Experimental investigation of time-dependent shear deformation in RC beams strengthened with CFRP straps

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ABSTRACT: Understanding the long-term shear performance of un-strengthened and FRP-strengthened reinforced concrete (RC) beams is important. The shear behaviour under sustained loads impacts the load-sharing between the concrete, internal and external reinforcement. This in turn influences the reliability of a strengthening system over the longer-term. The current work considers RC beams strengthened in shear with transverse pre-stressed unbonded carbon-fibre-reinforced polymer (CFRP) straps. CFRP-strap strengthened beams have previously been shown to exhibit substantial increases in shear capacity when subjected to short-term monotonic loading. However, after diagonal shear cracks occur, shear deformations can start to become significant. To investigate the time-dependent shear behaviour, an un-strengthened control beam and a series of RC beams strengthened with pre-stressed CFRP straps were subjected to sustained loads. Using a detailed measurement scheme, the time-dependent deformations of the experimental beams were recorded over a duration of up to 523 days. The primary objective was to extract the shear components of deflection and to thereby assess the longer-term interactions. The measured shear deformations were found to increase with time and depended on the sustained load level.

1 INTRODUCTION

Extensive research has been conducted on the time-dependent flexural behaviour of reinforced concrete (RC) beams. However, even for unstrengthened RC beams, investigations of the long-term shear deformations have been much more limited. The situation is further complicated by the addition of unstressed, or prestressed, external FRP reinforcement.

The innovative development and use of pre-stressed unbonded carbon-fibre-reinforced polymer (CFRP) straps to strengthen existing concrete structures was championed by Professor Urs Meier and Dr Andreas Winistörfer at Empa in the 1990's (Winistörfer, 1999). Since then, the number of studies relating to the experimental and analytical behavior of CFRP-strap strengthened concrete structures has grown e.g. Stenger (2001), Lees et al (2002), Kesse & Lees (2007), Motavalli et al (2011), Dirar et al (2013), Koppitz et al (2014), Yapa & Lees (2014). However, with the exception of two beams tested by Hoult & Lees (2009), to the authors' knowledge, there has not been a focus on the long-term behavior of the strengthened structures.

One consequence of strengthening structures such that a structure can continue to sustain load after shear cracks have occurred is that shear deformations in cracked concrete become more significant. An increase in shear strains and displacements over time would place a greater demand on a strengthening system leading to greater strains in the FRP reinforcement. To explore some of these interactions, unstrengthened and CFRP-strap strengthened reinforced concrete beams were subjected to sustained loads to investigate the time-dependent progression.

2 EXPERIMENTAL INVESTIGATION

An unstrengthened control beam and three beams strengthened with vertical pre-stressed CFRP straps were tested under an applied load that was maintained over time. The main parameters were the concrete strength and the level of sustained load. The beam strains and deformations were recorded over time using a detailed measurement scheme such that it would be possible to isolate the shear components of the deflection.

2.1 Specimen details

The reinforced concrete beams had an overall height of 280 mm and a width of 105 mm. Compressive and tensile longitudinal reinforcement with a yield stress between 510 and 520 MPa was provided. The compression steel consisted of four 8 mm diameter bars placed in two layers with a centroid approximately 40 mm from the top surface of the beam. The tension steel was represented by four 16 mm diameter bars placed in two layers with an effective depth of 234 mm from the top surface. Steel shear links with a bar diameter of 4 mm were located at spacings of 200 mm throughout the shear spans to provide nominal internal steel reinforcement. The beams were tested in four-point bending with an overall clear span of 2200 mm and a distance between the supports and loading points of 700 mm. The overall beam length was 2600 mm.

In the strengthened beams, the CFRP straps consisted of 10 loops of 12 mm wide by 0.16 mm thick thermoplastic CFRP tape wound around steel pads placed on the top and bottom surfaces of the beam. The outer tape layer was fusion-bonded to form a closed loop but the inner tape layers were non-laminated. Further details regarding non-laminated straps can be found in Winistörfer, 1999 and Lees & Winistörfer, 2011. The expected Young's modulus of the straps was 120 GPa and the ultimate strain capacity was 1.3%. There were two straps in each shear span where the first strap was located 300 mm from the beam support and the second strap 500 mm from the support (as shown schematically in Figure 1). For the selected beams, the initial strap prestress was 25% of the strap ultimate capacity.

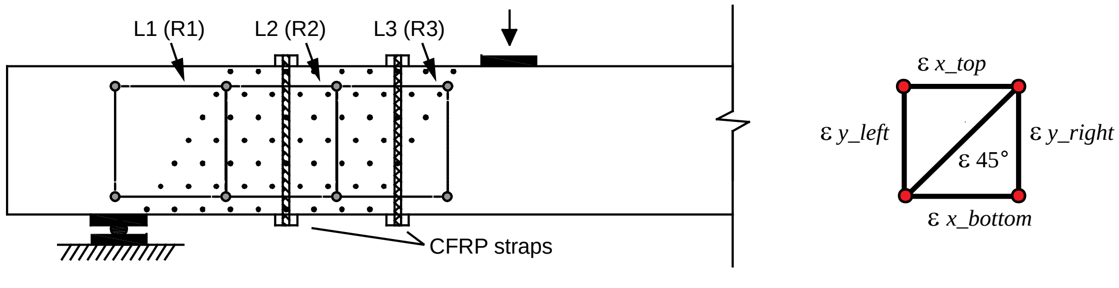


Figure 1. Beam layout and square demec element measurement scheme

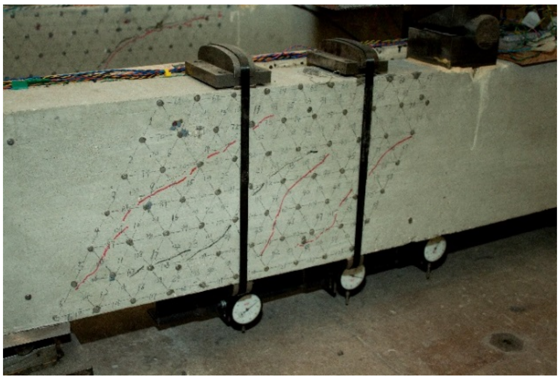


Figure 2. Photo of typical strengthened beam under sustained loading

Concrete mixes with two target compressive strengths, 30 MPa (mix 1) and 50 MPa (mix 2), were designed. The average measured 28 day concrete strengths for the two mixes were 26.6 MPa for mix 1 and 45.7 MPa for mix 2.

2.2 Measurement scheme

An extensive measurement scheme was implemented. The strains on the longitudinal bars at mid-span, each of the internal steel links and the CFRP straps were measured. In addition, the displacements along the length of the beams were manually recorded using dial gauges on the bottom beam surface (see Figure 2). The external surface strains were inferred from demec points adhered to the surface of the beams at regular intervals to create a grid of strains. A further set of three 'square' elements with 200 mm sides formed using demec points were located in both the left (L) and right (R) shear spans (see Figures 1 and 2). Measurements of the lengths and diagonals of the square can lead to an indication of the average shear strains and deformations within the element. These measurements will be the focus of the current work.

2.3 Applied loading

The level of long-term sustained load was defined based on a separate series of short-term monotonic static failure tests. An equivalent unstrengthened control beam with a concrete compressive strength of 27 MPa and strengthened beams with a compressive strength of either 29 MPa or 47 MPa were tested. These beams failed at applied loads of 50.2 kN, 91.4 kN and 114.7 kN respectively. The difference between the short-term failure load of the unstrengthened control beam and the CFRP strap strengthened beams demonstrates the level of enhancements that can be achieved with the strap system. The sustained load levels were then fixed at either 50% or 75% of the static failure strength of a given beam. This represents a fairly extreme load condition but is representative of the region of behavior where the shear cracking will be more influential.

The sustained load was applied through a steel I-beam that was bolted through a cross-head into the laboratory strong floor. The applied load was obtained using load-calibrated strain gauges attached to the bolts secured into the floor. Over the first few days, the load tended to drop off but was then adjusted such that it returned to the target load level. Thereafter the required adjustments were minimal. The beams were subjected to the target sustained loads for up to 523 days and regular measurements were taken throughout this period. The relative humidity and temperature of the laboratory were also monitored. For a given beam, the average relative humidity during the period of sustained loading was between 44% and 48% and the average temperature was between 20.8°C and 22.3°C.

The beams reported here were denoted using four identifiers – BL#/C##/aa/S## - where the first category indicates the specimen number, the second is the target concrete compressive strength – either 30 or 50 MPa –, the third is either ‘nS’ for no straps or ‘P%’ where the ‘%’ indicates the strap prestress as a percentage of the failure stress, and the final grouping relates to the sustained load as a percentage of the static failure load. Hence BL1/C30/P25/S50 represents a long-term beam with a target concrete strength of 30 MPa, straps with an initial prestress of 25% and subjected to a sustained load that is 50% that of an equivalent strengthened beam’s short-term static failure strength.

3 RESULTS

3.1 Global beam deflections

None of the beams failed during the test duration while under sustained load. In Figure 3, the dial gauge displacements measured along the beam upon initial loading and at specified times after loading are presented. The corresponding mid-span deflection increases are summarized in Table 1. In all cases the global beam deflections increased over time. The percentage increases in deflection were between 82.4% and 109.2% of the initial short-term deflections.

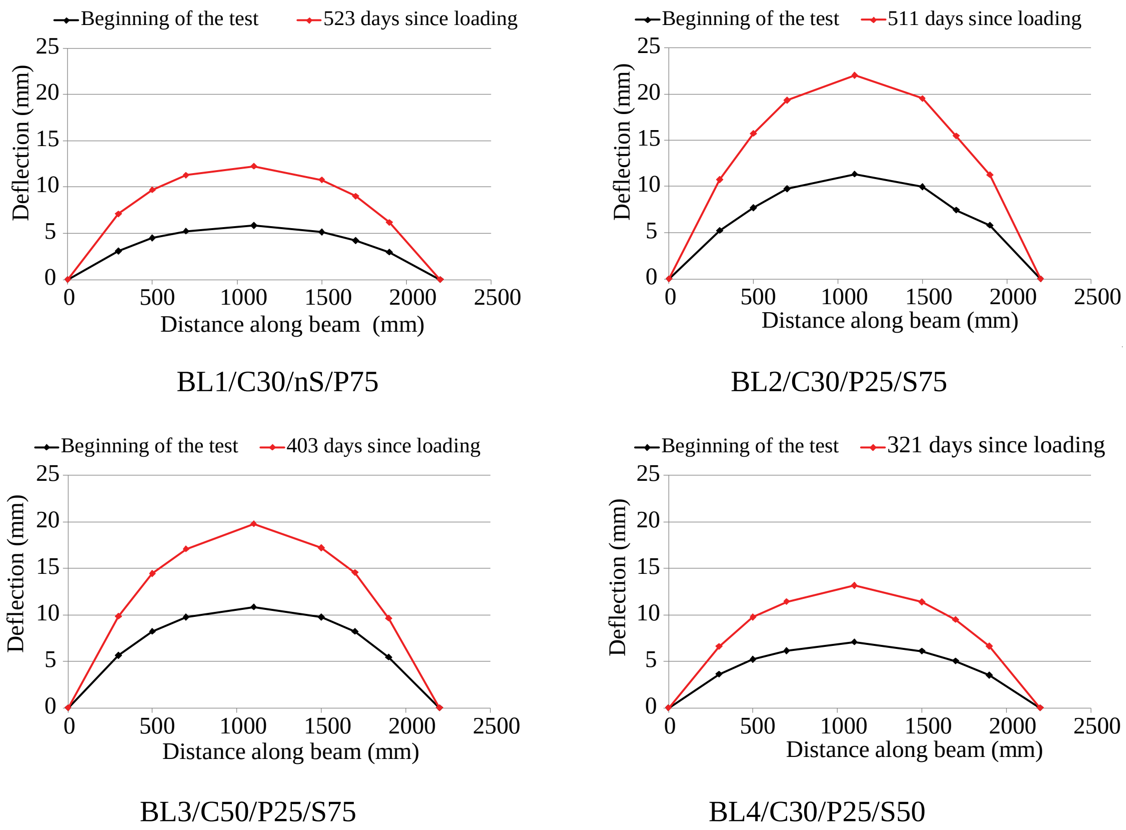


Figure 3. Initial and long term global displacements along the length of a beam

Table 1. Global mid-span deflection development

Beam	Load duration (days)	Initial deflection (mm)	Final deflection (mm)	% increase
BL1/C30/nS/P75	523	5.8	12.2	109.2%
BL2/C30/P25/S75	511	11.3	22.0	94.2%
BL3/C50/P25/S75	403	10.8	19.8	82.4%
BL4/C30/P25/S50	321	7.1	13.2	86.3%

A comparison of beams BL2/C30/P25/S75 and BL3/C50/P25/S75 which had different concrete strengths but the same percentage of sustained load suggests that the higher concrete strength resulted in somewhat smaller initial and long-term deflections. However, the differences were not great (around 10% over the long-term). The level of sustained load was a more dominant factor in an absolute sense where the mid-span displacements both in the short- and long-term for BL4/C30/P25/S50 were about 60% of those observed in BL2/C30/P25/S75.

3.2 *Isolation of flexural and shear deflection components*

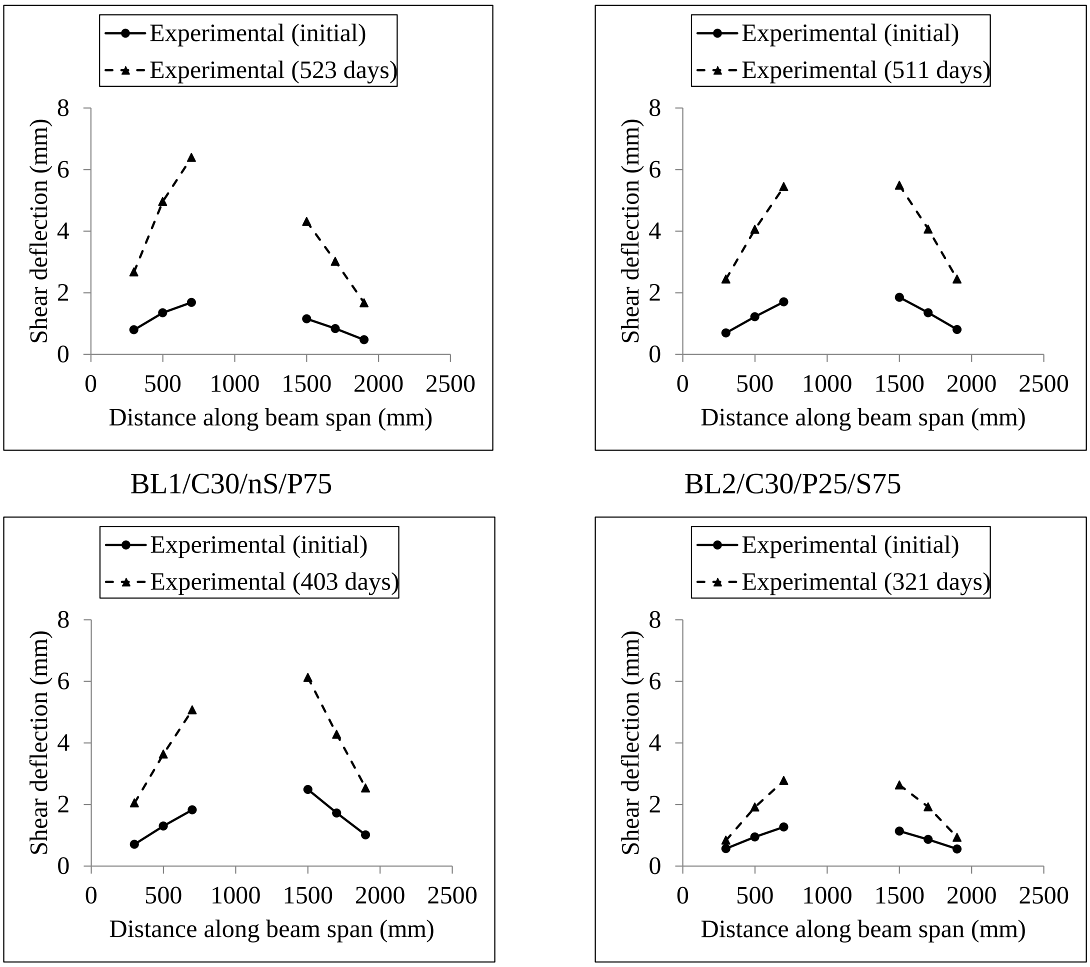
The dial gauge displacement readings give a good indication of the global deflections. However, it is of interest to separate the flexural deflection components from the shear deflection components. To do this, the mean shear strain was calculated from each of the individual square demec elements (L1-L3 and R1-R3 as shown in Figure 1) using:

$$\gamma_{xy} = 2\varepsilon_{45^\circ} - \frac{\varepsilon_{x\_top} + \varepsilon_{x\_bottom}}{2} - \frac{\varepsilon_{y\_left} + \varepsilon_{y\_right}}{2} \qquad (1)$$

The shear displacement of each element was found by multiplying the strain by the square element length of 200 mm. For ease of comparison with the measured global deflections, a linear shear displacement profile within each element was assumed and interpolation and/or extrapolation was used to calculate the shear displacements at the locations of the dial gauges. The resulting displacements along the span corresponding to the initial and long-term shear deflection components are summarised in Figure 4.

The shear strains and displacements along the shear span were typically fairly linear. Some differences were noted between the left and right shear spans of a given beam and so the short and long term values for both spans at a distance of 700 mm from the supports are presented in Table 2 (denoted as x = 700 mm for the left span and x = 1500 mm for the right span).

The initial shear deflections were betweeen 1.1 and 2.5 mm and then increased by between 215% and 376% over the long-term. For the unstrengthened control beam, the long term shear deflections were higher in the left (6.4 mm) than the right span (4.3 mm) and this was attributed to a more dominent shear crack in the left span. From Figure 3, it can be seen that for the control beam the total long-term deflection at x = 700 mm was 11.3 mm so the shear deflection at x = 700 mm represented a significant component (57%) of the global deformation. The long-term shear deflections in BL2/C30/P25/S75 and BL3/C50/P25/S75 were between 5.1 and 6.1 mm at x = 700 and 1500 mm and there did not appear to be a significant dependency on concrete strength. In absolute terms the sustained loads on these beams were much higher (approximately twice that of the control beam). So the straps were effective in controlling the shear displacements. The percentage of the shear component at x = 700 was around 30% of the total deflection for these beams. The level of sustained load appeared to have an influence as the final x = 700 mm deflection in BL4/C30/P25/S50 only reached 2.8 mm.



BL1/C30/nS/P75 BL2/C30/P25/S75

BL3/C50/P25/S75 BL4/C30/P25/S50

Figure 4. Initial and long term shear displacements along the length of a beam

Table 2. Shear deflection development at x = 700 and 1500 mm

Beam	Load duration (days)	Initial shear deflection (mm)		Final shear deflection (mm)	
		Left	Right	Left	Right
BL1/C30/nS/P75	523	1.7	1.2	6.4	4.3
BL2/C30/P25/S75	511	1.7	1.9	5.4	5.5
BL3/C50/P25/S75	403	1.8	2.5	5.1	6.1
BL4/C30/P25/S50	321	1.3	1.1	2.8	2.6

4 CONCLUSIONS

The time-dependent behavior of beams with external prestressed CFRP straps was investigated. An unstrengthened control beam and three CFRP-strengthened beams were subjected to sustained loads for up to 523 days. In all cases, the global deflections increased with time. The percentage increases in the mid-span deflections were found to be between 82.4% and 109.2%. The shear components of deflection were isolated based on measurements of square demec elements in the shear spans. The shear deflection component at a distance 700 mm from the support for the unstrengthened beam with a load equal to 75% of the static strength was around 57% of the total deflection. Strengthened beams loaded to 75% of their static capacity were subjected to higher sustained loads in absolute terms. However, the shear components were a lower percentage of the total deflection and in absolute terms were in the range of the long-term deflection results of the unstrengthened beam. Whereas the concrete strength did not appear to have a significant impact on the shear deflection behavior of the strengthened beams, the level of sustained load was important. The strengthened beam with a 50% static load exhibited the lowest long-term shear deflections. The CFRP straps were found to be effective in helping to control the shear displacements.

Acknowledgements

We gratefully acknowledge Professor Meier’s significant contributions from which we have benefited greatly. Professor Meier’s influence is at the heart of this research and his innovations and leadership have transformed the field of advanced FRP composites.

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