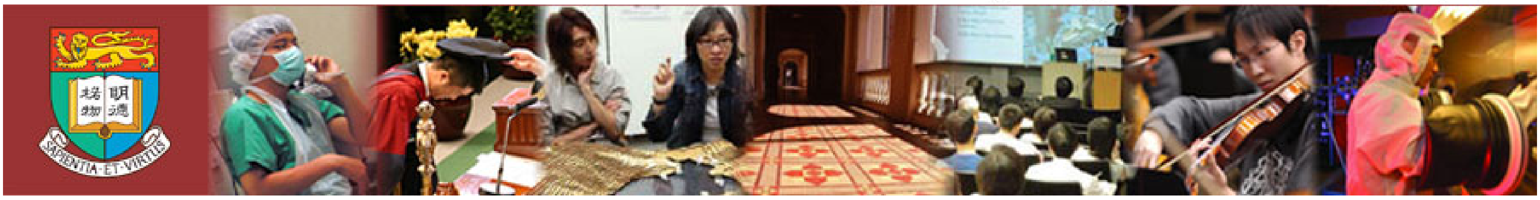

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STRENGTHENING OF RC SLABS WITH LARGE PENETRATIONS USING ANCHORED FRP COMPOSITES

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ABSTRACT

Large penetrations are routinely made in existing reinforced concrete (RC) slabs due to structural and/or functional changes. Externally bonded fibre-reinforced polymer (FRP) composites can in turn be bonded to the tension face of the slab in the immediate vicinity of the penetration in order to restore the strength of the slab due to the lost internal steel reinforcement. In order to prevent premature debonding failure of the FRP strengthening, anchors can be applied. The results of tests on the strength and behaviour of one-way spanning RC slabs with large central penetrations which have been strengthened with unanchored and anchored FRP composites are presented in this paper. The FRP strengthening was found to be effective in strengthening penetrated slabs and the anchors were found to be effective in controlling the propagation of debonding cracks.

KEYWORDS

FRP, RC slabs, strengthening, cutouts, penetrations, anchorage.

INTRODUCTION

Extensive experimental investigations have demonstrated the effectiveness of externally bonded FRP composites in strengthening existing RC structural elements such as beams, column and slabs (Bank 2006, Hollaway and Teng 2008). While the majority of research has focused on the strengthening of beams and columns, much less research by comparison has been conducted on slabs and indeed slabs with large penetrations. A detailed review of research on one-way spanning slabs with penetrations and strengthened with externally bonded FRP plates is given in Smith and Kim (2009). In the majority of strengthening cases, the FRP was observed to debond before its strain capacity was reached with the failure mode commonly intermediate crack induced debonding (IC debonding) (Hollaway and Teng 2008). In order to prevent debonding occurring or to halt the propagation of debonding cracks then anchorage of the FRP may be considered. Several different anchorage systems have been developed over the years on anchors made from FRP (known as FRP anchors or FRP spike anchors, amongst other names) are promising as they can be applied to slabs. Detailed investigations on FRP anchors, and reviews of others anchorage systems, can be found in Smith and Kim (2008) and Kim and Smith (2009).

In this project, the tests results of three one-way spanning RC slabs with large central penetrations are presented. The first test is on an unstrengthened control slab while the remaining two tests are on slabs strengthened with FRP strips. One of these strengthened slabs is also fitted with FRP anchors. The tests reported here form part of a much larger experimental investigation reported in Kim (2009).

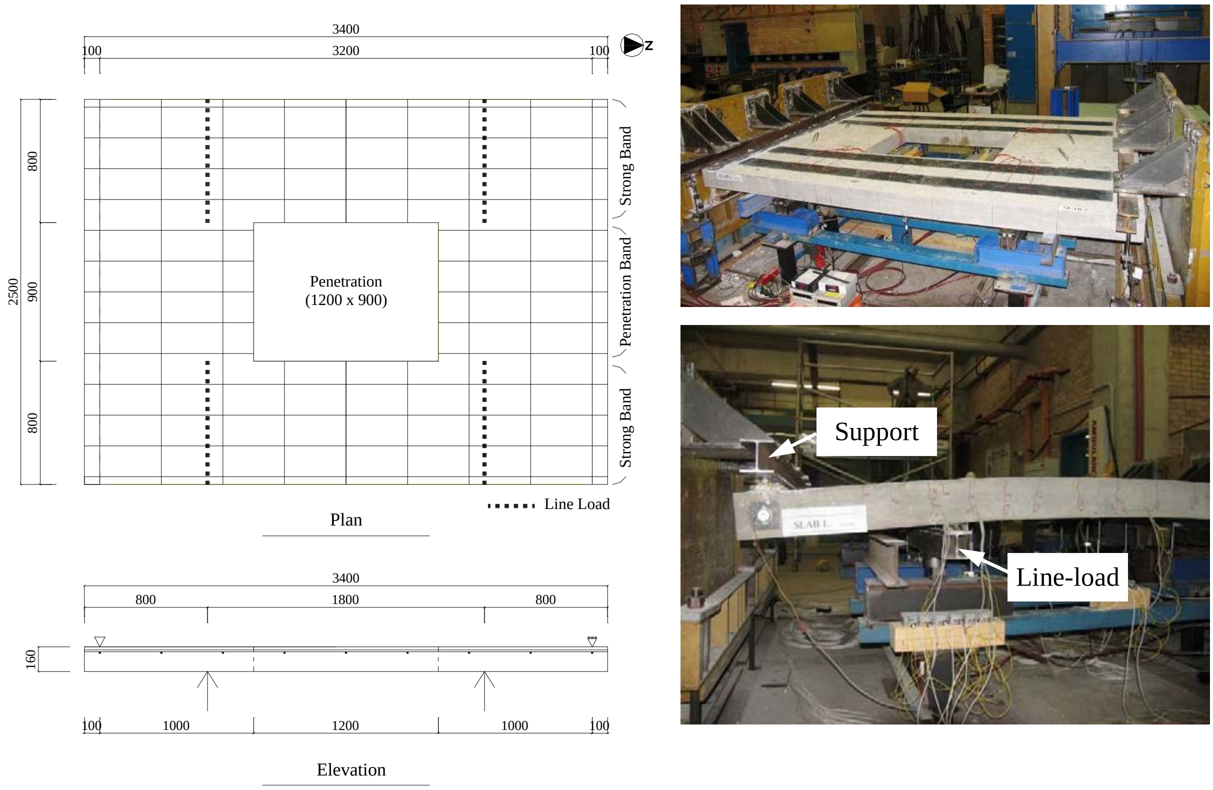
EXPERIMENTAL DETAILS

Details of Test Specimens

The tested three inverted simply-supported one-way spanning RC slabs (Slabs S1, S2 and S7) are shown in Figure 1. All slabs were prismatic, rectangular in cross-section, and nominally 3400 mm long, 2500 mm wide and 160 mm deep with a clear span (distance between supports) of 3200 mm. The slabs had penetrations of 900 mm width (parallel to the supports) and 1200 mm length and the penetrations were located in the constant moment region produced by line loads applied to the strong bands as shown in Figure 1.

The three slabs were constructed from two different pours of ready-mix concrete. The tested cylinder compressive strengths at the time each slab test being 42 MPa (Slabs S1 and S2 from batch 1) and 35 MPa (Slab S7 from batch 2). All slabs were reinforced with ductile hot-rolled deformed steel reinforcing bars of 12 mm diameter (AS/NZS4671 2001) of which the test yield strength and elongation at fracture were 546 MPa and 10.5 % for Slabs S1 and S2, and 606 MPa and 10.0 % for Slab S7 respectively. The ultimate moment capacity of the slab in the transverse direction was approximately half the capacity of the slab in the longitudinal direction without the effect of FRP considered. The FRP strengthening scheme for slabs S2 and S7 is shown in Figure 2. Also shown in Figure 2 is the FRP anchor layout for Slab S7. The FRP plate consisted of two layers of carbon fibre sheets of 0.117 mm nominal thickness each and 175 mm width. The FRP anchors were applied in a staggered arrangement with the anchor fan component (the part of the anchor bonded into the FRP plate) being orientated in the direction of the unidirectional plate fibres in a bid to optimize the performance of the anchors. The anchor dowel was embedded 40 mm into the concrete slab. Figure 3 shows selected pictures of the FRP plate and FRP anchor application and a much more detailed description of the installation as well as construction of the FRP anchors is given in Smith and Kim (2008).

The amount of FRP plate strengthening was calculated based on the loss of steel reinforcement in the penetration region. The calculation of the FRP strength contribution considered IC debonding failure and a detailed description of the analytical procedure is given in Smith and Kim (2009). The effect of the anchors was not considered in the analysis as an IC debonding based analysis was expected to give a lower-bound strength. In order to avoid the internal steel reinforcement interrupting the placement of the FRP anchors, the outermost two FRP strips were shifted toward the penetration region by 30 mm for Slab S7 (i.e. each strip was located 230 mm away from the free edges of the slab for Slab S7 while this distance was 200 mm for Slab S2). In addition, the shear strength of the strengthened slabs was calculated to be sufficient. Eighteen FRP coupon specimens were tested in accordance with ASTM (2000) then averaged to produce mechanical properties of the FRP of elongation at rupture = 10,405 $\mu\varepsilon$ (standard deviation, sd. = 1785 $\mu\varepsilon$), tensile strength = 2735 MPa (sd. = 156 MPa) and elastic modulus = 268 GPa (sd. = 46 GPa).

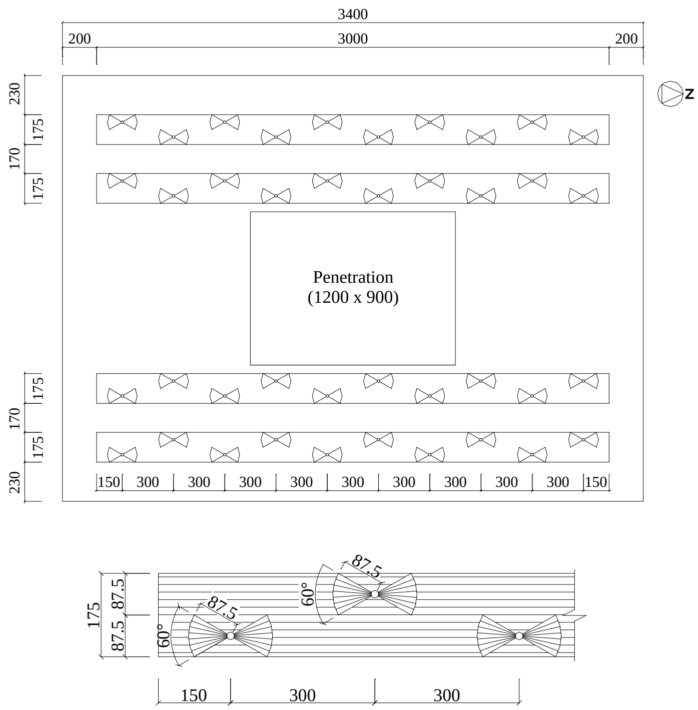


(a) Slab details (b) Test set-up

Figure 1. Test slabs

Instrumentation and Test Procedure

Each slab was loaded monotonically at approximately 70 N/sec and the load was paused at regular intervals in order to mark the new crack positions and also to inspect the condition of the FRP. The load was continually applied after approximately 65% of the predicted capacity of the slabs for safety reasons.



(a) FRP strengthening scheme and anchor layout

(b) Detailed view of FRP anchor geometry (Slab S7)

Figure 2. FRP strengthening scheme for Slabs S2 and S7 and anchor layout for Slab 7

(a) Inserted FRP anchors and prepared concrete surface

(b) Passing parted sheet fibres over FRP anchor

(b) Splaying and epoxying of fan-out fibres onto fibre sheet

Figure 3. Installation of FRP strengthening and FRP anchors for Slab S7

EXPERIMENTAL RESULTS

The behaviour and failure modes of the three test slabs are described in this sub-section. In addition, a snapshot of the overall behaviour of the three slabs can be seen in load-deflection plots given in Figure 4. In this figure, the beneficial effect of the FRP strengthening can be seen. The contribution provided by the anchors can also be observed.

Control Slab (S1)

Loading of the control slab was stopped when the deflection increased without a significant increase of load and after the internal steel had yielded. The load was also stopped on account of the actuator ram reaching its maximum extension. It is expected that additional loading would eventually lead to crushing of the compressive concrete in the constant moment region.

Unanchored Strengthened Slab (S2)

The unanchored strengthened slab failed by IC debonding with the debonding believed to have originated from the intersection of major cracking extending from the corners of the penetration and intersecting with the FRP plates. After loss of the strengthening plate, the behaviour of the slab resorted to approximiately that of the unstrengthened control slab S1 as can be seen in Figure 4. Figure 5a shows the sequence of FRP debonding as well as the extent of debonding in each region of the plate. The first portion of strip to debond is indicated as ① and subsequent debonding zones are numbered sequentially. Selected photographs of FRP strips in the process of debonding, extracted from digital video taken during the test, are shown in Figures 5b and 5c. As evident in Figure 5, a large portion of the strip adjacent to the penetration debonded first (i.e. debond ①). As the load was applied directly to each strong band either side of the penetration, the strip adjacent to ① then debonded (i.e. debond ②). The two remaining strips on the opposite side of the penetration then debonded. Upon debonding of ①, the load carrying capacity of the slab was compromised as indicated by a drop in the load in Figure 4. Each strong band of the slab either side of the penetration essentially acted independently, indicating the slab acted as a system of independent beams either side of the penetration.

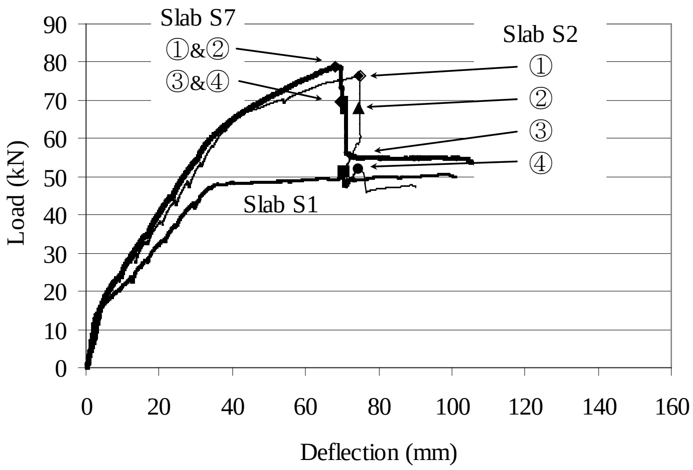
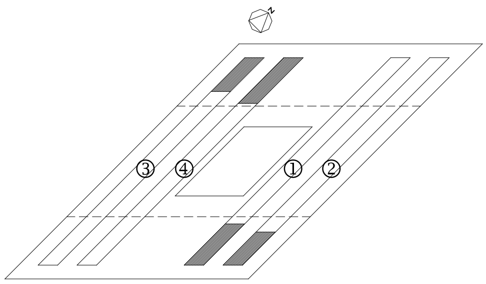
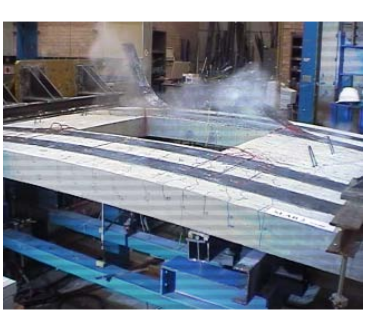


Figure 4. Load- midspan deflection response



(a) Debonding sequence and extent of debonding



(b) Debond ①

(c) Debond ②

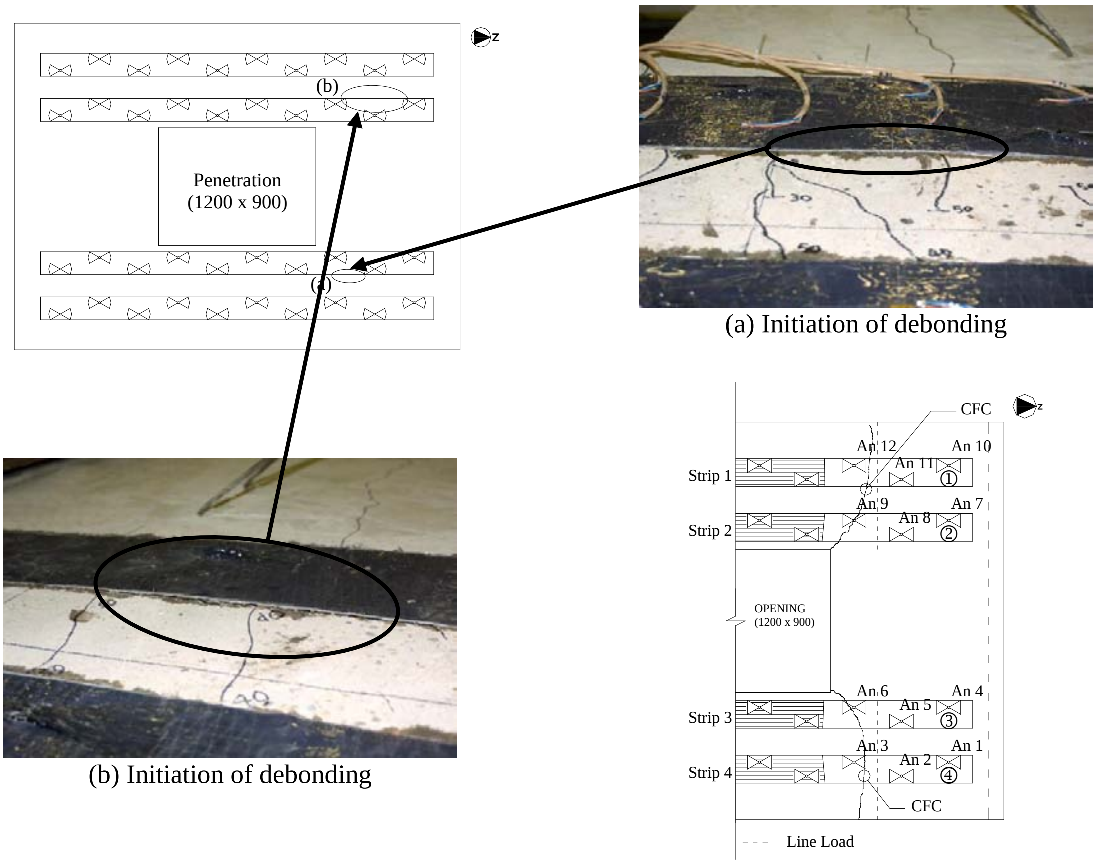
Figure 5. Debonding behaviour of Slab S2

Anchored Strengthened Slab (S7)

The anchored strengthened slab S7 failed firstly by debonding of the plate followed by concrete compressive failure and rupture of the internal tensile steel reinforcing bars. Debonding cracks between the FRP and concrete substrate (in the concrete) originated near the region of peak bending moment. Based on test observation as well as analysis of video and data logged data, the anchors in the debonded plate regions stopped the propagation of debonding cracks and effectively held the plates in place until eventual concrete crushing failure. Figure 4 shows the increase in strength offered by the anchors of about 5 % as well as the residual strength of Slab S7 after debonding of the FRP strengthening of about 10 %. Such enhancement of strength is directly due to the anchorage. In addition, this increase post-peak will also be due to friction between the roughened debonded FRP and concrete surfaces. It is hypothesised that stronger and stiffer anchors will increase the residual strength of the debonded system. The optimal result would be to have a residual strength plateau approximately equal in magnitude to the peak load. If such a behaviour can be attained then the system will have ductility; something which is missing in unanchored strengthening systems but essential for safety.

Initiation of debonding was observed around the 60 to 70 kN load range. Localised debonding was observed between anchors at the outer-most side of the plate in the constant moment region as indicated in Figure 6a and extended toward to the plate end as the load increased as indicated in Figure 6b. Figure 6c shows a schematic representation of the debonded portion of the plates and the sequence of debonding (denoted as ① to ④). Two plates (strips 1 and 2; areas ① and ② in Figure 6c) on one of the strong bands debonded one after the other firstly and then the strips on other side of the slab (strips 3 and 4; areas ③ and ④ in Figure 6c). Although all debonded parts of the plates completely separated from concrete surface, all plates were still connected to the anchor fan components of the anchors. As the slab deflection increased, the portion of debonded plate increased and eventually anchors attached to plates failed. Three out of four plates completely separated from the anchor fan while one plate (strip 1 in Figure 6.c) remained attached until complete failure of the slab.

The anchors in strips 2 to 4 failed in a pull-out mode (e.g. anchor AN2 in Figure 7a) or a shear mode (e.g. anchor AN4 in Figure 7a). Anchor AN1 was an exception as it failed in a mixed mode of local bond failure between the anchor fan and FRP plate + anchor dowel shear failure as shown in Figure 7b. The anchors generally failed in modes consistent with those observed by Smith and Kim (2008) in anchored FRP-to-concrete joint tests and also by Kim and Smith (2009) on pull-out tests. All the anchors puling out were located adjacent to or directly in line with wide cracks in the slab. Such cracking severely affected the strength of the anchor.

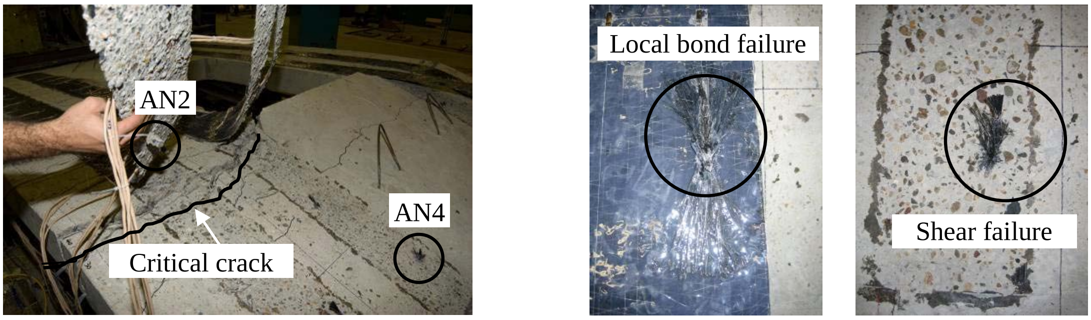


(a) Initiation of debonding

(b) Initiation of debonding

(c) Propagation of debonding

Figure 6. Debonding behaviour of Slab S7



(a) Pull-out and shear failure (b) AN1

Figure 7. Plate and anchor failure modes of slab S7

DESIGN APPROACH

In order to calculate the sectional strength of a plated slab, a standard sectional analysis can be undertaken and such work has been extensively reported in the open literature (e.g. Hollaway and Teng 2008). To consider premature failure due to IC debonding, the maximum stress in the FRP can be limited (ACI 440 2008) and an expression of such stress has typically been derived from FRP-to-concrete joint shear strength tests. In order to consider the strengthening effect provided by the FRP anchors, the same approach can be adopted via an increase in the allowable stress. Calculation of the contribution provided by each anchor in slab S7 (largely as a function of the distance between the anchor and the nearer slab crack) gives a strength increase of about 5 % which is consistent with the increase in the strength of an anchored FRP-to concrete joint of same anchor position as tested by Smith and Kim (2008). The relationship between anchor contributions in the slab tests to the anchor contribution in FRP-to-concrete joint tests is therefore established.

CONCLUSIONS

The effectiveness of strengthening RC slabs with large penetrations with FRP composites has been demonstrated in this paper. Load-displacement responses as well as detailed descriptions of the behaviour, strength and failure of all three slab specimens have been reported. FRP anchors were found to increase the strength of the system and delay complete loss of the strengthening plates due to debonding. Anchors also offered a post-debonding reserve of strength and introduced ductility in the system.

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