International Institute for FRP in Construction
FRPRCS-14, Belfast - June 2019

Evaluation of design models for predicting the strength of prestressed T beams using CFRP and patch anchors

Kalfat R[1], Jumaah R[1], Al-Mahaidi R[1], Abdouka K[1], Hashemi J[1]

[1] *Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC, Australia, 3122*

Abstract

The strengthening of existing bridges is on the rise due to factors such as population growth, higher traffic volumes and heavier vehicles. Currently, traditional strengthening methods have been superseded by newer strengthening technologies such as the use of fibre reinforced polymer composites (FRP's). Despite the many advantages of FRP systems, the bond between the FRP and the concrete remains a zone of weakness which often results in FRP debonding failure at relatively low levels of FRP strain utilisations. Research has been in progress over the past two decades in order to develop anchorage systems which mitigate the occurrence of premature FRP debonding, however their widespread use has been offset by the lack of strength prediction models. In this paper, we will evaluate the accuracy of both the ACI318-14, general and simplified MCFT in predicting the shear capacity of three prestressed beams strengthened using FRP laminates and patch anchors. The contributions from the FRP laminates was estimated using ACI440.2-17 and AS5100.8-17. A semi empirical (SE) model was used to obtain the contributions from the patch anchored laminates.

Keywords: Shear strengthening, MCFT, Anchorage systems, FRP, Post-Tensioned

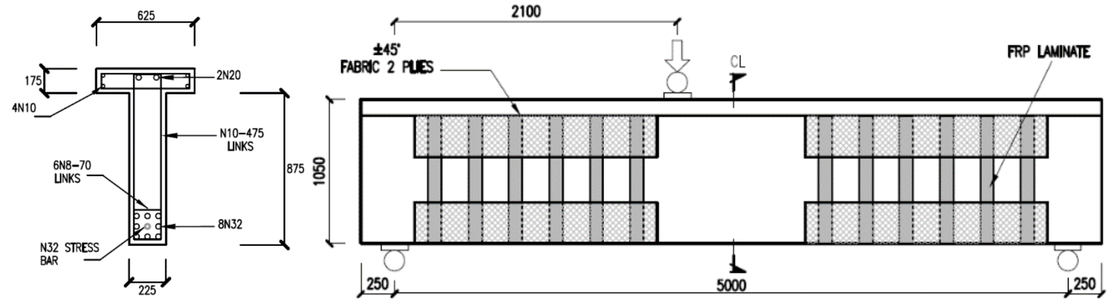
Corresponding author's email: rkalfat@swin.edu.au

Introduction

Existing bridges may also require strengthening due to deterioration caused by reinforcement corrosion, concrete carbonation, sulphate attack or alkali aggregate reaction (AAR). Currently, traditional strengthening methods such as: concrete jacketing, externally bonded steel plates or external post tensioning have been superseded by newer strengthening technologies such as the use of fibre reinforced polymer composites (FRP's) as externally bonded or near surface mounted reinforcement. Fiber reinforced polymers possess many advantages over traditional strengthening methods due to their light-weight, high tensile strength, resistance to corrosion, durability and ease of installation. Despite the many advantages of FRP systems, the bond between the FRP and the concrete remains a zone of weakness which often results in FRP debonding failure at relatively low levels of FRP strain utilisations. Research has been in progress over the past two decades in order to develop anchorage systems which mitigate the occurrence of premature FRP debonding. Patch anchors consist of bi-directionally orientated fibre sheets bonded to the ends of the FRP laminate and adjacent concrete (Al-Mahaidi and Kalfat 2011) have shown exceptional performance in increasing the bond perforamnace between FRP and concrete and have to increase the maximum FRP strain achieved prior to debonding from 2875 με to up to 5600 με, a 95% increase based on FRP-to-concrete joint tests. The present study aims to capture the omited variables in previous experimental studies by evaluating the performance of patch anchors applied to post tensioned beams strengthened in shear with FRP laminates. The experimental results are evaluated agaist existing shear strength prediction models such as the general and simplified modified compression field theories (MCFT) and the models available in ACI318 (2014). Models to predict the strength of the strengthened and anchored beams will also be examined and reccommendations made based on the findings.

Experimental Program

Three full scale post-tensioned T-beam were designed with span length of 5000 mm, a whole depth of 1050 mm. 625 mm, 175 mm flange width and depth respectively. Web width of 225 mm and depth 875 mm. Eight Ø32 mm diameter as longitudinal reinforcement and one Ø32 mm post-tensioned bar as shown in Figures (1a), which represent the cross section of the beam. In order for the beam to fail in shear, the spacing between the stirrups, which is 475 mm, is made to be more than the minimum spacing required for the shear reinforcement. Ø10 mm bars were used for the stirrups, and the duct of the post tensioned bar had a diameter of 38 mm. Three T-Beams were tested under three point bending moment loading. The first specimen was left without Strengthening as a control beam (C). The second specimen (ST) was strengthened using CFRP laminates strips of 100 mm width, and with spacing of 300 mm c/c, twelve strips were placed at each side of the beam divided into two groups of six strips in the shear areas of the beam. The third beam (STA) was strengthened using CFRP laminates with epoxy as an adhesive, with the same spacing and configurations of the strengthening in beam two. The laminates were anchored at both ends using two plies of CFRP bi-directional sheets with ± 45° fabric as shown in Figure (1b).



(a) (b)

Figure 1: (a) Cross section of the beam; (b) strengthened specimen with CFRP sheets anchors

Before the experiments, steel plates were applied at top and bottom of half of the beam, followed by applying high tensile steel bars at both sides of the flange through pre-drilled holes. Later, these bars were post-tensioned to a certain force with a hydraulic jack. This measure was taken, so that half of the beam would fail during the test, and for each beam to be tested twice.

Evaluation of design models for predicting the strength concrete beams strengthened in shear with CFRP

In this paper, we will evaluate the accuracy of both the general and simplified MCFT in predicting the shear capacity of the tested beams. An evaluation will also be made with the shear design provisions present in the current American Concrete Institute Concrete Structures code, ACI318 (2014). The general MCFT predictions were obtained using Response 2000 and the simplified MCFT results were obtained using the design procedures in the AS3600 (2018). The calculations were first performed on the unstrengthened control beam and the results are summarised in table 1 below:

Table 1: Results summary of models used to predict the strength of the unstrengthened control beam

	V_c kN	V_s kN	θ_v °	V_u kN	P_u kN
Simplified MCFT	374.8	254.9	29.7	629.7	1085.7
Response 2000				737.0	1270.7
ACI318	594.0	168.0	45.0	762.0	1313.8
Control, exp			40.0	705.3	1216.0

The concrete contribution (V_c) as well as the stirrup contributions (V_s), the total shear capacity (V_u) and the angle of inclination of the critical diagonal shear crack (θ_v) are presented in table 1 for the three design procedures and the experimental results (Control, exp). The results were indicative that the general MCFT offered the most accurate prediction of the failure load with an overestimation of 4.5%. In contrast, the ACI318 (2014) overestimated the capacity of the beam by 8.0% and the simplified MCFT was the most conservative and underestimated the strength of the beam by 10.7%.

Predicting the capacity of the strengthened beams

After determination of the capacity of the control beams in accordance with MCFT and ACI318 (2014), the capacity of the strengthened beams was computed by adding the contribution from the FRP reinforcement to the shear strength in accordance with the ACI 440.2 (2017). Table 2 summarises the results for the strengthened beams:

Table 2: Results summary of models used to predict the strength of the strengthened beams (ST1 and ST2)

	V_c+V_s	$\varepsilon_{fe,pred}$	θ_v	$\psi_f V_f$	$V_{u,\ pred}$	P_{pred}	P_{exp}
	kN	με	°	kN	kN	kN	kN
Simplified MCFT	635.7	2720	29.7	227.0	862.7	1487.4	1534.0
Response 2000	750.4	2720	29.7	227.0	977.4	1685.2	1534.0
ACI318	772.0	2720	45	129.5	901.5	1554.3	1534.0

Table 2 provides a completely theoretical prediction of the capacity of the strengthened beams in accordance with the simplified MCFT, Response 2000 and ACI318 (2014). The contribution of the FRP to the shear capacity of the beams was determined in accordance with ACI440.2 (2017) and AS5100.8 (2017). The key difference between the ACI440.2 (2017) and the AS5100.8 (2017) approaches is that the ACI440.2 assumes a fixed shear crack inclination angle of 45 degrees and the AS5100.8 assumes a variable shear crack inclination angle (θ_v) which is calculated based on the maximum longitudinal concrete strain at the critical shear section as per AS3600 (2018).

Predicting the capacity of the strengthened beams anchored with bidirectional fiber patches

In order to predict the capacity of the anchored beams using a purely theoretical approach, it is necessary to estimate the maximum strains in the FRP laminates prior to failure when anchored with bidirectional patches. Previous studies conducted by Kalfat and Al-Mahaidi (2014) derived a semi-empirical prediction model (herein SE model) for the strength of FRP-to-concrete patch-anchored joints using the same framework. Using the SE model described above, a patch anchor laminate strain of 5537 με was estimated for the anchored beams which when combined with the shear crack inclination angle of 29.7 degrees and a reduction factor (ψ_f) of 0.85, a FRP contribution ($\psi_f V_{f,\ SE}$) of 462.1 kN to the shear strength was predicted. This correlated well with the measured FRP contributions of 420.1 kN and 464.4 kN summarised in table 3 for specimens STA1 and STA2.

Table 3: Results summary of SE model used to predict the strength of the anchored beams (STA1 and STA2).

	V_c+V_s	$\varepsilon_{fae,\ SE}$ Model	θ_v	$\psi_f V_{f,\ SE}$ Model	$V_{u,pred}$	P_{pred}	P_{exp}
	kN	με	°	kN	kN	kN	kN
Simplified MCFT	641.0	5537	29.7	462.1	1103.1	1901.8	1957.5
Response 2000	759.2	5537		462.1	1221.3	2105.6	1957.5
ACI318	781.0	5537	45.0	263.6	1044.6	1801.0	1957.5

Conclusion

Three different shear strength prediction models were used to estimate the strength of the unstrengthened control specimen: general MCFT, simplified MCFT and ACI318 (2014). The results were indicative that the general MCFT offered the most accurate prediction of the failure load with an overestimation of 4.5% followed by the ACI318 (2014) which overestimated the strength by 8%. When predicting the capacity of the strengthened beams (ST1 and ST2), a variable inclination angle of the critical diagonal compression strut was found to give the best estimates for the shear contribution of the FRP and a fixed angle of 45 degrees was found to provide very conservative predictions. A semi empirical (SE) model was evaluated to estimate the maximum FRP laminate strain for the patch anchored laminates which was combined with the simplified MCFT and a variable inclination angle of the critical diagonal compression strut used to determine the FRP contribution. Using this approach the load was predicted within an error of 2.8%.

References

[1] ACI Committee 318. 2014. "Building Code Requirements for Structural Concrete (ACI 318-14) and Commentary," American Concrete Institute, Farmington Hills, MI.

[2] ACI 440.2. 2017. "Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures". American Concrete Institute, Farmington Hills, Michigan.

[3] Al-Mahaidi, R. and Kalfat, R. 2011. "Investigation into FRP laminate anchorage systems utilising bi-directional fabric wrap." Composite Structures 93(4): 1265-1274.

[4] AS3600. 2018. "Concrete Structures", Standards Australia, SAI Global Limited,

[5] AS5100.8. 2017. "Bridge design Part 8: Rehabilitation and strengthening of existing bridges", Standards Australia, SAI Global Limited.

[6] Kalfat, R. and Al-Mahaidi, R. 2014. "A prediction model for bidirectional fiber patch anchors used to enhance the performance of FRP materials bonded to concrete." Composite Structures 117: 51-58.

[7] Response-2000, available for download at www.ecf.utoronto. ca/~bentz/r2k.htm.