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# STRENGTHENING CONCRETE BEAMS USING FIBRE REINFORCED POLYMER

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**Abstract**
In the last decade, the use of fibre reinforced polymers (FRP's) as a preferred method of retrofitting existing structures has dramatically increased. This has brought about improvements in the mechanical properties of the materials and greater options for engineers and designers. This research has determined the most suitable fibre material to provide a maximum increase in structural performance at the lowest possible cost. Carbon fibre sheet and yarn were used. A unidirectional CFRP sheet and CFRP wrapped yarn had a cotton sheath attached that was been designed to promote resin impregnation and thus improved bond performance, dependant upon the viscosity of the glue used.

The test methodology was to statically test concrete beams with surface applied FRP to comparatively examine the flexural strength and toughness (energy absorption). Sixteen beams were manufactured, eight with rebar and eight plain. Carbon fibre sheet and carbon fibre yarn was applied to all beams in equal proportions. The theoretical moment capacity was calculated for the steel reinforced beams using Eurocode 2 and compared against the actual moment capacity derived from the three point loading test.

The findings displayed a tendency for higher flexural strength, moment capacity and toughness (energy absorption) due to the surface application of FRP composite sheet and yarn. The carbon fibre sheet provided the most suitable form of retrofitted reinforcement. However the loose yarn was 25% cheaper than the sheet and may be a consideration where maximum performance is not an issue. The beam performance was dependant upon the effective epoxy bond and between the carbon fibre sheet and the concrete surface and this is a key area for further research.

Key words: Fibre reinforced polymer sheet and yarn, toughness, flexural strength, cost

## 1.0 Introduction

The need for increasing the capacity of a structural element is founded in the real world, where the use or condition of a building/structure changes over a period of time. An example of this is the modern railway system where bridges were designed to carry the load from trains half the weight or less than the ones used today; which are supported by the same infrastructure. A change of use of a building may require additional floor loading to be accounted for, or where structures have marginally deteriorated, a means of remedying the situation without rebuilding or replacement of the structural element has the advantage of lower cost and little disruption to the operation of the structure/building (Jeslin and Woo, 2009).

Priestley and Seible (1996) first noted the suitability of fibre reinforced polymers with regard to seismic retro-fitting. The use of 'composite materials as an alternative for steel jacketing for enhanced shear strength, flexural ductility and lap slice performance'. This suggests FRP's may be suitable for seismic retro-fitting. In the last decade, the use of fibre reinforced polymers (FRP's) as a preferred method of retrofitting existing structures to increase the toughness (energy absorption) and flexural load bearing capacity has dramatically increased. This has brought about improvements in the mechanical properties of the materials and better working practices with regard to the glue used for fixing. Furthermore, a reduction in price has occurred due to the material's wider application, due to economies of scale. This research will aim to determine the most suitable material to provide maximum increase in structural performance using carbon fibre sheet and yarn.

Methods of seismic design often employed in first world countries include the use of steel framed buildings and dampening technology (Vijay, 2011). Despite the wide application of this technology in countries such as the United States of America and Japan, it still remains unattainable in the majority of third world countries due to the high financial cost of such methods. As a result, in these countries, concrete - inexpensive and readily available - forms the material most predominantly used in construction. However, whilst concrete has good compressive strength it has relatively low tensile and flexural strength (Nilson et al, 2010:1) which under high stress can lead to collapse disproportionate to its cause.

Having established that FRP's could potentially provide an economically viable solution to increasing earthquake resilience, consideration must now be made to which fibre is most appropriate for the purpose of this research. There are different fibre reinforced polymers most commonly used for reinforcing concrete: carbon, aramid and glass. Table 1 details (shaded area) the properties of the carbon fibres used in this research.

Table 1: Typical Dry Fibre Properties
(The Concrete Society, 2004)

| **Fibre** | **Tensile Strength (N/mm²)** | **Modulus of Elasticity (kN/mm²)** | **Elongation (%)** | **Specific Density** |
|---|---|---|---|---|
| **Carbon: high strength** | 4300-4900 | 230-240 | 1.9-2.1 | 1.8 |
| **Carbon: high modulus** | 2740-5490 | 294-329 | 0.7-1.9 | 1.78-1.81 |
| **Carbon: ultra-high modulus** | 2600-4020 | 540-640 | 0.4-0.8 | 1.91-2.12 |
| **Aramid:** | 3200-3600 | 124-130 | 2.4 | 1.44 |
| **Glass** | 2400-3500 | 70-85 | 3.5-4.7 | 2.6 |

From analysis of Table 1 it can be deduced that whilst aramid fibres provide adequate performance, the carbon fibre provides better material properties.

Figure 1 shows that the tensile properties of high strength carbon fibres are far greater than that of aramid fibres. Tensile properties are of critical importance because, as previously noted, concrete has a relatively high compressive strength but low tensile strength. Consideration must now be given to the cost of these fibres to determine which can provide the greatest strength increases at the lowest cost.

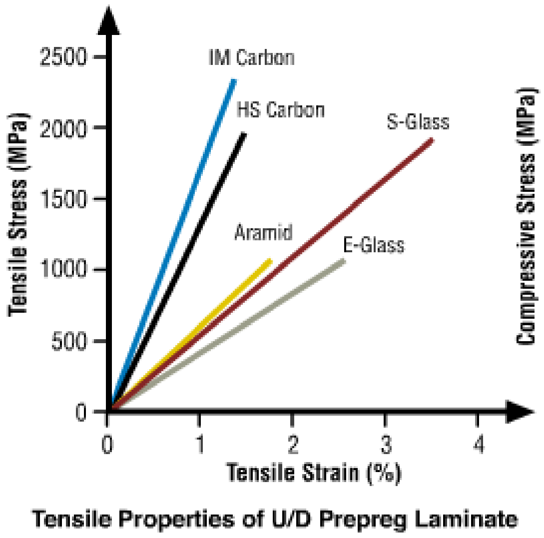

Figure 1: Comparison between Tensile Strength of Material Fibres. (Gurit, 2012)

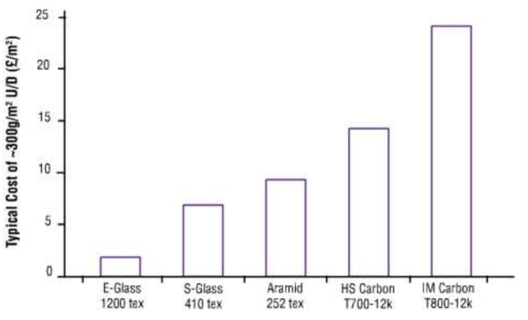

Figure 2: Cost Comparison of Fibres (Gurit, 2012)

Figure 2 shows the current (2012) typical cost of one m² of each type of carbon FRP and high strength carbon fibre which is more expensive than glass and aramid fibres. As previously noted in Table 1 and Figure 1 the mechanical properties of high strength carbon fibre are greater, which may be value for money in the longer term. The cost of carbon fibre sheet is 25% more expensive to purchase than carbon fibre yarn.

Nilson et al (2010) deduced that there are two possible methods for dealing with the forces acting on a structure due to ground motion. These are either: to provide a lower strength structure that has the ability to withstand in-elastic deformations whilst maintaining their vertical load carrying equipment; or alternatively, to provide adequate stiffness and strength to limit the response of the elastic range. The retro-fitting of existing building stock is an area where the use of FRP's may provide adequate strength and stiffness for many types of construction.

## 2.0 Test Methodology

The concrete batching was carried out using a rotary drum mixer. The mix design is in accordance with BS EN 12390 – 2:2009 and Table 2 shows the mix design used.

Table 2: Concrete Mix Design

| **Material** | **Design Mix (kg/m³)** |
|---|---|
| Cement - CEM 1 | 403 |
| Sand – coarse < 4mm | 837 |
| Gravel – crushed gravel 12mm angular | 987 |
| Water – BS EN 1008:2002 | 0.5 |

This mix design, as detailed in Table 2, was selected to represent structural concrete of characteristic design strength of C35.

This mix was utilised in the production of sixteen beams measuring 500mm x 100mm x 100mm. Half of the beams were reinforced with steel rebar, thus extending the application of this research. The re-bar was a single 6-mm-diameter type-T steel with a characteristic strength of 500 N/mm$^2$ and the cross-sectional area of the steel reinforcement bar was measured against the cross-sectional area of the beam and it was found to make up 0.79% of the total cross-section. An outline of the methodology to be undertaken for testing is displayed in Figure 3.

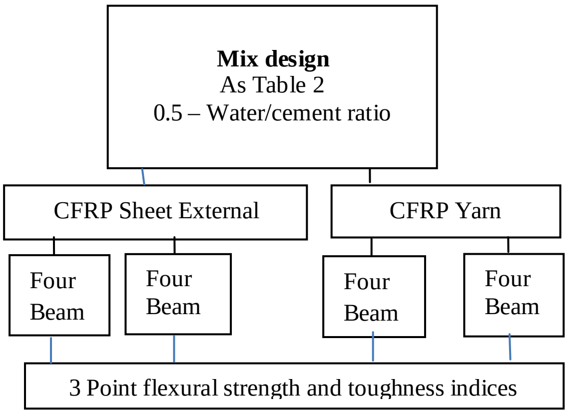

Figure 3: Outline of test methodology

To ensure that the CFRP's achieve a satisfactory bond to the carbon fibre, the concrete surface was prepared prior to the application of the resin. To prepare the surface, a wire brush was used to remove cement laitance, loose and friable material and to achieve an open textured surface. A vacuum cleaner was used to remove any dust, as this would reduce the bond strength. Once the beams were prepared, the resin was mixed and used to bond the CFRP to the beams within the manufacturers permitted working time allowance. The resin was then allowed to cure for seven days at room temperature (18 - 20°C).

The samples were prepared prior to undergoing a centre point load test using Lloyds apparatus with an applied rate of strain of 1.0 mm per minute, under a three point load arrangement as detailed in Figure 4. The flexural strength was calculated in accordance with BS EN 12390-5:2009.

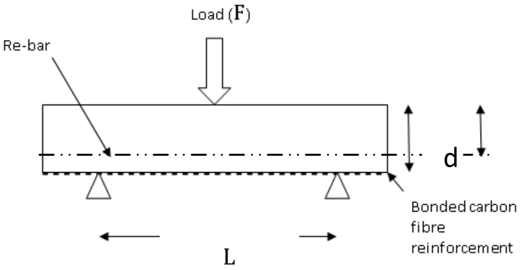

Figure 4: Three Point Flexural Strength Test

The point at which the strain imposed on the beam causes the concrete to crack must be accurately measured to facilitate a precise calculation of the flexural strength of the concrete. The only effective way of ensuring this is with the use of ultrasound. During the three point test, ultrasonic transducers were held at each end of the beam allowing direct transmission of ultrasonic pulses through the beam, highlighting the time at which the first internal crack occurred. Once the concrete had cracked, the load continued to be applied to the beam until the deflection reached 10.5 times the deflection at which the first crack occurred. This is in accordance with ASTM 1018 and, although this standard is no longer current, as the behaviour of the carbon fibre is unknown it is best to determine a point at which the test should be terminated and ASTM 1018 provided this test boundary.

When the beams underwent the three point flexural strength test, the load deflection was recorded by the Lloyds machine this is shown representatively in Figure 5. Through the analysis of load deflection graphs the mechanical properties of the beam can be determined with regard to relative toughness.

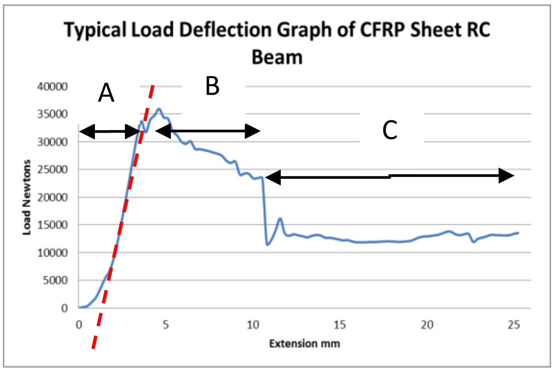

Figure 5 - Load deflection chart CFRP sheet RC Beam

Figure 5 depicts a typical load/defection graph of a reinforced concrete beam with an additional reinforcement in the form of an externally bonded CFRP sheet. A secant line (hatched red) was used to determine the deflection to first crack load based upon ASTM 1018 as shown in Figures 5 and 6.

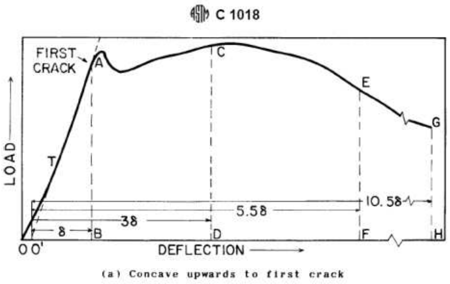

Figure 6 – Load deflection chart displaying toughness indices parameters (Taken from ASTM 1018)

Through the analysis of this load/deflection chart (Figure 5), it is possible to gain an understanding of how the load is being applied to the beam. Initially the load placed on the beam is supported by the concrete and this continues until the concrete yields (A). Whilst the stress induced on the beam by the three point test is supported by the concrete, the graph is linear. Beyond the point at which the concrete yields, the stress induced by the apparatus is supported by the steel reinforcement bar (B) and CFRP sheet, then once the steel reinforcement loses its structural integrity the stress is transferred to the CFRP sheet external reinforcement and this continues to support the load placed upon it without reaching ultimate failure at (C), defined at the ASTM maximum toughness parameter as Figure 6.

## 3.0 External reinforcement

A unidirectional CFRP sheet had a cotton sheath attached that was been designed to promote resin impregnation and thus improved bond performance. The carbon fibre sheet and yarn was externally bonded, to the concrete beams, using a two part epoxy impregnation resin. The CFRP sheet covered the entire area of the tensile face of the beam and the remaining beams had fifteen strands of yarn bonded along the length of the tensile face. The fibres of the unidirectional carbon fibre sheet were bonded parallel to the length of the beam, to resist the tensile forces.

The yarn was examined with an electron scanning microscope as shown in Figure 7 where the carbon fibre is clearly visible in the centre of the cotton surrounding fabric.

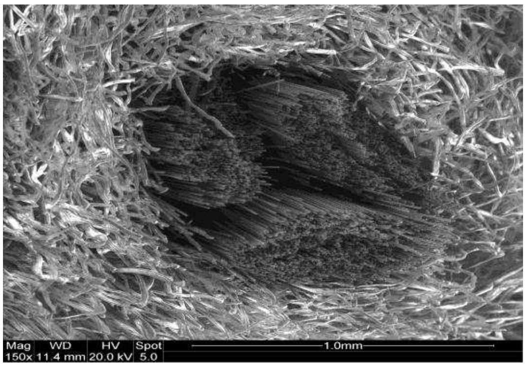

Figure 7 – End detail of yarn at magnification 150x

There are a variety of available methods for bonding fibre reinforced polymers to concrete structural members and include such methods as wet lay-up systems, pre-cured systems and near surface mounted systems. The most appropriate method of bonding for this research is wet lay-up systems as the simple installation method will further reduce the overall cost. Furthermore, it is more suitable than the other two methods as the CFRP will be easier to cut on site. Wet lay-up consists of on-site impregnation of fibre sheets or fabrics with a saturating resin. This resin provides both a binding matrix for the fibre and a bond to the concrete surface. An example of this bond method can be seen in Figure 8.

Figure 8 – Wet lay up CFRP application

Sikadur 330 epoxy resin was used as a bonding agent to the prepared concrete surface.

## 4.0 Results

The first crack and maximum load supported by the beam was used to calculate the flexural strengths of the beam. The external reinforcement increased the overall flexural strength of the concrete beam at maximum load.

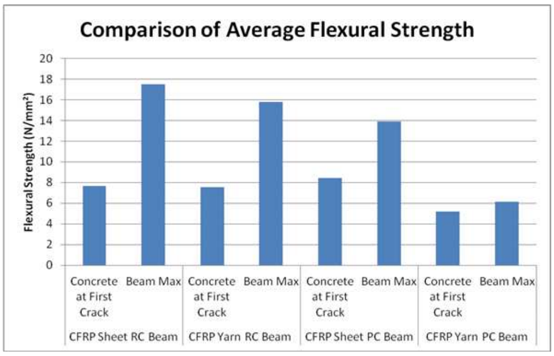

Figure 9: Comparison of Average Flexural Strength of Concrete at First Crack and Maximum Achieved by the Beam

Figure 9 illustrates the average concrete first crack flexural strength achieved by each of the samples, which has a low standard deviation of 1.3 across the range. The actual first crack flexural strength of the concrete is very similar across the range of samples as tested. The difference in performance is observed with the use of different CFRP materials at maximum load.

The concrete used had a characteristic strength of 35 N/mm$^2$, and it would be expected the flexural strength would be in the region of 3.5 to 4.0 N/mm$^2$ based upon this value, however all of the beams achieved a significantly higher flexural strength with the exception of the first crack plain yarn covered beam. The yarn covered beam still achieved a greater flexural strength than that expected based upon the compressive strength but not a high as the other beams. The difference in the mode of failure for CFRP sheet and yarn was sudden and gradual respectively. The yarn showed signs of slippage that may be attributable to incomplete saturation of the carbon fibre bundles within the yarn from observations made during and after the test. Yarn has the potential for providing residual strength at large deflections, when compared to CFRP sheet by providing a slower failure mode with higher strain capability.

The greatest beam flexural strength has been achieved by the CFRP sheet RC beam. It can be seen that the largest flexural strength of concrete at first crack is achieved by CFRP sheet PC beam; this can be attributed to the absence of an internal reinforcement (steel bar) coupled with a strong external reinforcement. The reduced performance of the CFRP yarn is notable when analysing the results.

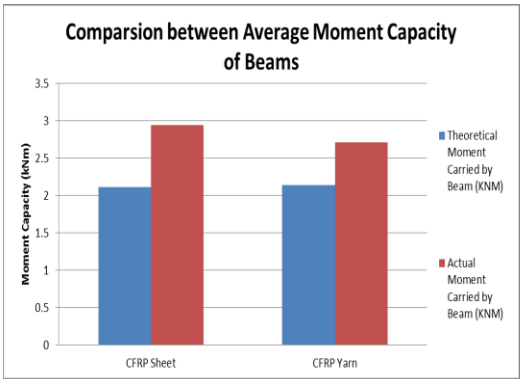

Figure 10 – Comparison between Average Moment Capacity of Steel and CFRP Reinforced Beams

The average percentage increase in moment capacity as shown in Figure 10 is a result of the external reinforcement is 27% for the CFRP sheet external reinforcement and 21% for the CFRP yarn reinforcement. A 6% performance differential may make the 25% cost differential for the yarn attractive. The addition of external bonded fibre reinforced polymers can increase a structures capacity to withstand additional loading.

Paired comparison tests(T tests) were used to draw a statistical comparison between the maximum flexural strength of concrete at first crack and the flexural strength of the beam. The null hypothesis only applied for the plain concrete beam reinforced with carbon fibre yarn. Therefore significant increases were made in the three other sample groups as a result of the external reinforcement.

## 4.1 Toughness indices (energy absorption)

The toughness indices which are based upon stress and strain measurements, can be defined as a measure of the energy absorption/dissipation capacity of the beam. Toughness and energy absorption/dissipation is measured by calculating the area beneath the load deflection graph. The total area (OAB as Figure 6) under the graph is divided by the initial area from the test commencing until failure or 10.5 x δ is achieved. Hence the toughness indices quantify the energy absorption capacity in relation to the initial strength of the material as shown in Figure 11.

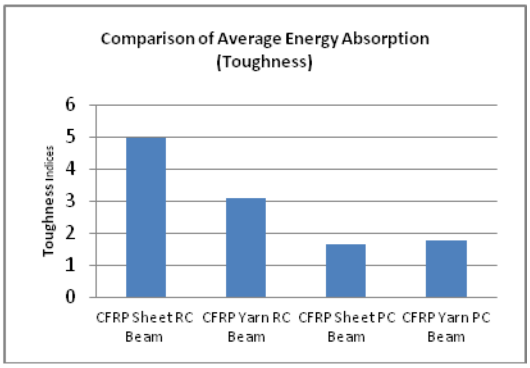

Figure 11- Comparison of Energy Absorption (Toughness)

The test shows that large increases in flexural strength were achieved with the use of carbon fibre external reinforcement. Due to the high flexural strengths the toughness values were not as high as would be expected using normal flexural strength concrete, because of the way toughness is calculated. Toughness and energy dissipation is an important parameter when considering seismology as increased toughness/ energy dissipation can reduce the probability of structural collapse, consequently providing increased safety to occupants residing within a building in the event of an earthquake.

## 5.0 Conclusion

The purpose of this research was to propose new, affordable methods of increasing the structural performance of existing concrete buildings by retro-fitting. The proposed method for achieving this was the application of fibre reinforced polymers to existing structures.

Laboratory testing provided conclusive evidence that the application of externally bonded CFRPs could provide increases to the flexural strength of concrete members. A statistically significant increase was observed for the samples; CFRP sheet RC Beam, CFRP Yarn RC Beam and CFRP sheet PC Beam. This shows that the application of a CFRP sheet is the most structurally effective reinforcement for providing increases in flexural strength.

The application of externally bonded CFRPs provided some strength after failure in all of the sample groups. When analysing the average toughness indices, the greatest toughness was achieved by the CFRP sheet RC.

An increase in moment capacity of twenty seven percent was achieved by the CFRP sheet and twenty one percent for the CFRP yarn. The CFRP sheet is most appropriate form of carbon fibre when considering improving the structural performance of concrete structures.

The cost differential between sheet and yarn was 25% and this may be a worthwhile cost saving if a lower structural performance was permissible. With regard to the ease of application, the CFRP sheet is a clear first choice.

Further work should be carried out to test the effectiveness of the cotton covering used to provide a glue reservoir and provide additional bond. When considering the use of carbon fibre FRP to increase tensile capacity, care must be taken not to over reinforce the beam or slab to the extent where compressive failure may occur. This was not observed during this test.

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