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Validation of ACI Models for Ultimate Flexural and Shear Capacities of CFRP Repaired RC Beams

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Abstract

Research is still ongoing to establish accurate models to predict ultimate capacity of Carbon fibre Reinforced Polymer (CFRP) repaired RC beams regardless the numerous studies conducted in the area. This study aims to experimentally validate the equations provided by ACI 440.2 Code for calculating ultimate flexural and shear capacity of damaged RC beams repaired with CFRP sheets. Two design criteria are considered being flexural and shear at quarter-span. The study concluded that current ACI models result in differences from experimental results of up to 21% and 64% for flexural and shear at quarter-span, respectively.

Keywords: CFRP repair; flexural capacity; shear capacity; RC structures; design criteria; damage location

1. Introduction

Research on the use of FRP began in Europe in the 1960s (Bakis et al. 2002). The first investigation on the use of FRP plate bonding was at Swiss Fedral Laboratory for Materials Testing and Research (EMPA) in 1984 (Teng et al. 2001). FRP materials have the advantage of high tensile strength and excellent corrosion resistance, fatigue resistance, good performance at elevated temperatures, low density, and high specific stiffness and strength [Meier (1992)].

Most research on using FRP plate bonding for flexural strengthening was carried out in the last decades [Saadatmanesh et al. (1991); Triantafillou and Plevris (1992)]. There has been tremendous growth in recent years as result of increasing global needs for structural performance improving and retrofitting works. Repair of a real bridge with externally bonded FRP plates was found to decrease the flexural stresses in the steel reinforcements and the mid-span deflection (Stallings et al. 2000). Strengthening of the RC beam with one layer of the CFRP plate was found to increase the ultimate capacity by 200% and strengthening with two layers increased it by 250% (Capozucca and Cerri 2002). Fayyadh and Razak (2012) uses flexural stiffness change index to evaluate the effectiveness of CFRP repaired RC beams and found that CFRP repair system recovers stiffness and increases load capacity by up to 83%. CFRP plates increases ultimate load and decreases mid-span deflection and pre repair damage level have significant impact on the repair effectiveness (Fayyadh and Razak 2014). Al-Khafaji and Salim (2020) investigated strengthening of RC continues T-beams with CFRP sheet and found strengthen beams ultimate capacity increased by up to 90%, and for strengthen beams with CFRP to beam width ratio below 0.25 the strengthening system didn't increase stiffness however still increased ductility.

Studies on the use of the FRP plate bonding for shear strengthening started since 1990s (Malek and Saadatmanesh 1998, Khalifa and Nanni 2000), but they are still limited compared to the studies related to the use of FRP plates for flexural strengthening (Teng et. al. 2001). The strengthened beam stiffness was found to increase with the increase in the CFRP plates area on the beam sides which also delayed the appearance of

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the first flexural cracks (Li et. al. 2001). Use of U-shape anchored CFRP sheets for shear strengthening can increase the capacity up to 20% (El-Ghandour 2011). Ahmed et. al. (2015) investigated effect of plate thickness on the shear repair effectiveness of CFRP and steel plated for RC beams with web opening and found that increase steel plate thickness had small effect on maximum load capacity, while CFRP plate thickness have higher effect of the ultimate load capacity. Ahmed et. al. (2016) investigated shear repair effectiveness of CFRP and steel plated for RC beams with web opening and found that both CFRP and Steel plates are effective repair solution however CFRP plates perform better and that rectangular configurator is better than hexagonal one.

Many design equations and guidelines were proposed for calculating the flexural capacity of the strengthened RC beams with bonded FRP plates based on the design approach of ACI-318 code (Malek and Saadatmanesh 1998, El-Mihilmy et. al. 2000). The effect of the pre-strengthening or existing strain in the beam soffit on the FRP bonded plates contribution to the flexural capacity has been studied by Lam and Teng (2001) and the effect was considered in the design equations as shown by Saadatmanesh et al. (1998). In the last decade, many studies have proposed mathematical models for the calculation of the FRP plate contribution to the shear capacity of the strengthened beams (Chaallal et. al. 1998, Khalifa et. al. 1998 Chen and Teng 2001, Chen and Teng 2003). A simple approach for the design of the concrete beams strengthening with externally bonded FRP plate was proposed where the maximum and minimum limits of the FRP plate were established (El-Mihilmy and Tedesco 2000). The contribution of the FRP plate to the ultimate shear of strengthened beams depends on the quantity of the FRP and ratio between the steel stirrup and the FRP plates (Pellegrino and Modena 2002). Shaw and Andrawes (2017) studied the effect of accelerated aging on CFRP laminate repair effectiveness and found that the repair system are effective regardless the environmental aging condition. Al-Karkhi and Aziz (2018) investigated the effect of CFRP strips on shear strength of self-compacting concrete hammer head beams and concluded that strengthened beams shows enhance in shear capacity by up to 30%. El-Taly et. al. (2018) investigated the performance enhancement of precast-prestress hollow core slabs strengthen with GFRP and CFRP strips and near surface mounted GFRP bars, and found that GFRP strips are the most effective repair system also they found that adopted strengthening systems enhance ductility and energy observation. Xie and Wang (2019) conducted reliability analysis of the CFRP repaired RC bridges considering effect of CFRP sizes and concluded that CFRP strengthening system improves safety of structures effectively irrespective of the CFRP size.

The American concrete institute (ACI) started to consider the FRP bonded plate as construction material with the first work on the FRP plate being a state of the art report on the use of the FRP for concrete structures in 1996 (ACI-440R 1996). The first design guideline for the use of the fibre composite materials was released by the ACI-440-2R (2000), followed by a guideline for the design of externally bonded FRP system in ACI-440-2R (2002). The work in the ACI was continually updated on the use of the externally bonded FRP plate or using of FRP bars as reinforcement, according to the finding of new researches and the needs arising (ACI-440.3R 2004, ACI-440R 2007, ACI-440.2R 2008).

Although many studies have been carried out for the flexural and shear design of RC structures repaired with externally bonded CFRP sheet, research is still ongoing in the area of failure mechanism and prediction of ultimate capacity. Based on previous studies, more research needs to be done for better understanding of the concrete behaviour at flexural and shear and interaction with CFRP sheets. Therefore, this study aims to evaluate the equations provided by the ACI 420.2 Code for prediction of flexural and shear ultimate load capacity of RC beams repaired with CFRP sheets.

2. Experimental work program

Total of 7 reinforced concrete beams were prepared for this study. These were divided into two damage location scarious being, flexural damage at mid-span with total of 3 beams, and shear damage at quarter-span with total of 4 beams. The design criteria for the flexural case adopted minimum (ρ_{min}) flexural steel limit. Two design criteria for shear case are adopted as RC beam with shear steel stirrups and RC beams without shear steel stirrups. Three pre-repair damage levels were considered for the flexural scenario, and these being damage at design load limit, damage at steel yield load limit and damage at failure load. Two pre-repair damage scenarios were considered for the shear damage at quarter span being damage at design load limit and damage at failure load. Table 1 presents the classification of the tested RC beams.

Table 1 Classification according to damage scenario, design case and damage level

Beam No.	Damage Location	Design Case	Pre-repair damage level
B122m	Flexural	ρ_{min}	Design load limit
B123m	Flexural	ρ_{min}	Steel yield load limit
B124m	Flexural	ρ_{min}	Failure load
B212q	Shear at quarter-span	With stirrups	Design load limit
B211q	Shear at quarter-span	With stirrups	Failure load
B222q	Shear at quarter-span	Without stirrups	Design load limit
B221q	Shear at quarter-span	Without stirrups	Failure load

The clear span length for each beam is 2.2m, with a beam cross section of 150mm and a width of 250mm. For flexural structural design of the pre-repaired beams, ACI 318 (2008) was used. Based on the ACI Code, there is provision for two limits of the steel ratio in the tension layer as reinforcement requirements for structural elements are subjected to flexure. Minimum steel limit (ρmin) is provided to prevent cracking due to thermal expansion while the maximum steel limit (ρmax) is provided to prevent brittle failure due to crushing of concrete. Thus, in this study, taking into consideration the minimum steel limit (ρmin). The flexural beams were designed in shear to make sure that the beam will not fail in shear failure, by using shear stirrups with close spacing to ensure high shear resistance. Two 12 mm diameter deformed steel bars as the main flexural reinforcement, two 8 mm diameter round steel bars were used as the compression reinforcement, and for the shear design 6mm diameter with spacing of 50mm where used along the beam length in order to achieve the highest shear resistance. Fig. 1 shows the cross-section detail for flexural beams.

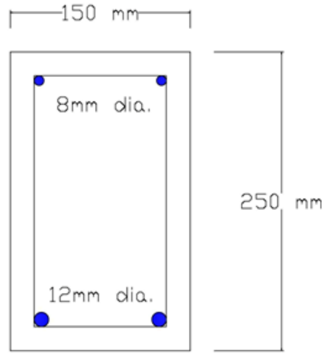

Fig. 1 Cross section detail for flexural beams, with ρmin

For the shear structural design of the pre-repaired beams, ACI 318 (2008) was used. There are two shear design cases i.e. one with internal shear stirrups in which the shear forces are resisted by the stirrups and concrete, while another without the internal shear stirrups in which all the shear forces are resisted solely by the concrete. This study will consider both design cases, with and without shear stirrups. The RC beams were designed to resist a concentrated load located at the quarter-span in addition to the self-weight of the beams. The shear group beams were designed in flexural to make sure that the beam would not fail in flexural, by using flexural steel bars with ρmax to ensure high flexural capacity. For the group without shear stirrups, two 16 mm diameter deformed steel bars were used as the main flexural reinforcement and no shear stirrups were used. For the group with stirrups, 6mm diameter steel bars with spacing of 100mm c/c were used as shear stirrups, two16 mm diameter deformed steel bars were used as the main flexural reinforcement and two 8 mm diameter not-deformed steel bars were used as the compression reinforcement. Fig. 2 shows the cross-section detail at the shear zone of the RC beams of both cases, with and without shear stirrups. The concrete material properties in term of compressive strength and modulus of elasticity; and steel reinforcement material properties in term of yield stress, rapture stress and modulus of elasticity of the 7 tested beams are shown in Table 2.

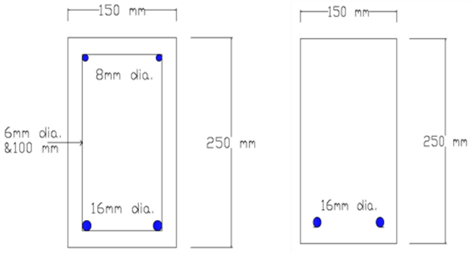

Fig. 2 Cross section detail for shear beams, with stirrups (left) and without stirrups (right)

Table 2 Concrete and Steel material properties

Beam No.	Concrete Compressive strength (MPa)	Concrete Elasticity Modulus (GPa)	Steel Yield Stress (MPa)	Steel Rapture Stress (MPa)	Steel Elasticity Modulus (GPa)
B122m	36	30	535	665	180
B123m	36	33	565	785	180
B124m	35	31	565	785	180
B212q	33	30	520	680	180
B211q	32.3	29	520	680	180
B222q	41	36	520	680	180
B221q	38	35	520	680	180

The ACI 420.2R (2002) is used as the design guideline for externally bonded CFRP for repairing RC structures. The design of flexural repair with externally bonded CFRP sheets was based on achieving the maximum capacity without debonding failure of CFRP sheets in order to achieve the highest CFRP strength. CFRP sheet with 100mm width and 1.2 mm thickness was found to give the highest increase in the capacity before the CFRP debonding. The CFRP sheets were designed to be placed on the beam soffit and along the beam length between the supports. The ACI 420.2R (2002) is used as the design guideline for repairing damaged beams in shear with externally bonded CFRP sheets. The objective of the repair with CFRP sheets design is to achieve the highest capacity by using the CFRP sheets within the limits of the ACI Codes. Three CFRP sheets with width of 100mm and thickness of 1.2mm are used on both sides of the beam between the quarter-span and the support within an inclined angle of 45^0.

Sika-Carbo-Dur S1012 sheets were used as Shear repair systems. The properties of the CFRP sheets are adopted as given by the SIKA data sheet, refer to Table 3. Since the CFRP sheets used were externally bonded, the Sikadur-30 which is also the product of SIKA was used as the adhesive layer between the CFRP sheets and the concrete surface. The tension face was roughened to get a suitable face to give as much friction as possible with the CFRP sheet. Fig. 3 shows the roughened surface prepared using scaling hammer and fixing of the CFRP sheets. The surface was cleaned by using an air gun to avoid any dust on the surface, as the substrates must be sound, dry, clean and free from laitance, standing water, grease, oils, old surface treatments or coatings and all loosely adhering particles. The concrete was cleaned and prepared to achieve a laitance and contaminant free, open textured surface. When the concrete surface was prepared, the CFRP sheet was fixed by using Sikadur-30 adhesive material and then was left for one month for hardening to avoid the effect of adhesive setting time on the dynamic properties, as advise by Fayyadh & Razak (2013).

Fig. 3 Surface preparation and CFRP fixing for flexural and shear

Table 3 CFRP material properties

	Longitudinal direction
Tensile strength (MPa)	2,800
Modulus of Elasticity (MPa)	165,000
Ultimate strain (mm/mm)	0.017

Static test is used in this study to induce damage into the RC beams at pre-repair damage stage as per damage levels illustrated in Table 1 above, then to apply load at the post-repair stage to find the ultimate failure load. The static load test includes application of concentrated load to the RC beams at different locations to induce damage as illustrated in Table 1 above, i.e. load at mid-span for flexural scenario, and load at quarter-span for shear scenario at quarter span. A steel frame is used to apply the load using a load actuator controlled by a servo hydraulic pump. Load was applied gradually at a loading rate of 0.75 kN/min. and applied in cycles of loading and unloading. A 50mm displacement transducer was placed at the point of the maximum deflection to measure the displacement. The load cell of 250 kN capacity was placed directly below the hydraulic load actuator to measure the loads, as shown in Fig. 4. The CFRP sheets strain was measured using strain gauges fixed on the CFRP sheets surface at the maximum expected strain positions.

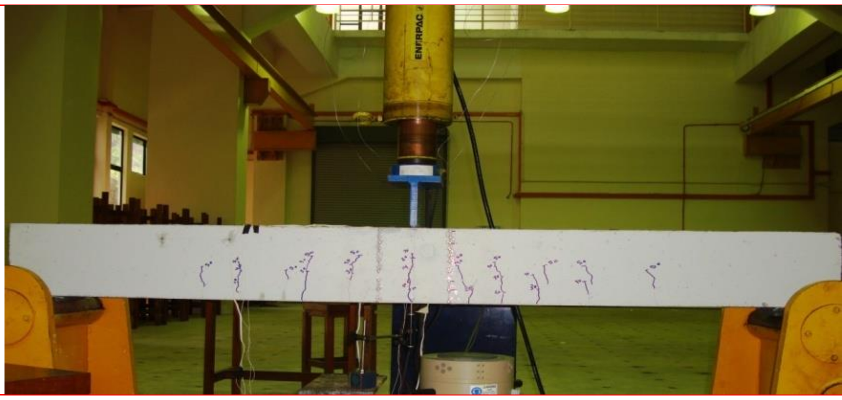

Fig. 4 Beam under static test – flexural scenario

3. Results and Discussion

After carrying out the static tests and obtaining the ultimate loads for CFRP repaired RC beams in flexural and shear, the ACI models results for predicting ultimate capacities are compared to that of the experimental work. For the purpose of the evaluation and since the comparison with the experimental results is based on the ultimate capacity, all the safety factors are neglected from the ACI equations in order to find the actual ultimate capacity of the RC beams.

3.1 Repaired RC beams in Flexural

This section presents the comparison between ACI model and experimental results for the flexural repaired RC beams. The comparison covers the results for beams B122m, B123m and B124m. The comparison highlights the values of the ultimate load capacity and CFRP debonding strain as shown in Table 4. The CFRP debonding strain is in better agreement than the ultimate capacity results. The ACI model results show a higher CFRP debonding strain values compared to the experimental results with maximum difference of 11%. The difference in the CFRP debonding strain could be due to the assumption of the ACI model, that is, the stress distribution corresponding to the depth of the cross section.

Table 4 Results for the repaired flexural beams - original ACI model

Beam	Case	Ultimate load capacity (kN)			CFRP debonding strain (µst)		
		Experimental	ACI Code	Dif. %	Experimental	ACI Code	Dif. %
B122m	ρ_{min} & Damage at design load limit	131	103.4	-21.0	6100	6780	11.1
B123m	ρ_{min} & Damage at steel yield load limit	130.7	105.2	-19.5	5400	5900	9.
B124m	ρ_{min} & Damage at Failure load	128	101	-21.1	5890	5460	-7.3

For the ultimate load capacity, the ACI model results show smaller values than the experimental results by 21.1%. The differences between ACI model and experimental results could be due to the ACI model assumptions for the ultimate concrete crushing strain which is taken to be 3000 µst while the actual value can be higher. The ACI model advises not to consider the steel reinforcement at the compression zone when calculating the ultimate capacity for the repaired section and this can be another reason behind the smaller ACI model results compared to the experimental results. In the actual repaired RC beam the steel reinforcement at the compression zone are still working and sharing the compression stresses. Therefore, considering the compression zone steel reinforcement can reduce the difference between ACI model and experimental results.

3.2 Repaired RC beams in shear – damage at quarter span

This section presents the comparison between ACI Code and experimental results for the shear scenario when the load is applied at the quarter-span. The results for the repaired beams with CFRP sheets are presented. For the repaired shear beam when the load is applied at quarter-span, four beams are tested in two groups. The first group is designed with the shear stirrups, that is, B211q and B212q, where beam B211q is damaged under the ultimate load capacity at the pre-repair damage stage and beam B212q is damaged under the design load limit at the pre-repair damage stage. The second group is designed without the shear stirrups, that is, B221q and B222q, where beam B221q is damaged under the ultimate load at the pre-repair damage stage while B222q is damaged under the design load limit at the pre-repair damage stage.

The comparison between ACI Code model and experimental results is based on the ultimate repair capacity and the maximum CFRP sheet strain at failure, and the results are shown in Table 5. The results show very large differences between ACI model and experimental results in terms of ultimate shear capacity and CFRP strain at failure. The difference in the CFRP strain is higher than the ultimate shear capacity. For both ultimate capacity and CFRP strain values, ACI model results show much higher values than the experimental results which an overestimate of the shear capacity. Repaired beams that where damaged under ultimate load at pre-repair damage stage show a higher difference in terms of ultimate capacity, and the beams without stirrups show lower difference than the beams with stirrups. The significant difference between the ACI model and the experimental results could be due to the assumptions of the ACI Code while calculating the contribution of concert, steel reinforcements and CFRP to the ultimate capacity.

Table 5 Comparison of ACI Code and experimental results for repaired shear beam at quarter-span

Beam	Case	Ultimate load capacity (kN)			CFRP debonding strain (μst)		
		Experimental	ACI Code	Dif. %	Experimental	ACI Code	Dif. %
B212q	With stirrups & Damaged at design load limit	120	178.5	48.8	660	1490	125.8
B211q	With stirrups & Damaged at ultimate load	107	176.4	64.9	695	1460	110.1
B222q	Without stirrups & Damaged at design load limit	120	165.2	37.7	800	1750	118.8
B221q	Without stirrups & Damaged at ultimate load	101	155.3	53.8	720	1630	126.4

The main considerations which can be taken into account in modifying the ACI Code equations are as follows:

- The ACI equations show no consideration for the pre-repair damage level on the calculation of the ultimate capacity in the repair stage.
- The contribution of the shear stirrups to the ultimate capacity is higher than the actual values, where beams with stirrups show higher difference.
- The CFRP contribution to the ultimate capacity is higher than the actual values, where the CFRP strain is much higher than the actual values.

4. Conclusions

From this study, the following conclusions can be drawn:

- ACI Code model for calculating ultimate flexural capacity of CFRP repaired beams shows smaller values than the experimental results since the ACI assumptions neglect steel bars at the compression zone.
- ACI Code model for calculating ultimate shear capacity of CFRP repaired beams shows significantly higher results than the experimental results since ACI question did not consider pre-repair damage effect.
- ACI Code models correlate better in flexural than shear, however the differences between ACI code and experimental results are still significant.

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References

ACI 318 (2008), *Building Code Requirements for Structural Concern,* American Concrete Institute, Farmington Hills, MI, USA.

ACI-440.2R (2008), *Guide for the Design and Construction of Externally Bonded FRP Systems For Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, MI, USA.

ACI-440.3R (2004), *Guide for Test Methods for Fiber Reinforced Polymers (FRP) for Reinforcing and Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, MI, USA.

ACI-440-2R (2000), *Design Guidance for Strengthening Concrete Structures Using Fiber Composite Materials*, American Concrete Institute, Farmington Hills, MI, USA.

ACI-440-2R (2002), *Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*, American Concrete Institute, Farmington Hills, MI, USA.

ACI-440R (1996), *State-of-the-Art Report on FRP for Concrete Structures, Manual of Concrete Practice*, American Concrete Institute, Farmington Hills, MI, USA.

ACI-440R (2007), *Report on Fiber-Reinforced Polymer (FRP) Reinforcement for Concrete Structures*, American Concrete Institute, Farmington Hills, MI, USA.

Ahmed, A., Naganathan, S., Nasharuddin, K., and Fayyadh, M.M. (2015), " Repair Effectiveness of CFRP and Steel Plates in RC Beams With Web Opening: Effect of Plate Thickness", *International Journal of Civil Engineering*, **13** (2 And A), 235-244. DOI: 10.22068/IJCE.13.2.234

Ahmed, A., Naganathan, S., Nasharuddin, K., Fayyadh M.M., and Hamali, S. (2016), " Repair Effectiveness of Damaged RC Beams with Web Opening Using CFRP and Steel Plates", *Jordan Journal of Civil Engineering*, **10** (2), 163-183. https://jjce.just.edu.jo/issues/paper.php?p=3534.pdf

Al-Khafaji, A., and Salim, H. (2020), "Flexural Strengthening of RC Continuous T-Beams Using CFRP", *Fibers*, **8** (6), 41. https://doi.org/10.3390/fib8060041

AL-Kharkhi, H., and Aziz, A. (2018), "Shear Strengthening of Reinforced Self-Compacted Concrete Hammer Head Beams Using Warped CFRP Strips: Experimental and Theoretical Study", *Jordan Journal of Civil Engineering*, **12**(4), 629-636..

Bakis, C.E., Bank, L.C., Cosenza, E., Davalos, J. F., Lesko, J.J., Machida, A., Rizkalla, S.H., and Triantafillou,T. (2002), "Fiber-Reinforced Polymer Composites for Construction - State of the art Review", *Journal of Composites for Construction*, **6**(2), 73-87. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(73)

Capozucca, R., and Cerri, M.N. (2002), " Static and Dynamic Behaviour of RC Beam Model Strengthened by CFRP-Sheets", *Construction and Building Materials*, **16**(2) 91-99. https://doi.org/10.1016/S0950-0618(01)00036-8

Chaallal, O., Nollet, M.J., and Perraton, D. (1998), " Strengthening of Reinforced Concrete Beams with Externally Bonded Fiber-Reinforced-Plastic Plates: Design Guidelines for Shear and Flexure", *Canadian Journal of Civil Engineering*, **25**(4), 692-704. https://doi.org/10.1139/l98-008

Chen, J.F., and Teng, J,G. (2003), "Shear Capacity of FRP-Strengthened RC Beams: FRP Debonding", *Construction and Building Materials*, **17**(1), 27-41. https://doi.org/10.1016/S0950-0618(02)00091-0

Chen, J.F., and Teng, J.G. (2001), "Anchorage Strength Models for FRP and Steel Plates Bonded to Concrete", *Journal of Structural Engineering*, **127**(7), 784-791. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:7(784)

El-Ghandour, A.A. (2011), "Experimental and Analytical Investigation of CFRP Flexural and Shear Strengthening Efficiencies of RC Beams", *Construction and Building Materials*, **25**(3), 1419-1429. https://doi.org/10.1016/j.conbuildmat.2010.09.001

El-Mihilmy, M., and Tedesco, J.W. (2000), "Analysis of Reinforced Concrete Beams Strengthened with FRP Laminates", *Journal of Structural Engineering*, **126**(6), 684-691. https://doi.org/10.1061/(ASCE)0733-9445(2000)126:6(684)

El-Taly, B., HasabElnaby, Y., and Meleika, N. (2018), "Structural Performance of Precast–Prestressed Hollow Core Slabs Subjected to Negative Bending Moments", *Asian Journal of Civil Engineering*, **19**, 725–740. https://doi.org/10.1007/s42107-018-0061-0

Fayyadh, M.M., and Razak, H.R. (2012), "*Assessment of Adhesive Setting Time in Reinforced Concrete Beams Strengthened with Carbon Fibre Reinforced Polymer Laminates*", *Materials & Design*, **37**, 64-72. https://doi.org/10.1016/j.matdes.2011.12.031

Fayyadh, M.M., and Razak, H.R. (2012), "Assessment of Effectiveness of CFRP Repaired RC Beams Under Different Damage Levels Based on Flexural Stiffness", *Construction and Building Materials*, **37**, 125-134.

https://doi.org/10.1016/j.conbuildmat.2012.07.021

Fayyadh, M.M., and Razak, H.R. (2014), "Analytical and Experimental Study on Repair Effectiveness of CFRP Sheets for RC Beams", *Journal of Civil Engineering and Management*, **20** (1), 21-31. https://doi.org/10.3846/13923730.2013.799095

Khalifa, A., and Nanni, A. (2000), " Improving Shear Capacity of Existing RC T-Section Beams Using CFRP Composites", *Cement and Concrete Composite*, **22**(3), 165-174. https://doi.org/10.1016/S0958-9465(99)00051-7

Khalifa, A., Gold, J.W., Nanni, A. and Adbel-Aziz, M.I. (1998), "Contribution of Externally Bonded FRP to Shear Capacity of RC Flexural Members", *Journal of Composites for Construction*, **2**(4), 195-203. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:4(195)

Lam, L., and Teng, J.G. (2001), " Strength of RC Cantilever Slabs Bonded with GFRP Strips", *Journal of Composites for Construction*, **5**(4), pp. 221-227. https://doi.org/10.1061/(ASCE)1090-0268(2001)5:4(221)

Li, A., Assih, J., and Delmas, Y. (2001), " Shear Strengthening of RC Beams With Externally Bonded CRRP Sheets", *Journal of Structural Engineering*, **127**(4), 374-380. https://doi.org/10.1061/(ASCE)0733-9445(2001)127:4(374)

Malek, A.M., and Saadatmanesh, H. (1998), " Ultimate Shear Capacity of Reinforced Concrete Beams Strengthened With Web-Bonded Fiber Reinforced Plastic Plates", *ACI Structural Journal*, **95**, 391-399.

Meier, U. (1992), "Carbn Fiber Reinforced Polymers: Modern Materials in Bridge Engineering", *Structural Engineering International*, **2**(1), 7-12. https://doi.org/10.2749/101686692780617020

Pellegrino, C., and Modena, C. (2002), " Fiber-Reinforced Polymer Shear Strengthening of Reinforced Concrete Beams with Transverse Steel Reinforcement", *Journal of Composites for Construction*, **6**(2), 104-111. https://doi.org/10.1061/(ASCE)1090-0268(2002)6:2(104)

Saadatmanesh, H. and Malek, A.M. (1998), "Design Guidelines for Flexural Strengthening of RC Beams with FRP Plates:, *Journal of Composites for Construction*, **2**(4), 158-164. https://doi.org/10.1061/(ASCE)1090-0268(1998)2:4(158)

Saadatmanesh, H., and Ehsani, M.R. (1991), "RC Beams Stregthened with GFRP Plates I:Expermintal Study", *Journal of Structural Engineering*, **117**(11), 3417-3433. https://doi.org/10.1061/(ASCE)0733-9445(1991)117:11(3417)

Shaw, I.D., and Andrawes, B. (2017), " Finite Element Analysis of CFRP Laminate Repairs on Damaged End Regions of Prestressed Concrete Bridge Girders", *Advances in Computational Design*, **2**(2),147-168. DOI: https://doi.org/10.12989/acd.2017.2.2.147

Stallings, J.M., Tedesco, J.W., El-Mihilmy, M., and McCauley, M. (2000), "Field Performance of FRP Bridge Repairs", *Journal of Bridge Engineering*, **5**(2), 107-113. https://doi.org/10.1061/(ASCE)1084-0702(2000)5:2(107)

Teng, J.G., Chen, J.F., Smith, S.T. and Lam, L. (2001), *FRP-Strengthened RC Structures*, John Wiley & Sons England, UK.

Triantafillou, T.C., and Plevris, N. (1992), "Strengthening of RC Beams with Epoxy-Bonded Fiber-Composite Materials", *Materials and Structures*, **25**, 201-211. https://doi.org/10.1007/BF02473064

Xie H.B.,and Wang Y.F. (2019), "Reliability Analysis of CFRP-Strengthened RC Bridges Considering Size Effect of CFRP", *Materials*, 12 (14): 2247. https://doi.org/10.3390/ma12142247