Fibre reinforced polymer grids as shear reinforcement in fabric formed concrete beams.

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ABSTRACT

Steel reinforced concrete is perhaps our most widely used man-made material (approximately 1.5m^3 of concrete[1] and 23kg of deformed steel bar[2] were produced for every person on the globe in 2008) and whilst its constituent materials are widely and readily available, cement manufacturing is estimated to account for some 3% of global carbon dioxide emissions[3]. Recent research[4] has suggested that as much as 40% of the concrete used in new office buildings does little but increase structural deadweight, adding credence to the motion that concrete should be cast in optimised elements whose final form is determined by the requirements of their loading envelope.

Using fabric formwork, it is possible to cast architecturally interesting, structurally optimised shapes based on simple design rules and research has shown that material savings up to and in excess of 30% can be achieved[5]. Whilst fabric formwork offers unique opportunities for the design of low embodied energy concrete structures, the provision of transverse reinforcement in non-prismatic elements can be complex and may lead to increased construction cost.

This paper reports on recent research in which fully and partially resin coated carbon fibre reinforced polymer (CFRP) grids have been used in place of conventional steel stirrups as shear reinforcement. The results of both feasibility studies and full scale structural testing are presented, wherein the concept is successfully demonstrated. The application of current shear design methods to advanced composite reinforcement is discussed before opportunities for further work are highlighted.

INTRODUCTION

It can readily be seen that when subject to a uniformly distributed load, a prismatic steel reinforced concrete beam with constant longitudinal and transverse reinforcement percentages is inherently inefficient. However, by following a simple optimisation routine (such as that described by Figure 1) it is possible to design beams whose flexural and shear capacities reflect the requirements of the loading envelope applied to them. Such elements tend to be non-prismatic.

The widespread use of optimised structures, which offer immediate opportunities for reductions in embodied carbon, may previously have been hampered by two factors. First, the behaviour of tapered reinforced concrete beams in shear is not well addressed in most design codes of practice[6]; and second the construction of non-prismatic elements is often deemed to be complex and therefore expensive. As a result, fluid concrete tends to be cast into zero-deflection orthogonal moulds, and in doing so designers fail to capitalise on its inherent ability to take up almost any shape.

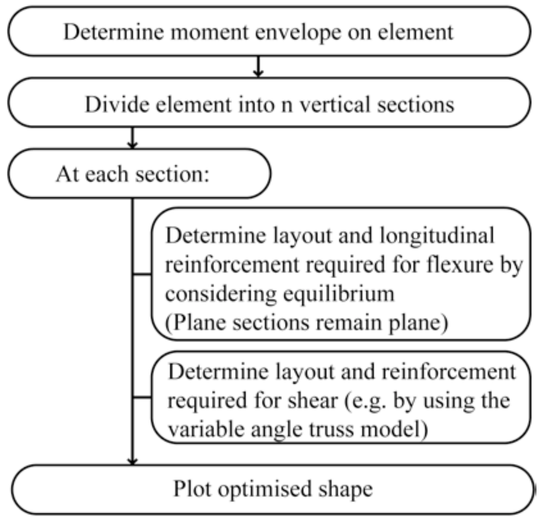


Figure 1. Optimisation routine for a simply supported reinforced concrete beam.

Fabric formwork

Fabric formwork describes a method of construction for concrete elements in which rectangular sheets of fabric are used in lieu of steel or timber moulds. Originally used in the construction of underwater structures, fabric formwork allows complex shapes to be easily cast, thus facilitating the construction of optimised structures.

Architecturally, work is underway around the world to develop systems for the design of fabric formed elements. In Japan, Kenzo Unno's 'zero waste formwork' system for concrete walls uses just two sheets of fabric as formwork[7], while in North America fabric tubes and bags are commercially available for the construction of circular columns and footings. Perhaps most influential of all is the work of Professor Mark West and his team at the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba, Canada, where the use of fabric formwork for beams, trusses, panels, shells and walls[8-10] continues to be explored (Figure 2).

In addition to architectural applications, by casting concrete into a permeable membrane excess pore water is allowed to bleed from the concrete during curing. The resulting reductions in the surface zone *water:cement* ratio thus bring improvements in durability (as documented elsewhere for controlled permeability formwork[11, 12]).

Figure 2. Fabric formwork (images courtesy Mark West, CAST).

In contrast to the architectural developments described above, there has been relatively little research undertaken into the structural behaviour of fabric formed steel reinforced concrete beams. Although some of the available test data[13, 14] suggests a propensity for variable section beams to fail in shear, work by the author has indicated that in some cases shear failures in optimised concrete beams may be avoided through the application of the BS EN 1992-1-1[6] variable angle truss model.

Whilst this has been successful, the recent construction and subsequent testing of 4m span structurally optimised double 'T' beams by the author required that a large number of links be fabricated, each of which was replicated four times, as illustrated in Figure 3.

Given that the variation in depth between neighbouring links is relatively small, the fabrication method shown in Figure 3 may lead to an increase in the risk of erroneous construction. It would therefore be advantageous to introduce a new process by which a variable depth reinforcement cage could quickly and easily be manufactured. One solution may be provided through the use of flexible, high strength, carbon fibre grids, as discussed below.

Figure 3. 4m span double T beam construction

SHEAR BEHAVIOUR

The behaviour of concrete structures in shear is arguably yet to receive a fundamental solution and American and European design codes continue to rely on empirical formulae in some situations[6, 15], although alternative design methods are available[16, 17]. In Europe, the variable angle truss model[6] has been adopted for the shear design of transversely steel reinforced concrete beams, while empirical formulae are used to assess the shear capacity of transversely unreinforced concrete beams. The variable angle model is derived from original work undertaken over 100 years ago by Ritter[18] and Mörsch[19] and is widely accepted as a convenient method for the shear design of ductile steel reinforced concrete structures.

However, the applicability of such a model to structures transversely reinforced with materials that display linear elastic behaviour is less clear, as described by Ibell and Burgoyne[20]. In structures reinforced in both flexure and shear with advanced composites the truss model is therefore not considered to be a theoretically suitable design method, although experimental results suggest that its use can be successful in some situations[21].

In beams using advanced composites as transverse reinforcement, there may be an opportunity to provide ductility to the system by using steel bars as flexural reinforcement. Provided that the strain in the composite material is less than its failure strain, then such a beam may behave in a generally similar manner to one transversely reinforced with steel.

Perhaps the most important behaviour to consider when using CFRP as transverse reinforcement is its bond to the surrounding concrete. An infinitely strong bond is not desirable, as small cracks will precipitate the local development of large strains and the bar will fail[22]. It may therefore be preferable to have a partially bonded system in which the bar is able to strain over a greater length.

In the following, it will be premised that by using conventional steel reinforcement for flexure, adequate ductility can be provided such that the variable angle truss model may be used for the design of advanced composite transverse reinforcement, provided it has an intermittent bond to its surrounding concrete and adequate anchorage at its ends to allow vertical force capacity to be generated.

Carbon fibre grids.

Carbon fibre reinforced polymer grids are often used in place of welded wire steel mesh in architectural panels, prismatic beams[23] and retro-fit applications, where their high strength to weight ratio and stiffness are advantageous. However, they can be expensive and require specialist design knowledge to ensure failure modes remain safe.

When coated with resin, such grids are rigid and will readily snap if bent around too small a radius. This behaviour is ill suited to beams with a variable cross section, where complex curves may need to be accommodated if the grid is to be used as transverse reinforcement. It would therefore be advantageous to use an uncoated CFRP grid which could be simply draped into the desired profile before concrete is cast around it. Research has shown that in contrast to both glass and aramid, carbon fibres have sufficient resistance to the alkaline environment within concrete to make such a solution feasible[24]. However, the bond between concrete and CFRP when resin coated and when raw remains an issue of concern, since in both cases only the outer fibres will be in contact with the concrete.

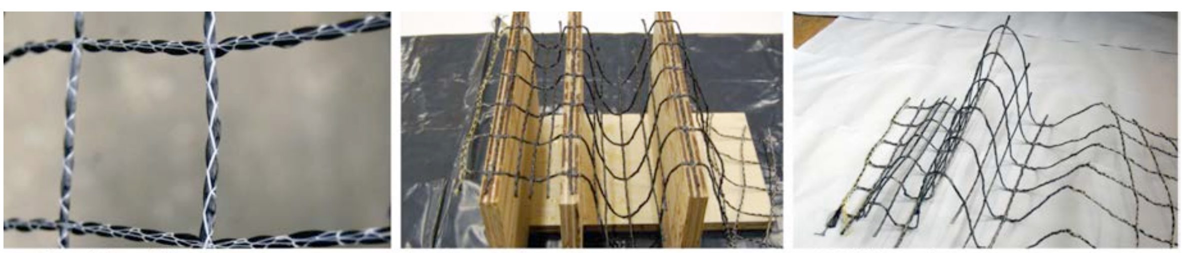
Characterisation

A CFRP grid supplied by Fortress Stabilisation[25] was used in the tests described in this paper. Material properties of the grid, which is supplied in 1.2m wide rolls with a 50mm mesh spacing, are given in Table 1. These properties were measured by tensile testing of individual tows (approximate external diameter 2.4mm). During manufacture the material is stitched into a grid and can easily be formed into any desired profile, as the tows are able to move over one another.

Initial work was undertaken to assess the feasibility of construction using the CFRP grid. A section of the CFRP grid was hung between timber supports to a predetermined profile before being coated with an araldite based epoxy resin (described in Table 2) and allowed to cure for 8 hours. The resulting element is shown in Figure 4.

Table 1. CFRP Grid properties

Property	Measured value	Property	Measured value	Property	Measured value
Ultimate tensile strength of a single CFRP tow	4226N	Strain in the tow at ultimate strength	0.013	Young's Modulus	74kN/mm^2



a. Flexible grids b. Coated in resin c. Rigid mesh

Figure 4. CFRP grid feasibility study.

Table 2. Epoxy resin

	Component	Mixing – parts by weight	Pot life of mixed resin
Hardener	Aeropia Araldite HY5052	100	@18ºC: 280 – 320 mins
Resin	Aeropia Aradur 5052	38	

The coating process is time consuming and difficult, making the use of the CFRP grid without a full resin coating a desirable alternative. However, such an approach could limit the effectiveness of the grid as very few of the individual carbon fibres within each tow would be bonded to the surrounding concrete. This may then allow the fibres to slip past one another, leading to a progressive failure of the tow.

A partially coated solution, as demonstrated elsewhere[26] and shown in Figure 5, may therefore be preferable. Coating the ends of each tow in resin prevents individual fibres from slipping past one another and, provided these ends remain anchored in the concrete, the tow may then be able to provide its full capacity. Such an approach would allow flexible grids to be used in conjunction with a flexible membrane in fabric formed concrete structures. To assess the use of both fully and partially coated grids, three 3m span concrete beams were tested.

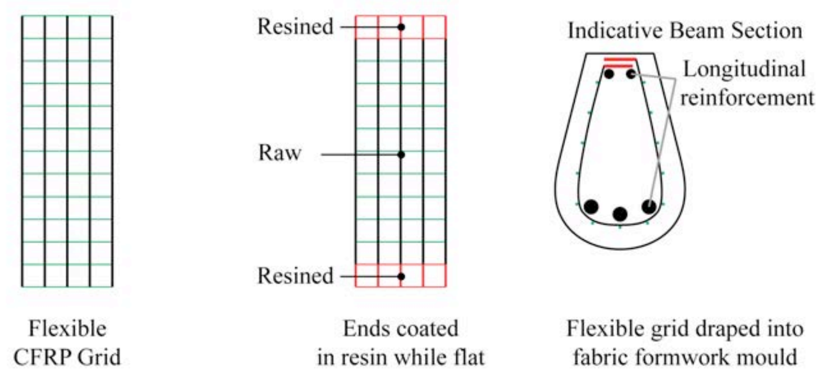


Figure 5. Partially bonded grids

STRUCTURAL TESTS

Three prismatic beams (110mm x 220mm x 3000mm) were tested. All beams were designed for three point loading, with the single point load located a distance of 2.5*d* from the support, where *d* is the effective depth of the beam (*d* = 195mm). All beams were longitudinally reinforced with two 10mm diameter high yield (500N/mm^2) deformed steel bars with 20mm cover and had a design concrete cube strength of 40N/mm^2. The resulting shear and bending moment diagrams are shown in Figure 6. Beams 1 and 2 were provided with transverse reinforcement in the form of a draped CFRP grid, the properties of which are described in the preceding section. A fully coated grid was used in Beam 1, while in Beam 2 a partially coated grid was used.

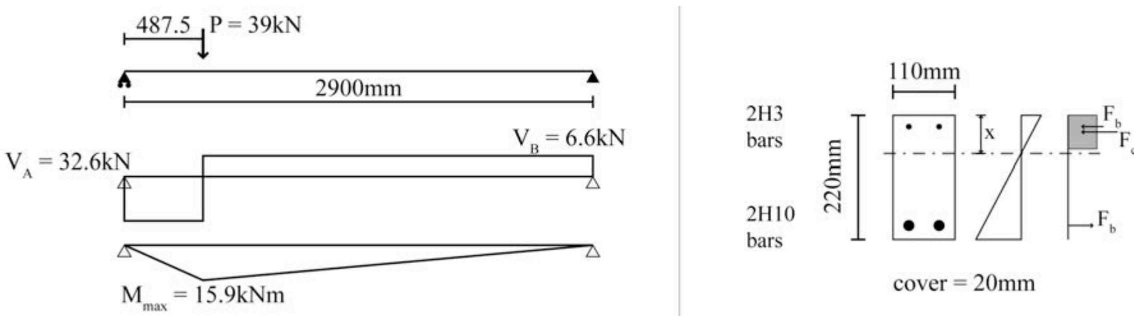


Figure 6. Force envelope (left); Section layout (right).

The CFRP grid tow spacing required to resist the full shear force along the beam was determined using the variable angle truss approach for shear (Eq.(1)), with the stress in the CFRP being initially given by the minimum of Eq.(2a) and Eq.(2b). This approach is taken from ACI440[27], where Eq.(2a) is intended to prevent large shear crack widths and limits the strain in the FRP to 0.4% and Eq.(2b) is intended to prevent the stirrup from snapping prematurely at the bend portions.

Taking this approach would thus limit the value of F_f to 1.341kN. However, given the limited test data used to determine E_f and that the manufacturer's available test data[25] suggests a much higher E_f should be expected, it was decided for the purposes of this paper to limit F_f to 1.902kN (representing a reduction of 55%) while also taking a truss angle of 45º in Eq.(1). Assuming plane sections remain plane, the neutral axis depth at the position of maximum moment (Figure 6) required to satisfy equilibrium was calculated as 27mm, giving a lever arm between the centres of tension and compression of 181mm. A CFRP grid spacing of 21mm is therefore required according to Eq.(3). Beam 3 was not transversely reinforced, and using BS EN 1992-1-1[6] was predicted to fail in shear at P = 29kN (V_A = 24kN). The resulting beam layouts are shown in Figure 7.

$$s = \frac{2F_f}{V}(z)(\cot\theta) \qquad \text{Eq.(1)}$$

$$F_f = \min\begin{cases} a)\ \ 0.004E_fA_f = 0.004(74000)(4.53) = 1.341kN \\ b)\ \ \left(0.05\dfrac{r_b}{d_b} + 0.3\right)F_{fu} = (0.45)4.226 = 1.902kN \end{cases} \qquad \text{Eq.(2)}$$

$$s = \frac{2(1.902)}{32.6}(181)(1) = 21mm \qquad \text{Eq.(3)}$$

Where s = spacing (mm); V = shear force (kN); F_f = tensile strength of each tow, as given by Eq.(2)); A_f = area of tow; E_f = Young's Modulus; r_b is the bend radius, d_b is the bar diameter (the value r_b / d_b is taken as 3.0) and F_{fu} = ultimate tensile strength of each tow.

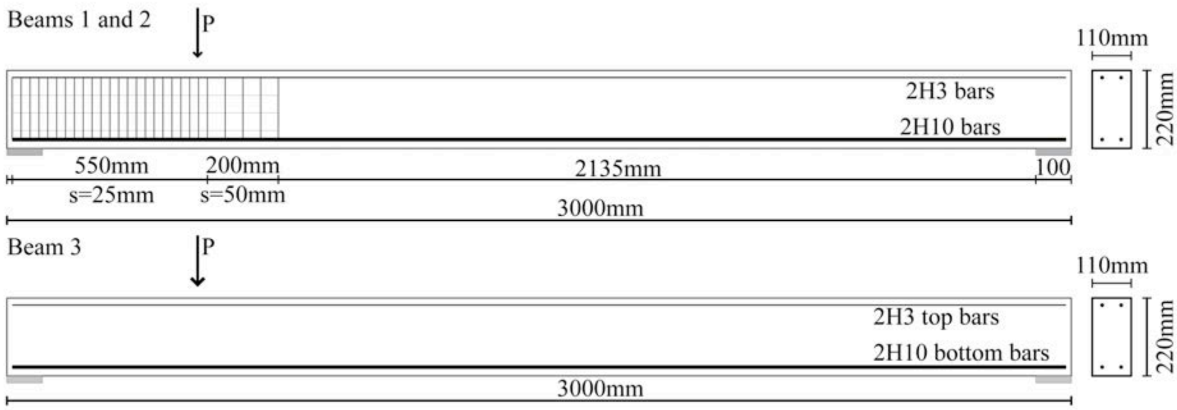


Figure 7. Beam layouts

Construction

The CFRP grids for Beams 1 and 2 were fabricated as described previously and shown in Figure 8. Three batches of the same concrete mix design were made, and the beams were cast in steel moulds of the required dimensions. A vibrating poker was used to achieve sufficient compaction of the mix. The beams were all demoulded after 72 hours. Six concrete cubes were cast for each beam, these were demoulded after 24 hours and dry stored at constant temperature and humidity until testing.

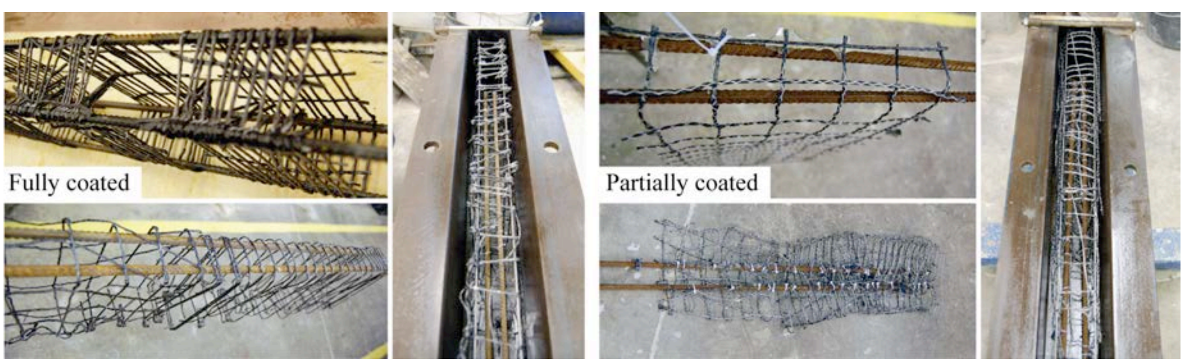


Figure 8. CFRP grid fabrication for Beam 1 (left) and Beam 2 (right).

Testing

All three beams were tested 7 days after casting. Concrete strengths were recorded prior to testing and are given in Table 3 (average compressive strength given by three 100mm cube tests). Load was applied to the beams by a hydraulic jack in 2kN increments, as measured by a load cell placed beneath the jack head. Displacements were measured below the load point and at the quarter points of each beam, as shown in Figure 9. The test results are summarised in Figure 10, with diagrams of each beam at failure provided in Figure 11.

Table 3. Concrete strengths as measured at testing.

Beam	Average compressive strength (MPa)	Standard deviation on compressive strength
1	38.20	0.89
2	38.24	1.09
3	38.71	0.64

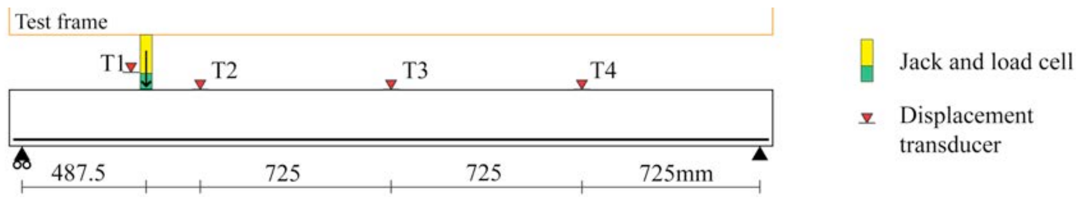


Figure 9. Test set up

Beam 3 failed in shear at P = 35.8kN, an increase of 23% above the predicted failure load of 29kN. Beam 1 and Beam 2 did not fail in shear and achieved peak loads of P = 49.5kN and P = 52.0kN respectively. This is greater than the load corresponding to the flexural capacity of the steel reinforced section (P = 39kN).

It is notable that both Beam 1 and Beam 2 exhibited some deformability at their peak load, before showing a loss of load capacity and then further deformability at the predicted flexural failure load of 39kN, as shown in Figure 10. Beams 1 and 2 showed considerable inclined shear cracks prior to failure (Figure 11) but ultimately failed in flexure by crushing of the top face of the beam. Failure of Beam 1 was confined to a zone of approximately 100mm in width while in Beam 2 multiple large cracks formed to the right of the point of load application.

The apparent increase in load capacity over the theoretical predictions seen in Beams 1 and 2 may be partly attributed to the behaviour of the FRP-confined concrete (as discussed for steel reinforced sections in [6]) but the majority of the increase in load capacity is likely to have arisen from the additional flexural capacity provided to the section by any carbon fibre tows lying in the longitudinal direction of the beam. In Beams 1 and 2 the increase in capacity was approximately equal to 11kN, and such an increase in capacity may feasibly have been provided by three CFRP tows located at an effective depth greater than or equal to that of the steel bars.

The subsequent drop in beam capacity from this peak value to the predicted flexural capacity of the section (as shown in Figure 10) is considered to represent the point at which these longitudinal tows failed, leaving the section reinforced only by the longitudinal steel bars. As the tests described above did not have strain gauges located on the CFRP grid it is difficult to more accurately determine the behaviour of the section, but these results do suggests that the CFRP grid may be used as both shear and flexural reinforcement in future tests.

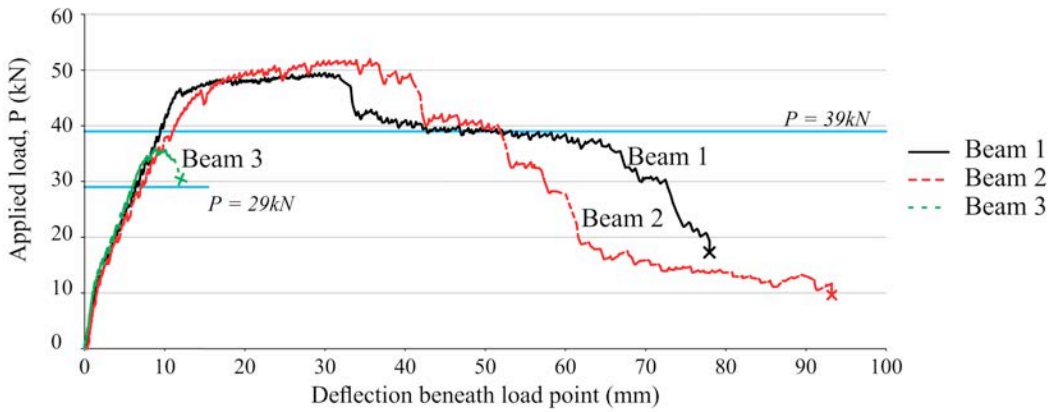


Figure 10. Load-displacement results.

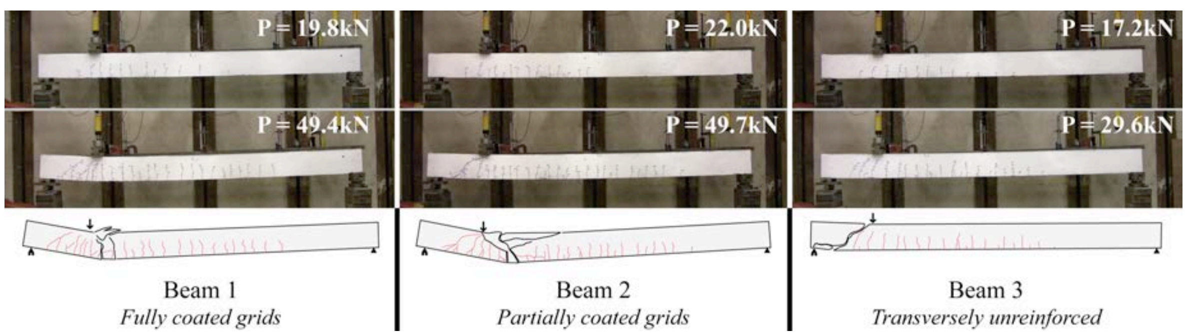


Figure 11. Failure diagrams.

CONCLUSIONS

In this paper, advanced composites have been successfully demonstrated for use as shear reinforcement in concrete beams reinforced in flexure using ductile deformed steel bars. Given that fibre reinforced polymer bars are relatively inefficient when used as passive flexural reinforcement due to their high strains[22], such an approach is an attractive and logical proposition. Two methods for the fabrication of CFRP reinforcement have been demonstrated, wherein the use of partially bonded grids was seen to provide significant advantages in reducing construction time and complexity.

However, since neither Beam 1 nor Beam 2 failed in shear it is difficult to assess the full effect of the resin coating on the behaviour of the beams and further tests on shear-critical CFRP reinforced beam sections are therefore required. Such tests would further help to verify the combined use of the ACI 440[27] and BS EN 1992-1-1[6] models for concrete structures reinforced in shear with fibre reinforced polymers.

The use of carbon fibre grids may now be considered in conjunction with fabric formwork. Here, partially bonded flexible grids hold significant advantages as they may simply be draped around the flexural reinforcement to take up the optimised shape of the surrounding fabric form. Such an approach would greatly simplify the transverse reinforcement of variable section members, making them more economical to construct.

In addition, it may be possible to utilise the longitudinal tows of the carbon fibre grid as flexural reinforcement in place of steel bars, thus facilitating the complete reinforcement of an optimised beam with one sheet of carbon fibre grid. Further work is required to demonstrate this concept.

Using fabric formwork to create an optimised external geometry in combination with steel flexural reinforcement and advanced composite grids as transverse reinforcement may facilitate the construction of materially efficient, low carbon concrete structures. Such an approach may help to precipitate the more widespread use of fabric formwork.

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