Concrete cover separation failure in near-surface mounted CFRP strengthened concrete structures

Gary Corden, Prof. Tim Ibell and Dr Antony Darby of Bath University report research which won IStruct's Model Analysis Award 2007

Near surface mounting (NSM) fibre reinforced polymer (FRP) rods is a novel method for strengthening reinforced concrete structures. Slots are cut into the cover concrete of the section to be strengthened and FRP rods are fixed into the slots using adhesive. The FRP acts as additional tension reinforcement to the section. The main advantage of this technique is that the bars can be installed relatively quickly since temporary supports are not required while the adhesive sets due to the light weight of the FRP bars. Additionally, the advantages over surface mounted FRP strengthening are that a high degree of bond between the concrete and FRP bars can be achieved due to the bar being bonded around a large proportion of its perimeter, and that the FRP is protected from damage by being embedded into the concrete surface, which is particularly useful in strengthening hogging regions.

However, there is a distinct lack of knowledge regarding concrete cover separation failures in NSM FRP strengthened structures. Existing literature only considers simply supported beam structures. This is absurd considering the fact that the majority of the practical applications of FRP strengthening are performed on continuous structures, especially those which employ the NSM technique. As a result, no guidance exists for designers of NSM FRP strengthening solutions regarding the potential dangers of concrete cover separation or methods of avoiding such premature failures.

The original aim of the work presented in this article was to assess the potential for moment redistribution in NSM carbon-FRP (CFRP) strengthened reinforced concrete structures. An experimental programme which was undertaken at the University of Bath consisted of four 2-span continuous reinforced concrete beams with various strengthening regimes. The specimens were loaded to failure in an attempt to corroborate analytical research suggesting that despite the inherently brittle material characteristics of CFRP strengthening elements, significant ductility can be displayed in NSM CFRP strengthened structures, allowing moment redistribution to occur[1].

The experimental programme produced unexpected results, in which all of the CFRP strengthened beams failed at an ultimate load lower than that of the unstrengthened control beam. Whilst failure of the strengthened beams at unexpectedly low loads did not provide any insight into the potential for ductility to be displayed in such structures, the mode of failure of the beams, by concrete cover separation, highlights a potentially significant phenomenon in the behaviour of structures strengthened in this manner.

Concrete cover separation failure

The mechanism of concrete cover separation failure is well documented, primarily considering failure of simply supported concrete beams strengthened with steel or FRP sheets[2,3,4]. The failure mechanism is instigated at the end of the FRP, where a strain discontinuity exists between the concrete and the CFRP. This discontinuity is due to the fact that the FRP does not usually continue right to the position of zero moment in the beam (this could be due to the fact that the exact position of zero moment is unknown for a continuous beam, or that the FRP is curtailed since it is not required for strengthening in regions where low moment occurs). This means that there is a bending moment in the beam at the location of the end of the FRP, resulting in a tensile stress in FRP where, at the same location, the axial stress in the FRP must be zero since the FRP ends. The

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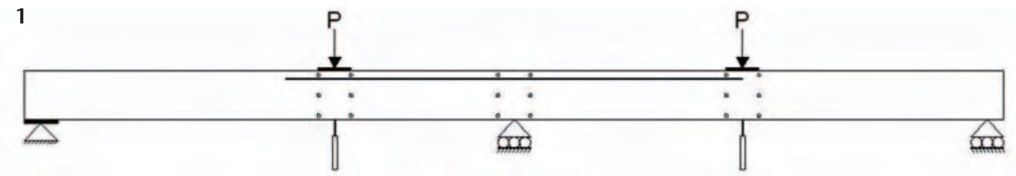

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Fig 1. Test set up (Beam 2 shown) / Fig 2. Concrete cover separation failure in Beam 3

only way in which the axial force at the end of the FRP can be equilibrated is by shear transfer to the concrete. The shear stiffness of the resin bond between the concrete and the FRP causes large local shear stresses and, as a result, local cracking. Horizontal propagation of these cracks can result in peeling of the concrete cover at the tension steel reinforcement interface. It follows that the greater the distance between a support and the extreme edge of the FRP in a simply supported beam, the greater the moment and, hence, greater the strain discontinuity between the two elements, and the more likely it is that premature failure by concrete cover separation occurs[4].

Experimental investigation

An unstrengthened control specimen and three differently strengthened specimens were examined in the investigation. Details of the strengthening provision in each of the test specimens are given in Table 1. In the beams strengthened in the hogging region (beams 2 and 4), CFRP rods were positioned on the side face of the beam, rather than into the top surface. This represents a practical strengthening technique for RC beams over column supports where access to the top surface may be impossible. Strengthening in the sagging regions (beams 3 and 4) was provided by bars mounted into the soffit of the beams, between supports. Fig 1 shows a schematic of the test set-up. The predicted and actual failure loads, together with the observed failure mechanisms are indicated in Table 1. All predictions of beam capacity in Table 1 were found in advance under Class A conditions by assuming the yield strength of steel reinforcement to be 460N/mm^2. In fact, the real yield strength of these bars was significantly higher than this, accounting for the discrepancy between the predicted and ultimate loads in the control beam. Longitudinal shear failure at the location of the FRP reinforcement was not considered as a potential failure mechanism on the basis that the support conditions in the tests would force such a failure to occur where the FRP is in a non-linear section in the compression zone. Current UK design guidance assumes such failures occur in the tension zone only.

All the strengthened beams failed by concrete cover separation, as can be observed in Fig 2 for beam 3. In order for this type of failure to occur, the longitudinal shear stress in the concrete cover region must be high enough to allow horizontal propagation of local shear cracks. For the given failure loads, the longitudinal shear stresses were assessed for all of the test specimens at the position of maximum sagging moment, maximum hogging moment and points of contraflecture on the relevant failure plane (Fig 3) using elastic beam theory, the results of which are shown in Table 2.

In beams 3 and 4, resistance to longitudinal shear stress in the sagging region was provided by plain concrete alone. Hence, it is clear that the stresses were sufficient to cause horizontal shear crack propagation. In beam 2, which was strengthened in the hogging region only, resistance to longitudinal shear stresses was also provided by shear reinforcement since the CFRP rods were located on the sides of the specimen. This explains why the shear stresses calculated on the failure plane in beam 2 were significantly higher at the failure load.

Several factors in the experimental programme encouraged concrete cover separation failures in all of the strengthened beams:

- The continuity of the beams. Consider the failure of the beams strengthened in the sagging moment region. The cut off position of the strengthening CFRP bars was 20mm away from the central support. Here the hogging moment in the beam was near maximum, producing huge strain discontinuity between the concrete (under significant compressive strain) and the CFRP (zero strain), producing local shear cracking. Furthemore, a geometric discontinuity exists between the curvature of the CFRP at the cut end (zero) and the curvature of the surrounding concrete. This of course is exacerbated in a continuous beam, where the curvature at the central support is at a maximum.
- The shear forces which are induced when generating bending failures in continuous beams are also significantly higher than those required to produce similar failures in simply supported beams. This encourages propagation of local shear cracks.
- Low levels of cover (15mm) and the use of relatively weak concrete (20-25N/mm^2) gave the test specimens low resistance to concrete cover separation failure.

[i] This was allowable given that all of the strengthened specimens remained linear elastic at the onset of longitudinal shear failure due to the high grade of reinforcing steel used.

Avoiding concrete cover separation failures

The test results discussed in this article demonstrate that due to the high degree of bond achieved by NSM reinforcement, concrete cover separation may dominate the failure behaviour. This risk of concrete cover separation failure in strengthened continuous RC structures must be checked by examining the longitudinal shear stress on all planes in which concrete cover separation failure is possible. If the longitudinal shear stress on these planes exceeds the limits for shear in plain concrete, then there is significant potential for

Table 1: Test configuration and results

Beam	Strengthening provision	Predicted ultimate load P (kN)	Ultimate load P (kN)	Predicted failure mechanism	Actual failure mechanism
1	None	33.5	47.5	Concrete crushing in sagging moment region	Concrete crushing in sagging moment region
2	2, 6mm diameter CFRP rods in hogging moment region	42.3	43.0	Concrete crushing in sagging moment region	Concrete cover separation in hogging moment region
3	2, 6mm diameter CFRP rods in sagging moment region	52.5	45.6	Concrete crushing in hogging moment region	Concrete cover separation in sagging moment region
4	2, 6mm diameter CFRP rods in sagging and hogging moment regions	57.8	40.5	Concrete crushing in hogging moment region	Concrete cover separation in sagging moment region

Table 2: Longitudinal shear stresses in beam 2, 3 and 4

	Position in span		
	Max sagging moment	Point of contraflecture	Max hogging moment
Beam 2 failure plane (N/mm^2)	2.15	1.92	2.75
Beam 3 failure plane (N/mm^2)	0.69	1.14	1.41
Beam 4 failure plane (N/mm^2)	0.55	1.20	1.33

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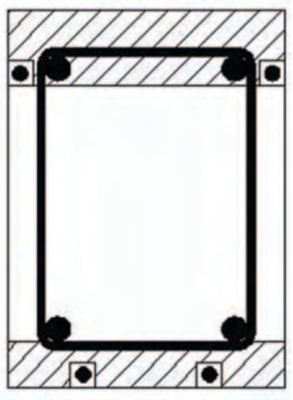

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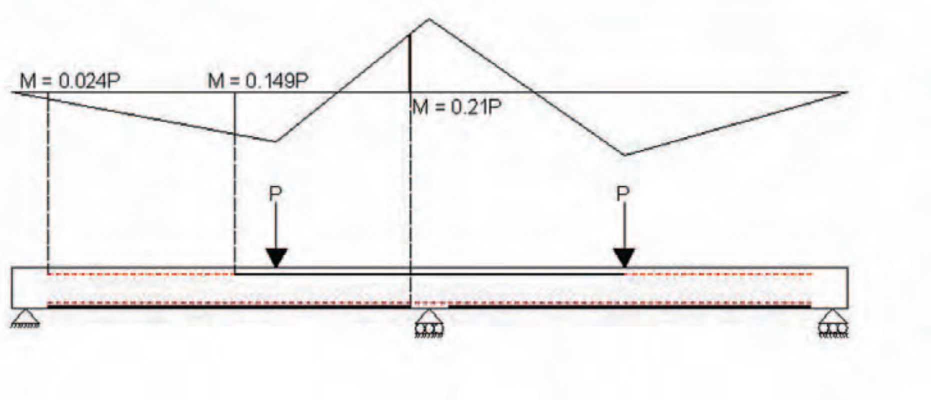

Fig 3. Location of failure planes in a typical section / Fig 4. Potential extension of anchorage zones to avoid separation failure

localised shear cracks produced at the ends of the FRP reinforcement to propagate into horizontal shear cracks. In surface mounted FRP reinforcement debonding tends to occur before these shear stresses start to dominate, but this is not the case for NSM, since greater bond is achieved.

The effect of high longitudinal shear forces might be reduced by following the practical measures below, which control the variables that lead to concrete cover separation failures.

Extending the anchorage zones of the FRP beyond the region of high bending moments will reduce the likelihood of localised shear cracking at the end of the FRP by reducing the concrete-FRP strain discontinuity. Fig 4 shows how increasing the anchorage length of the FRP bar providing hogging strengthening in the tests described could have reduced the bending moment at the position of the end of the FRP by a factor of 6. This is difficult in the sagging zones, as central supports in continuous beams will often prevent the extension of the anchorage zones. A potential solution to this problem is to position the sagging strengthening on the side of the beam, allowing a single bar to strengthen both of the spans. An additional advantage of positioning the sagging reinforcement on the side of the beam is that shear links may be mobilised on the critical failure plane, as observed in beam 2 of the experimental programme.

Additional care should be taken when strengthening concrete structures with either low concrete strength or low levels of cover, both of which reduce the level of longitudinal shear stress required to instigate the concrete cover separation mechanism.

Conclusion

Given that all of the 'strengthened' beams tested in the programme were in fact weakened by the presence of NSM FRP bars, the potential for concrete cover separation failure in continuous beams is clearly worrying, especially as it is so poorly understood. This should be the subject of extensive research in order to provide a more complete understanding of the mechanisms involved in concrete cover separation failures. Designers employing NSM FRP strengthening solutions must be aware of this potential failure mechanism and act with caution. se

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