in excess of 75 years, significantly longer than the 23 year life which was achieved with the previous steel columns.

Figure 3 Dundas Point Boardwalk – Upgrade Completed

REFERENCES

ACI Committee 440, 2006, "Guide for the Design and Construction of Structural Concrete Reinforced with FRP Bars (ACI 440.1R-06)," American Concrete Institute, Farmington Hills, MI, 44 pp.

Alsayed, S. H.; Al-Salloum, Y. A.; Almusallam, T. H.; and Amjad, M. A., 1999, "Concrete Columns Reinforced by GFRP Rods," *Fourth International Symposium on Fiber-Reinforced Polymer Reinforcement for Reinforced Concrete Structures*, SP-188, C. W. Dolan, S. H. Rizkalla, and A. Nanni, eds., American Concrete Institute, Farmington Hills, MI., pp. 103-112.

Deitz, D. H.; Harik, I. E.; and Gesund, H., 2003, "Physical Properties of Glass Fiber Reinforced Polymer Rebars in Compression," *Journal of Composites in Construction*, ASCE, V. 7, No. 4, Nov., pp. 363-366.

Standards Australia, 2009, AS3600 Concrete Structures, Standards Australia International, Sydney.