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Externally Bonded FRP Applications in RC Structures: A State-of-the-Art Review

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ABSTRACT

Reinforced concrete (RC) structures suffer deterioration over the years when exposed to external loads, such as earthquakes, traffic, blasts and vibrations. Consequently, they require repairs to recover stiffness and enhance their performance. Some of the repair procedures are still based on the traditional methods of adding new structural elements or steel sections, which are time-consuming and costly, require intensive equipment and labour requirements and disrupt usage of RC structures. In recent years, externally bonded fibre-reinforced polymer (FRP) sheets have become viable alternatives to traditional methods due to their excellent characteristics. This paper presents a review of the use of FRPs as externally bonded strengthening and repair systems in RC structures. The paper presents both static and dynamic assessments based on modal parameters for the assessment of FRP system effectiveness, with special focus placed on flexural and shear applications. Finally, the paper covers the mathematical assessment of FRP system effectiveness.

KEYWORDS: Fibre polymer composite, FRP, Concrete bond, Modal testing, Static assessment, Shear failure, Debonding failure.

INTRODUCTION

Research on the use of fibre-reinforced polymer (FRP) began in Europe in the 1960s (Bakis et al., 2002). The first investigation concerning the use of FRP plate bonding was conducted at the Swiss Federal Laboratory for Materials Testing and Research (EMPA) in 1984 (Teng et al., 2001). FRPs have the advantages of high tensile strength fibres and excellent corrosion resistance, fatigue resistance, good performance at elevated temperatures, low density and high specific stiffness and strength (Meier, 1922; Almakt et al., 1998). Many experimental and analytical studies have been conducted on the strengthening of RC beams with different FRP types. Much of the research is related to the design criteria and failure modes for strengthening RC beams with FRPs. This paper presents a review of the use of externally bonded FRP plates in RC structures, as described in the flowchart in Figure (1). The paper presents static assessment studies for both the flexural and shear applications of FRP systems, with special focus placed on failure modes and the effect on the ultimate load capacity. Moreover, the paper presents dynamic assessment studies-based on natural frequency and mode shape– and mathematical assessment studies.

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Static Assessment Studies

This section presents previous studies based on static assessment methods for the flexural and shear applications of FRP systems, with particular focus on failure modes and ultimate load capacity.

Flexural Applications of FRP

Most research on the use of FRP plate bonding for flexural strengthening was conducted in the last decade of the twentieth century (Ritchie et al., 1991; Saadatmanesh et al., 1991; Triantafillou et al., 1992). There has been explosive growth in recent years due to the increasing global needs for structural performance updating and retrofitting works. Three schemes exist for the adhesion of FRP plates to the soffit of RC beams: 1) adhesive bonding of prefabricated FRP plates, 2) wet lay-up and 3) resin infusion. The use of bonded prefabricated FRP plates was found to ensure the highest degree of material uniformity and quality control (Saadatmanesh et al., 1991; Triantafillou et al., 1992; Quantrill et al., 1996; Ross et al., 1999). The wet lay-up method gives the greatest flexibility for field use and is the cheapest option; however, it is sensitive to the unevenness of the beam's soffit, which can lead to debonding (Meier, 1995; Karbhari and Zhao, 1998). The characteristics of resin infusion are similar to those of wet lay-up; however, this option is used less often (Karbhari and Zhao, 1998; Varastehpour and Hamelin, 1997). The end anchorage prevents the plate end debonding and can be bonded or bolted (Ritchie et al., 1991). The use of the end anchorage was found to at least delay the plate end debonding (Sharif et al., 1994; Garden and Hollaway, 1998). Properly designing the anchorage system can increase the load capacity by up to 70% (Spadea et al., 1998). The CFRP strain was found to reach 50% of its ultimate capacity without anchorage, whereas it was found to reach 86% when an anchorage system was used (Spadea et al., 1998). More studies are required to develop the understanding of the effect in the anchorage regions of the FRP plates (Buyukozturk and Hearing, 1998).

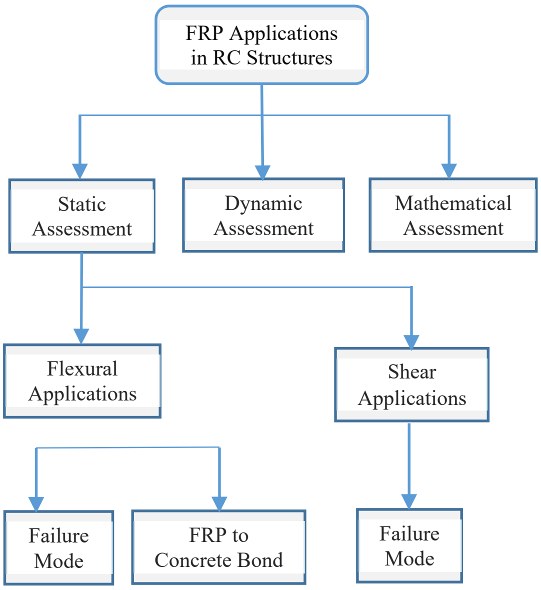

Figure (1): Flowchart illustrating the study structure

CFRP plates were found to increase the flexural capacity within certain limits (Almakt et al., 1998). Externally bonded CFRP plates were found to perform well under the effect of the impact loading (Erki and Meier, 1999). Adding an anchorage system at the end of the plates can improve the impact performance of the strengthened beam (Erki and Meier, 1999). The 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). The strengthening of concrete beams with externally bonded FRP plates was found to increase the ultimate capacity by 70% and reduce the size and density of cracks along the beam's length (Fanning and Kelly, 2001). A significant increase in the ultimate capacity was observed after externally bonded CFRP sheets were added (Nguyen et al., 2001). The ultimate capacity of strengthened beams increased by up to 230%; even for the preloaded beam before strengthening, the ultimate capacity significantly increased. This indicates good performance for repair situations (Rahimi and Hutchinson, 2001). The magnitude of the increase in the ultimate capacity is related to the content of the tensile and shear steel reinforcement and the properties of the concrete cover (Rahimi and Hutchinson, 2001). Externally bonded CFRP sheets were found to enhance the performance and increase the capacity of concrete beams under high rates of loading. The magnitude of the increase in the ultimate capacity depends on the amount of CFRP, steel reinforcement and failure mode (White et al., 2001).

The strengthening of corroded RC beams with externally bonded CFRP plates was found to increase the ultimate capacity by 37% to 87% (Masoud et al., 2001). Strengthening an RC beam with one layer of the CFRP plate was found to increase the ultimate capacity by 200%, while strengthening with two layers increased it by 250% (Capozucca and Cerri, 2002). Furthermore, strengthening cracked bridge cap beams with externally bonded FRP sheets reduced the stresses of the steel reinforcement at the positive and negative moment regions. In addition, the location of the neutral axis at the positive moment region shifted downwards (Hag-Elsafi et al., 2002). An art review for the application of FRP plates in construction was performed by Bakis et al. (2002). The use of CFRP plates for the repair of damaged prestress bridge girders restored a portion of the lost flexural stiffness and reduced the mid-span deflection (Klaiber et al., 2003). Repairing corroded concrete beams with externally bonded CFRP sheets was found to increase the load capacity by up to 30% (Kutarba, 2004).

Blast-damaged RC beams repaired with FRP sheets showed significant improvement in flexural stiffness over unrepaired beams, even exceeding that of undamaged beams (Hudson and Darwin, 2005). When used to strengthen RC beams, CFRP laminates have been shown to be capable of doubling the load capacity, with deflection close to that of unstrengthened beams (Barros and Fortes, 2005; Barros et al., 2006). The load capacity of the strengthened beams can be increased if monolithic action exists between the beam and the FRP plates. This can be achieved by using either a chemical bonding material, epoxy resin or mechanical shear connectors (Jumaat and Ashraful-Alam, 2006). Premature plate end debonding was found to be a major problem regarding the use of FRP plates for strengthening RC beams. However, using proper end anchorage can prevent this (Jumaat and Ashraful-Alam, 2006). Repairing impact-damaged prestress concrete bridge girders with externally bonded CFRP sheets has been found to result in improved capacity, even surpassing the capacity of undamaged girders (Miller, 2006). CFRP sheets have been shown to have good ability to restore ultimate capacity and even increase it, regardless of the pre-repair damage level and the concrete class. Even when failure occurs as interfacial debonding, it has been possible to proceed with further CFRP replacement (Benjeddou et al., 2007). An experimental work on the flexural strengthening of RC beams with externally bonded plates, steel and CFRP found that strengthened beams have higher failure loads, better failure modes, less deflection and a better cracking pattern compared to unstrengthened beams (Jumaat and Ashraful-Alam, 2007).

Strengthening with wet lay-up-based fabric strips has shown strength enhancement of 73%, while strengthening with pultruded strips has shown enhancement of 59% (Ghosh and Karbhari, 2007). The use of CFRP sheets for strengthening RC beams can increase the strength by up to 220% and significantly reduce the deflection (Decker, 2007). The retrofitting using CFRP sheets of a bridge subjected to overloading was performed in October 2003. A significant increase in the bending stiffness was noticed at the ultimate limit state, with a relatively small increase at the service load levels. Moreover, the cracks were monitored for any movement; as of July 2006, none was found (Decker et al., 2007). Increasing the prestressing of the CFRP rod used for strengthening RC beams resulted in increased flexural capacity, but reduced ductility (Badawi and Soudki, 2009). The use of CFRP sheets for repairing steel beams of steel–concrete composite girders increased the flexural strength by 51% (Fam et al., 2009).

Repairing corroded RC beams with bonded CFRP sheets was found to restore the undamaged state stiffness and reduce the ultimate deflection compared to unstrengthened beams (Al-Saidy et al., 2010). A review of existing studies on the flexural strengthening of RC beams with CFRPs identified a need for greater research on the strengthening of continuous beams (Jumaat et al., 2010). In a study by Jumaat and Ashraful-Alam (2011), intermediate anchors were used to prevent the premature shear failure of flexural strengthened RC beams with CFRP sheets. Additionally, an optimization design guideline was proposed. It was found that optimally designing the intermediate anchor helps improve the ultimate capacity of the strengthened beams. A review conducted by Jumaat et al. (2011) of existing studies on the performance of RC beams strengthened with externally bonded plates, steel and FRPs described the materials and methods used for flexural and shear strengthening, as well as the weakness of plate bonding systems.

The use of CFRP sheets with U-shape anchorage can increase the capacity of strengthened RC beams by 10–24% depending on the number of the U-shapes anchored along the beam's length (El-Ghandour, 2011). Repairing damaged steel beams with CFRP sheets was found to increase the ultimate capacity by up to 22.5%. The pre-repair levels did not affect the strain development in the CFRP sheets, though the debonding progression of the sheet was affected (Kim and Brunell, 2011). CFRP plates were found to be unaffected by changes in environmental conditions due to superior quality control during the manufacturing, while hand laid-up CFRP fabric was affected by elevated temperature (Cromwell et al., 2011). Jeevan et al. (2018) studied the flexural strengthening of RC beams with externally bonded prestressed and non-prestressed CFRP laminates. Their study confirmed that all adopted CFRP repair systems are effective in increasing the ultimate load of control beams. Fayyadh and Razak (2012) used a flexural stiffness change index to evaluate the effectiveness of CFRP-repaired RC beams. They found that a) flexural stiffness change is a useful index to monitor the effect of damage on beams as well as the effect of CFRP repair effectiveness, b) the CFRP repair system recovers stiffness and increases it by almost 17% compared to the undamaged stiffness (as shown in Figure 2) and c) the CFRP repair system increases load capacity by up to 83% (as shown in Figure 3).

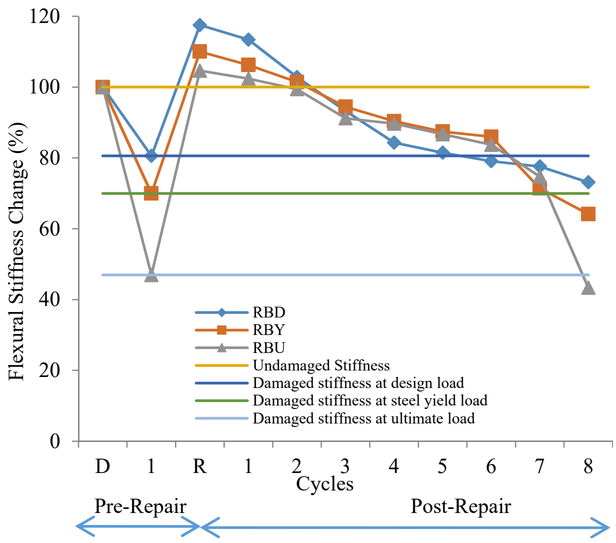

Figure (2): Flexural stiffness change corresponding to load cycles influenced by pre-repair damage levels (Fayyadh and Razak, 2012)

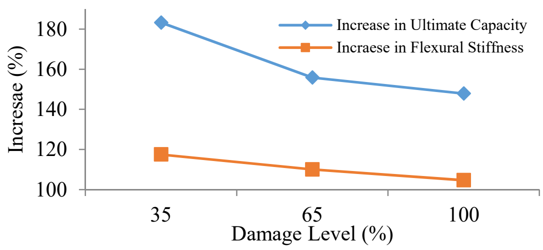

Figure (3): Increase in ultimate capacity and flexural stiffness corresponding to pre-repair damage levels (Fayyadh and Razak, 2012)

Fayyadh and Razak (2014) conducted an analytical and experimental study on the flexural repair effectiveness of CFRP sheets for RC beams. Their study discovered that CFRP plates increased ultimate load and decreased mid-span deflection. Moreover, it was found that the pre-repair damage level had a significant impact on the repair effectiveness, with higher pre-repair damage levels having lower CFRP repair effectiveness and higher steel strain, CFRP strain and deflection at the post-repair stages. Shaker and Kamonna (2016) investigated the effectiveness of prestress CFRP sheets as a strengthening system for RC beams and found that the application of CFRPs significantly increased the cracking load capacity. Jeevan and Reddy (2018) studied the flexural strength of RC beams with externally bonded CFRP laminates with and without end anchorages. They observed that the ultimate load was improved for all adopted strengthening systems. Hosen et al. (2019) studied the structural performance of lightweight concrete beams strengthened with the side externally bonded reinforcement (S-EBR) technique using CFRP fabrics. It was found that the adopted strengthening system significantly enhanced flexural capacity regardless of cracking status at the pre-repair stage. Al-Khafaji and Salim (2020) investigated strengthening of continuous RC T-beams with CFRP sheets and found that the ultimate capacity of the strengthened beams increased by up to 90%. For strengthened beams with a CFRP width to beam width ratio below 0.25, the strengthening system did not increase stiffness; however, it still increased ductility. Vuković et al. (2020) conducted an experimental analysis of RC elements strengthened with CFRP strips to determine whether the contribution of a composite material improved the mechanical behaviour of old, full-size RC T-beams in operating condition. They found that to strengthen simply supported beams, there was no need to extend the CFRP strip longer than half the span length. Furthermore, lateral anchorages were found to be not required.

In summary, there have been a significant number of studies on the use of externally bonded FRP systems for flexural strengthening or repairs. All of the previous studies confirmed the effectiveness of externally bonded FRP systems in increasing ultimate load capacity and decreasing mid-span deflection and steel reinforcement strain. Induced crack debonding and plate end depending were found to decrease the effectiveness of externally bonded FRP systems, while the use of end anchors significantly improved the effectiveness of FRPs. Finally, CFRP plates were found to be unaffected by changes in environmental conditions due to superior quality control during manufacturing.

Flexural Applications' Failure Modes

Based on studies from the last decade on the application of bonded FRP plates to the soffit of a beam as a flexural system, several failure modes have been observed. These modes can be generally classified as 1) flexural failure by FRP rupture, 2) flexural failure by the crushing of concrete at compression, 3) shear failure, 4) concrete cover separation, 5) plate end interfacial debonding, 6) intermediate flexural crack-induced interfacial debonding and 7) intermediate flexural shear crack-induced interfacial debonding, as shown in Figure (4) (Ritchie et al., 1991; Saadatmanesh and Ehsani, 1991; Triantafillou and Plevris, 1992; Ross et al., 1999; Sharif et al., 1994; Chajes et al., 1994; Heffernan and Erik, 1996; Arduini and Nanni, 1997; Bonacci and Maalej, 2000). Properly designing the anchorage system can transfer the failure mode from brittle failure to ductile failure (Spadea et al., 1998). Shear and stress concentration at the cut-off point of the FRP plate and the flexural cracks can lead to failure modes such as plate peeling, plate debonding or local failure in the concrete layer between the FRP plate and longitudinal reinforcements (Almakt et al., 1998). Strengthened beams with CFRP plates fail due to CFRP debonding under the effect of impact loading, but the use of the anchorage system prevents such a failure (Erki and Meier, 1999). The maximum and minimum limits of the FRP plate for flexural strengthening have been established to ensure ductile behaviour with the strengthened concrete beam (El-Mihilmy and Tedesco, 2000). Strengthening concrete beams with externally bonded FRP plates has been found to lead to plate peel-off, with plate strain rates of 5,000 to 6,000 µst (Fanning and Kelly, 2001). Three brittle failure modes were observed for beams strengthened with externally bonded CFRP sheets: 1) ripping of concrete, 2) premature shear failure and 3) a hybrid of modes 1 and 2 (Nguyen et al., 2001).

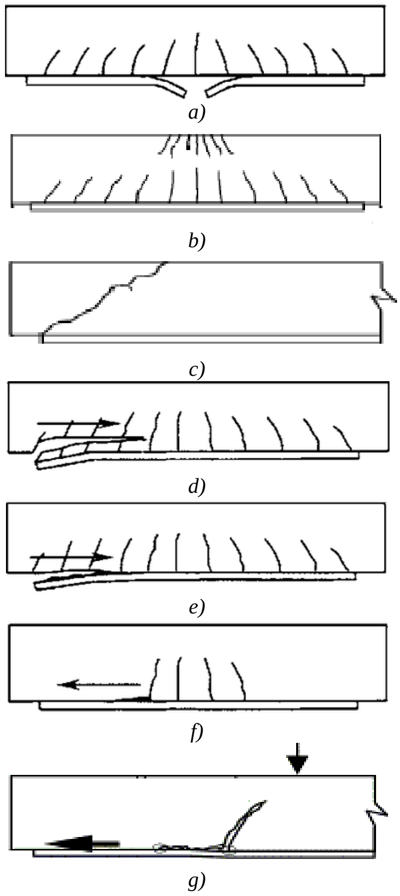

Figure (4): Failure modes of FRP flexural strengthening or repair [a) FRP rupture, b) Concrete crushing, c) Shear failure, d) Concrete cover separation, e) Plate end interfacial debonding, f) Flexural crack-induced interfacial debonding, g) Flexural-shear crack-induced interfacial debonding] (Ritchie et al., 1991; Saadatmanesh and Ehsani, 1991; Triantafillou and Plevris, 1992; Sharif et al., 1994; Chajes et al., 1994; Heffernan and Erik, 1996)

The use of externally bonded FRP plates for strengthening concrete beams was found to lead to concrete cover failure, with plate detachment at the point of the applied load within the shear span of the beam and moved towards the plate end with increases in the plate thickness (Rahimi and Hutchinson, 2001). The normal and shear stresses at the plate end were found to increase with greater plate thickness (Rahimi and Hutchinson, 2001). The CFRP strain at the mid-span reached about 6,000 to 7,000 μst prior to failure and the observed failure modes were bond splitting and plate peeling (White et al., 2001). More investigation is required regarding local debonding around the flexural cracks and its effect on the efficiency of the resisting tensile stress (Malek and Patel, 2002). The observed mode of failure was detachment of the concrete layer at the soffit of the beam, with a maximum CFRP strain of 62-92% of its ultimate strain (Barros and Fortes, 2005; Barros et al., 2005). The repair of damaged RC beams with bonded CFRP sheets shows two main failure modes: peeling off and interfacial debonding. The mode depends only on the sheet width, with a transition from interfacial debonding to peeling off seen when the CFRP sheet width increases from 50 mm to 100 mm (Benjeddou et al., 2007). Flexural failure with FRP debonding was the main mode of failure observed by Ghosh and Karbhari (2009). The use of U-wraps leads the FRP plates to reach fail capacity and fail in rupture (Decker, 2007).

Badawi and Soudki (2009) found that prestressing CFRP rods used to strengthen RC beams can result in CFRP rupture failure. They also discovered that using CFRP sheets to repair steel beams of steel–concrete composite girders can lead to CFRP debonding failure.

Al-Saidy et al. (2010) found that using a U-shape CFRP anchor system to repair corroded RC structures transferred the failure mode from CFRP debonding to CFRP rupture. El-Ghandour (2011) observed that using CFRP sheets with U-shape anchorage results in CFRP rupture failure mode, while increasing the number of U-shape anchorages can transfer the failure mode to a combined flexural–shear mode. Stress concentration at the damaged region prior to the repair of steel beams with CFRP sheets results in local debonding failure, as noted by Kim et al. (2011). Cromwell et al. (2011) found that exposing strengthened RC beams with externally bonded CFRP plates resulted in intermediate crack-induced (IC) debonding, with IC adhesive failure at the CFRP–concrete interface. They also observed that the use of the GFRP fabric led to failure, with a GFRP rupture. Jeevan and Reddy (2018) studied the flexural strength of RC beams with externally bonded CFRP laminates with and without end anchorages. They found that the end anchorages delayed the debonding to a certain extent. Fayyadh and Razak (2012) evaluated the effectiveness of CFRP-repaired RC beams and found that it is possible to re-repair failed CFRP-repaired beams after CFRP debonding. They also noted that failure modes are governed by pre-repair damage status and crack patterns, with pre-repair cracks leading to the intermediate crack-induced failure mode, as shown in Figures (5) and (6). Fayyadh and Razak (2014) conducted an analytical and experimental study on the repair effectiveness of CFRP sheets for RC beams and found that pre-repair cracks lead to intermediate crack-induced failure. Al-Khafaji and Salim (2020) investigated strengthening continuous RC T-beams with CFRP sheets and found that debonding of CFRP sheets before the ultimate failure provided additional ductility to tested beams and increased compressive strength, resulting in improved ductility in CFRP-strengthened beams. Hoque and Jumaat (2018) used a numerical method to predict debonding failure induced by intermediate cracks for prestress FRP-strengthened beams. They applied a modified Branson moment–curvature analysis together with the global energy balance approach and fracture mechanics criteria. Their proposed numerical method was compared to published experimental data. The theoretical to experimental debonding failure load was found to be 0.93, with a standard deviation of 0.09. Obaidat (2018) investigated the effects of different parameters on the failure mechanism of repaired RC beams with CFRP laminates and concluded that if the shear capacity of the beam is sufficiently high, potential debonding failure is most likely to take place through CFRP debonding at the area of high stress concentration at the laminate end and propagate to the mid-span of the beam. However, for beams with lower shear capacity, the failure mode was found to be debonding associated with shear cracking.

Figure (5): Intermediate crack induced in the adhesive layer (Fayyadh and Razak, 2012)

Figure (6): Crack pattern and failure mode (Fayyadh and Razak, 2012

In summary, there are a number of failure modes that control the flexural applications of FRP systems. These can be classified as flexural failure by FRP rupture, flexural failure by the crushing of concrete at compression, shear failure, concrete cover separation, plate end interfacial debonding, intermediate flexural crack-induced interfacial debonding and intermediate flexural shear crack-induced interfacial debonding. The application of FRP systems as repair systems is governed by pre-repair cracks, which lead to the intermediate crack-induced failure mode. The failure mode can be transferred from brittle to ductile failure if the end anchorage system is properly designed.

FRP to Concrete Bond

A significant number of experimental and analytical works have been conducted in the last decade on the bond strength and behaviour of the FRP plate-to-concrete interface. The experimental work has involved single shear tests, double shear tests or modified beam tests (Van Gemert, 1980; Swamy et al., 1986; Täljsten, 1994; Zirab et al., 1995; Chajes et al., 1996). Bond strength has been found to be limited and does not always increase with increased bond length, which means that the ultimate tensile strength of the FRP plate may never be reached regardless of the length of the bond area. This has resulted in the concept of effective bond length, beyond which there is no increase in bond strength (Täljsten, 1994; Chajes et al., 1996; Yuan et al., 2001; Maeda et al., 1997; Yaun et al., 1999). Most of the FRP/concrete joints have been found to fail due to crack propagation in the concrete adjacent to the adhesive/concrete interface, starting from the critically stressed position (Chen and Teng, 2001).

Increased plate thickness has been found to increase the bond stress along the interface between the externally bonded FRP plate and the concrete. The ratio of the plate width to the plate thickness is significant in influencing the bond stresses at the plate end (Etman and Beeby, 2000). Toutanji and Ortiz (2001) found that the concrete surfaces treated with water jets showed better bonding strength than those that underwent ordinary sanding treatments, as shown in Figure (7).

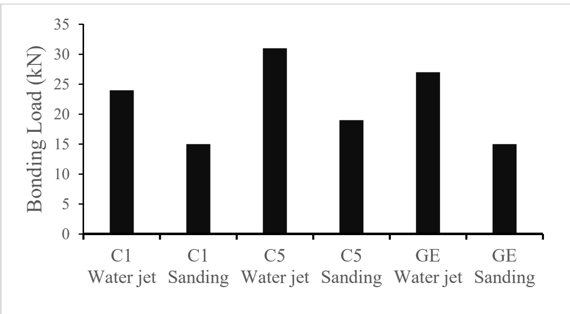

Figure (7): Comparison of bonding strength between using water jet and sanding treatment for the concrete surface (Toutanji and Ortiz, 2001)

The distribution of bond stress between the FRP plate and concrete is non-uniform and the flexural bond development length is three times the effective bond length (Xiao et al., 2004). The bond between the FRP plate and concrete is complex and involves several interacting parameters. It depends on the FRP's geometrical and mechanical properties, the concrete's compressive strength and the ratio between the FRP and concrete widths (Pellegrino et al., 2005). The bond strength is controlled by the ultimate strain of the viscoelastic interface layer and the anchoring mechanism of FRP sheets into concrete by FRP rods increases the capacity of the section and the anchoring strength, depending on the concrete strength (Huang and Chen, 2005). The bond capacity has little correlation to the concrete's compressive and tensile strength; however, it is related to the concrete's surface tensile strength and aggregate content (Leung and Pan, 2005). Debonding occurs in reinforced concrete prisms retrofitted with bonded FRP plates due to the initiation of cracks in the surrounding area of the most stressed end (Sharma et al., 2006). The tensile strength of the plate influences both the ultimate bond strength and critical bond length, as determined from the tests (Sharma et al., 2006). Wang (2006) established a bond-slip model to study the interface debonding induced by flexural cracks in FRP-plated concrete beams and the cohesive zone model was established to analyze the IC debonding failure of FRP-plated concrete beams. The ultimate load of the bonded interface increases with the bond length before achieving the effective length, remaining constant beyond that point (Teng et al., 2006). The inclusion of adhered shear deformations in RC beams considerably reduces the concentration of interfacial stresses (Benrahou et al., 2006). The existence of damage prior to strengthening with externally bonded CFRP sheets significantly affects the interfacial stresses, particularly when the damaged region is equal to or larger than the plate length (Büyüköztürk and Yu, 2006). Dawood et al. (2007) conducted a review to understand debonding failures in FRPs bonded to concrete systems. It was concluded that more research is needed for a better understanding and for quantification of environmental effects on the debonding failures in FRP/adhesive/concrete systems. The reverse taper configuration was found to be the most significant for reducing the bond stress concentration at the FRP plate end, while mechanical anchorage was found to be essential for ensuring the effectiveness of the FRP–concrete joint (Dawood et al., 2007). Ferracuti et al. (2007) developed a procedure for deriving a non-linear mode interface law for FRP–concrete bonding, starting from experimental data. Tounsi et al. (2007) developed an analytical method to predict the distribution of interfacial stress in concrete beams strengthened with FRP plates.

Silva and Biscaia (2008) reported that temperature cycles of -10 to 10^0C and moisture cycles result in concrete substrate failure, while salt fog cycles were observed to create failure at the interface. Immersion in saltwater and salt fog cycles caused considerable degradation of the bond between the FRP and concrete; however, it did not affect the load capacity of the beams. The bond strength between CFRP plates and concrete was found to increase corresponding to increased concrete strength or decreased CFRP plate width. The bond strength can be improved using rational mechanical anchorages (Xue et al., 2008).

Changing the interface parameters can transfer the failure modes from interface debonding to concrete cohesive cracking (Qiao and Chen, 2008). The higher elasticity modulus of the FRP sheets results in lower interfacial stress concentration at the end of the plate. The adhesive material's shear modulus has a significant effect on the interfacial stress at the end of the plate. Using flexible adhesive results in more uniform interfacial stress distribution and reduces the interfacial stress at the end of the plate and the FRP plate thickness and the fibre orientations have a significant effect on the shear and normal stresses in the composite member (Benachour et al., 2008). A proposed cohesive model was able to represent the bond behaviour between the CFRP plate and concrete and showed that the increase in the ultimate capacity depends on the CFRP plate length (Obaidat et al., 2010). Fayyadh and Razak (2012) studied the effect of adhesive setting time on the modal parameters in terms of natural bending frequency of RC beams repaired with CFRP laminates and found that: a) early setting time indicates a rapid increase in modal parameters up to the fifth day, then the increase rate decreases until day 18 when it achieves constant frequency values, b) the natural frequency of the first bending mode is the most sensitive to the setting time, c) 18 days is the suggested mature age of the adhesive material, d) the setting time affects modal parameters as tools for assessing CFRP-repaired structures, where using modal parameters after one day results in a 55% loss of actual capacity improvement and after seven days in a 23% loss, as shown in in Figure (8).

In summary, previous studies concluded that bond strength is limited and the ultimate tensile strength of the FRP plate may never be reached, regardless of the length of the bond area. This led to the concept of effective bond length, beyond which there is no increase in bond strength. FRP–concrete joints fail by crack propagation in the concrete adjacent to the adhesive interface, starting from the critically stressed position. The bond between the FRP plate and concrete is complex and involves several interacting parameters, such as the FRP's geometrical and mechanical properties, concrete surface tensile strength and aggregate content, concrete surface treatment prior to FRP application, pre-repair cracks, as well as the environmental conditions.

Shear Applications of FRP

Studies on the use of FRP plate bonding for shear strengthening started in the 1990s (Al-Sulaimani et al., 1994; Arduini et al., 1994; Chajes et al., 1995; Alexander and Cheng, 1996; Araki et al., 1997; Fanning and Kelly, 1999; Chaallal et al., 1998; Triantafillou, 1998; Malek and Saadatmanesh, 1998; Khalifa and Nanni, 2000; Khalifa et al., 2000). However, studies are still limited compared to studies related to the use of FRP plates for flexural strengthening (Teng et al., 2001). Studies show that the FRP plate fixed to the beam soffit for flexural strengthening does not influence the shear capacity of that beam (Buyukozturk and Hearing, 1998; Plevris, 1995). When both flexural and shear strengthening systems are suggested for an RC beam, it is advised to carry out shear strengthening first (Tan, 1999). More studies are required to better understand the shear capacity of beams retrofitted with FRP plates (Buyukozturk and Hearing, 1998). The strengthened beam's stiffness was found to increase with the increase in the area of CFRP plates on the beam's sides, which also delayed the appearance of the first flexural cracks (Li et al., 2001). Beams strengthened with bonded CFRP sheets showed an increase in load capacity by 9%, which is larger than that for beams reinforced with steel stirrups of an equivalent shear reinforcement ratio; the deflection was 16% smaller (Barros et al., 2006). The use of GFRP externally bonded plates with proper application can significantly improve the ultimate capacity and the overall behaviour of RC beams (Saafan, 2006). Shear strengthening of RC beams with FRP bonded plates shows improvements in the ultimate capacity, with a two-sided system increasing the capacity up to 7%, a U-jacket system increasing it 38-68% and a wrapping system increasing it up to 62%

(Bencardino et al., 2007). Bonding of CFRP sheets onto the beam soffit shows no effect on the ultimate capacity or the failure mode, while application of the CFRP as an externally anchored system with proper design can improve the performance and ultimate capacity of the RC beams (Bencardino et al., 2007).

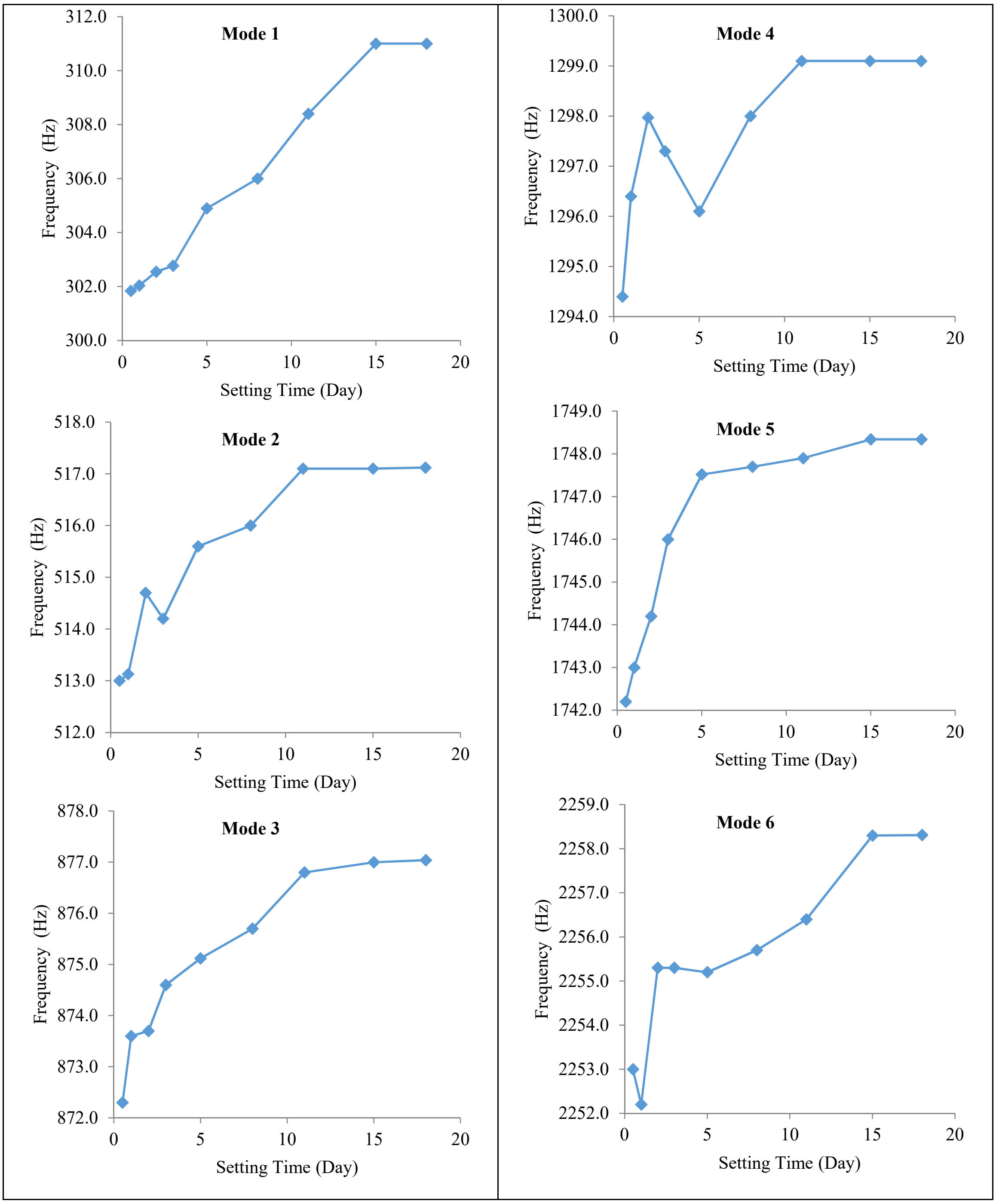

Figure (8): Change in frequency corresponding to adhesive setting time (Fayyadh and Razak, 2012)

The use of an anchorage system can enable the tensile steel reinforcement to yield before failure, the CFRP sheets to reach a higher portion of their failure strain and the concrete at compression to reach higher strain values (Bencardino et al., 2007). The use of CFRP plates for strengthening RC beams in shear strengthening results in a smaller shear crack width, which implies that the concrete's contribution to the ultimate capacity is higher than for unstrengthened beams (Lee and Al-Mahaidi, 2008). Inclined CFRP sheets were found to be more effective for shear strengthening of RC beams than vertical sheets and the contribution of the CFRP sheets to the ultimate shear capacity depends on the concrete tensile strength (Dias and Barros, 2010). The use of U-shape anchored CFRP sheets for shear strengthening can increase the capacity by up to 20% (El-Ghandour, 2011). Fibre direction of the CFRP sheets has a significant effect on the shear capacity of strengthened deep RC beams (Lee et al., 2011). The use of U-wrap CFRP strips increases the shear capacity of the RC beams up to 25%, while the use of CFRP sheets increased it up to 50% (Colalillo and Sheikh, 2011). The use of close-wrap CFRP strips increases the shear capacity up to 75%, while use of CFRP sheets increases it up to 114% (Colalillo and Sheikh, 2011). Ahmed et al. (2014) investigated the effect of plate thickness on the shear repair effectiveness of CFRP and steel plate for RC beams with web openings and found that increased steel plathickness had a small effect on maximum load capacity, while CFRP plate thickness had a greater effect on the ultimate load capacity. Ahmed et al. (2016) investigated shear repair effectiveness of CFRP and steel plates for RC beams with web openings and found that both CFRP and steel plates are effective repair solutions; however, CFRP plates perform better and rectangular configurators are better than hexagonal ones. Al-Karkhi and Aziz (2018) investigated the effect of CFRP strips on the shear strength of self-compacting concrete hammer-head beams and concluded that strengthened beams show enhancements in shear capacity by up to 30%. Strengthening of RC columns with CFRP subject to eccentric loading shows a significant improvement in ultimate capacity and ductility (Alhawamdeh and Alqam, 2020).

In summary, there has been an increased number of studies on the application of externally bonded FRP systems in shear strengthening, but they are still limited compared to the studies related to the application of FRP systems in flexure. All previous studies confirm the effectiveness of externally bonded FRP systems to increase the ultimate shear capacity and enhance the overall behaviour of RC structures. The application of FRP systems in the flexural zone has negligible effect on the ultimate shear capacity. The application of FRP systems in shear strengthening results in smaller shear crack width, which implies that the concrete's contribution to the ultimate capacity is higher than for unstrengthened beams and an inclined FRP system is more effective than a vertical system in shear applications. The effectiveness of the FRP system in shear applications depends on the concrete tensile strength as well as the FRP plate's geometrical and mechanical properties.

Shear Applications' Failure Modes

Studies carried out on shear strengthening using FRP plates in the last decade observed a number of failure modes: 1) shear failure due to FRP rupture, 2) shear failure due to FRP debonding, 3) shear failure without FRP rupture and 4) mechanical anchorage failure (Chajes et al., 1995; Araki et al., 1997; Chaallal et al., 1998; Funakawa, 1997; Sato et al., 1997; Kage et al., 1997). Beams strengthened with bonded CFRP sheets fail with shear failure due to the appearance of one major shear crack at the shear span of the beam, as shown in Figure (9) (Barros et al., 2006).

Figure (9): Failure modes found by Barros et al. (2006)

The use of GFRP bonded plate can improve the mode of failure and transfer it from brittle shear failure to ductile flexural failure (Saafan, 2006). Load capacity and FRP debonding strain predicted using the model given by Niu et al. (2001) showed better compatibility with the experimental results than that obtained using ACI-440 equations (Ghosh and Karbhari, 2007). Careful design of the anchorage system can transfer the predominantly brittle shear failure of strengthened beams with bonded CFRP sheets to ductile failure (Bencardino et al., 2007). Strengthening of RC beams with bonded FRP plates results in FRP debonding when the FRP ratio is minimum, while with a larger FRP ratio, the failure mode is transferred to the separation of the concrete cover (Dias and Barros, 2010). Strengthening deep T-section RC beams with externally bonded CFRP sheets can lead to failure with CFRP rupture or partial delamination of CFRP sheets between the concrete surface and CFRP sheets (Lee et al., 2011). The use of the close-wrap CFRP sheets or strips transfers the failure mode of the U-wrap system from FRP debonding to FRP rupture (Colalillo and Sheikh, 2011).

In summary, there is a number of failure modes that govern the application of FRP in shear strengthening and these are: FRP rupture, FRP debonding, shear failure without FRP rupture and mechanical anchorage failure. The application of FRP systems, including anchorage systems, can transfer the failure mode from brittle shear failure to ductile flexural failure.

Dynamic Assessment Studies

The first dynamic assessment of the use of FRP plate as an externally bonded strengthening system using modal testing was conducted by Capozucca et al. (2002). Since then, only a small number of researchers have used modal testing as a dynamic assessment tool for the strengthening or repair of RC beams with externally bonded FRP plate. Repair of damaged RC beams with FRP plate was found to result in a decrease in the natural frequencies for the first three bending modes, which seems to be an abnormal trend (Capozucca et al., 2002).

Dynamic parameters were used for the assessment of the use of FRP plate for the repair of damaged RC beams and the bending frequencies of the repaired phase after exposure to load as the design load showed a small increase compared to the pre-repair damage phase (Bonfiglioli and Pascale 2006). The fundamental mode showed lower sensitivity, while the third and fourth modes showed higher sensitivity and the modal damping was sensitive to both the damaged and the repaired cases (Bonfiglioli and Pascale, 2006). Strengthening of RC shear walls with externally bonded CFRP sheets was found to increase the first three bending frequencies (Meftah et al., 2006). Repair of damaged RC shear walls with externally bonded CFRP sheets resulted in an increase in the first seven bending frequencies over the damaged walls, while the frequency values were still less than for undamaged walls (Meftah and Touns, 2007).

Modal testing was used for the assessment of the repair of damaged RC beams with externally bonded CFRP sheets. There was a decrease in the natural frequencies of the repaired phase with self-weight when compared to the damage phase for all the modes. Exposure of the repaired beams to load as the pre-repair damage load resulted in an increase in the natural frequencies for some cases depending on the flexural steel ratio and the number of the mode. The authors justified the decrease in natural frequencies as the effect of environmental conditions such as ambient temperature on the material properties (Baghiee et al., 2009). There was a variance in the sensitivity of the bending modes to the repair of the damaged beams with bonded CFRP sheets depending on the flexural steel ratio and the pre-repair damage level (Baghiee et al., 2009). The use of the MAC index shows smaller change as affected by the damage and repair compared to the natural frequencies and the change was inconsistent, which implies that it is an unreliable index (Baghiee et al., 2009).

Dynamic assessment of damaged RC beams repaired with CFRP rods shows that there was a decrease in the natural frequencies for all the modes after repair compared to the damage phase, followed by a slight increase after exposing the repaired beams to load as the pre-repair damage load, as shown in Figure (10) (Capozucca, 2009). The author justifies the decrease in natural frequencies as due to the extra mass of CFRP rods on the beam (Capozucca, 2009). The fundamental mode was more sensitive to the damage and repair (Capozucca, 2009). Modal testing carried out on a real bridge repaired with externally bonded CFRP sheets showed that both vertical and horizontal excitation modes are affected, with all the modes experiencing an increase in the frequencies at the repair phase compared to the damage phase (Abdessemed et al., 2011; An et al., 1991).

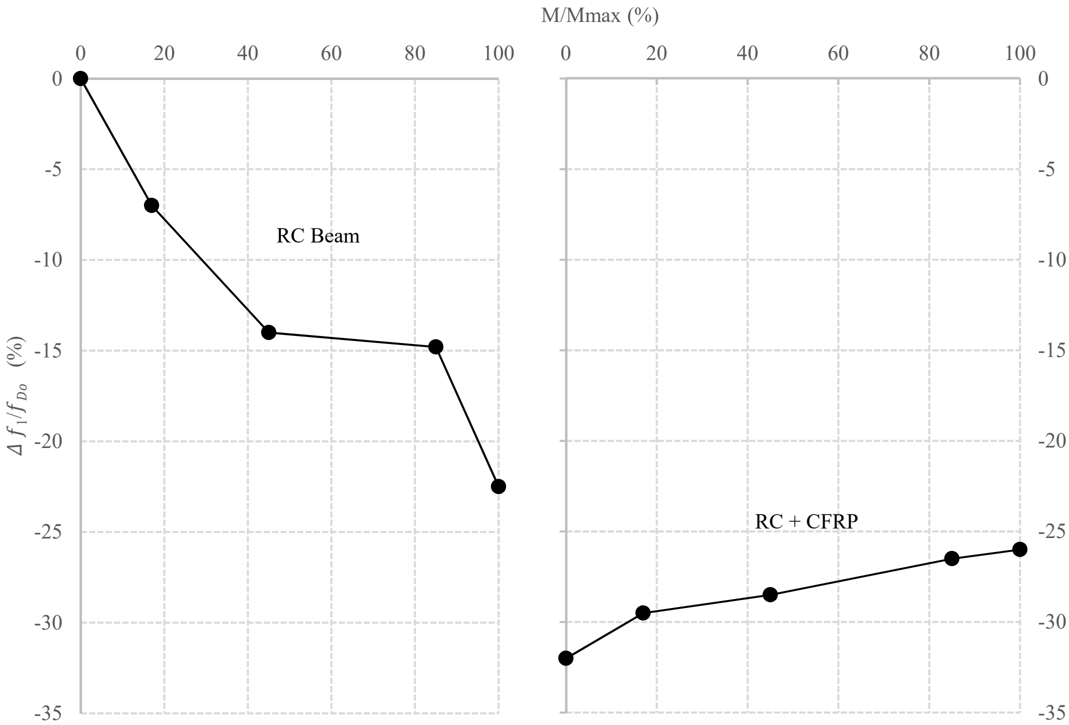

Figure (10): Frequency change against moment ratio (M/Mmax) for the first mode for beam B1 (Capozucca, 2009)

In summary, limited work has been carried out on the use of dynamic methods for the assessment of FRP applications in RC structures. There is an abnormal trend in the natural frequencies after the application of FRP in flexural strengthening, while applications of FRP in shear strengthening increase the natural frequencies. There is a variance in the sensitivity of the bending modes between lower bands and higher bands. The modal damping is sensitive to changes at both pre- and post-repair stages, while mode shape-based algorithms are less sensitive and inconsistent. More studies are required to investigate the use of the modal parameters for the assessment of FRP applications in RC structures and to investigate the effect of parameters such as pre-repair damage levels, flexural and shear steel reinforcement ratios and damage locations on the dynamic characteristics.

Mathematical Assessment Studies

Many studies conducted in the last decade have dealt with the equations and principles used to calculate the contribution of FRP bonded plates to the flexural capacity of strengthened/repaired beams. Most of those studies have suggested using the same design procedure for the unstrengthened beams while taking into consideration the brittle nature of the FRP plates (Chajes et al., 1994; Saadatmanesh and Malek, 1998). Therefore, many design equations and guidelines have been proposed for calculating the flexural capacity of strengthened RC beams with bonded FRP plates based on the design approach of the ACI-318 code (Chajes et al., 1994; Saadatmanesh and Malek, 1998; Nanni et al., 1998; El-Mihilmy et al., 2000; Chaallal et al., 1998; Lam and Teng, 2001; Teng et al., 2000). The effect of the pre-strengthening or existing strain on the beam soffit on the FRP bonded plates' contribution to flexural capacity has been studied by Lam et al. (2001) and the effect was considered in the design equations shown by Saadatmanesh et al. (1998). In recent decades, many studies have proposed mathematical models for calculating the contribution of FRP plates to the shear capacity of strengthened beams (Triantafillou, 1998; Funakawa, 1997; Chaallal et al., 1998; Chen and Teng, 2001; Chen and Teng, 2003; Chen and Teng, 2003; Khalifa et al., 1998; Gergely et al., 1998; Triantafillou and Antonopoulos, 2000; Triantafillou and Fardis, 1997).

The American Concrete Institute (ACI) started to consider the FRP bonded plate as a construction material in 1996, with the first work on FRP plate being a state-of-the-art report on its use for concrete structures (ACI-440R, 1996). The first design guideline for the use of fibre composite materials was released in ACI-440-2R (2000), followed by a guideline for the design of externally bonded FRP systems in ACI-440-2R (2002). The work of the ACI was continually updated on the use of externally bonded FRP plate or the use of FRP bars as reinforcement, according to needs arising and the findings of new research (ACI-440.3R, 2004, ACI-440.4R, 2004, ACI-440.1R, 2006, ACI-440R, 2007, ACI-440.2R, 2008, ACI-440.5, 2008, ACI-440.6, 2008, ACI-440.7R, 2010).

Normal and shear stresses near the cut-off point of the bonded FRP plate and the existence of flexural cracks need to be considered while calculating the ultimate capacity of the strengthened beams (Almakt et al., 1998). The contribution of the shear stirrups to the ultimate shear capacity of strengthened beams with FRP plate was found to depend on the load sharing relationship with the FRP plates and the mode of failure (Hutchinson, 1999). A simple approach for the design of the concrete beams strengthened with externally bonded FRP plate was proposed, where the maximum and minimum limits of the FRP plate were established (El-Mihilmy and Tedesco, 2000). A truss model was proposed for predicting the ultimate shear capacity and behaviour of strengthened beams with externally bonded FRP plates (Colotti and Spadea, 2001). Newhook et al. (2002) proposed a design procedure to calculate the required FRP plate area for the strengthening of concrete beams subject to bending loading. A straightforward approach for the design of concrete beam strengthening with externally bonded FRP plates was proposed by Malek et al. (2002). The contribution of the FRP plate to the ultimate shear of strengthened beams depends on the quantity of the FRP and the ratio between the steel stirrup and the FRP plates (Pellegrino and Modena, 2002). A theoretical method for predicting the ultimate capacity of cracked beams subject to flexural strengthening with FRP plates was proposed by Wu et al. (2003). A comparison of guides for the design of externally bonded FRP plates for strengthening concrete structures according to ACI-440-2R (2002) and the technical report CEB-FIB-14 (2002) was carried out by Nezamian et al. (2004). The ACI-440-2R (2002) guideline was more conservative in its predictions of flexural capacity, while the CEB-FIB-14 (2002) guideline was a more accurate approach to check debonding of FRP from the concrete substrate. The FRP bonded plate's contribution to the ultimate shear capacity was found to decrease as the effective depth of the beam increased and the FRP's contribution was found to contain two parts: the direct contribution and the indirect contribution (Qu et al., 2005). Shear capacity of the strengthened beam with externally bonded FRP plate calculated using the ACI-440R (1996) guideline was 20% less than the experimental results (Anil, 2006). A partial interaction model for the quantification of the interaction between the shear steel stirrups and the external bonded FRP plates and its contribution to the ultimate shear capacity was developed. It was found to be a complex problem, since the steel stirrups can yield while the FRP is only ruptured. It was concluded that more research is needed to be undertaken for better understanding of the interaction between the internal stirrups and the external FRP plates (Mohamed-Ali et al., 2006). A numerical model for the prediction of the FRP's contribution to the shear capacity of strengthened RC beams was proposed by Lu et al. (2009). Use of the equations of ACI-440-2R (2002) for predicting the CFRP plate's contribution to the ultimate shear capacity resulted in larger values than the experimental results, while using the equations of Nanni et al. (2004) resulted in predicted values 61% higher than the experimental results (Dias and Barros, 2010). The use of the equations of ACI-440-2R (2002) for the calculation of the CFRP sheet's contribution to the capacity of the strengthened deep RC beams showed an overestimate compared to the experimental results (Lee et al., 2011). Colotti and Swamy (2011) developed a mechanical model for predicting the failure load and mode of strengthened RC beams with FRP plates in flexural and shear applications. Xie and Wang (2019) conducted reliability analysis of CFRP-repaired RC bridges considering the effect of CFRP size and concluded that the CFRP strengthening system improves the safety of structures effectively, irrespective of CFRP size.

In summary, although many studies have been carried out to better understand the contribution of externally bonded FRP systems in the flexural and shear applications of RC structures, research is still ongoing. More studies are needed to better understand the interaction between internal stirrups/flexural steel and the external FRP plates and to evaluate the existing equations in predicting the ultimate flexural and shear capacities of repaired RC structures affected by different parameters, such as different damage levels, flexural and shear steel ratios and damage location.

Conclusions and Recommendations

Based on the aforementioned review regarding the application and assessment of using FRP bonded plates for strengthening or repairing RC structures, the following are the main conclusions and recommendations that could address the current shortcomings:

1- Previous studies have shown a growth in recent years in the global needs for structural performance updates and retrofitting works using FRP sheets as an externally bonded system. The use of prefabricated FRP plates has been found to ensure the highest degree of material uniformity and quality control. The pre-repair damage level and flexural steel reinforcement ratio were found to influence the repair effectiveness when using FRP bonded sheets. Although many researchers have examined the effectiveness and failure modes of FRP bonded sheets as a flexural strengthening system, only a very limited number have investigated the repair cases, with only a few taking into consideration the effect of both the pre-repair damage level and flexural steel ratio. Future studies are needed to investigate the effectiveness and failure modes of using CFRP bonded sheets for flexural repair of RC beams considering the effect of different pre-repair levels and the effect of the flexural steel code design limits.

2- Although many studies have been conducted on the use of FRP bonded sheets for flexural strengthening of RC structures, the use of FRP sheets for the shear strengthening of RC structures is still very limited. A number of researchers have pointed out that more studies are required for better understanding of the shear capacity and failure modes of repaired beams with FRP bonded plates. Moreover, the effects of the pre-repair damage level, shear stirrups ratio and the load location on the effectiveness and failure modes of the CFRP sheets as a shear repairing system need to be further investigated.

3- Existing studies on the bond problem between externally bonded FRP plates and concrete proved the complex phenomenon of FRP-to-concrete interface. But more research needs to be done in order to understand the behaviour of that interface under different physical properties, geometrical properties, environmental conditions and loading conditions and configurations.

4- Most of the existing studies are still based on the conventional static load test, which is time-consuming, equipment - and labour- intensive and causes major disruptions to existing use. Moreover, previous studies showed that only a very limited amount of work has been conducted on the use of modal testing for the assessment of using FRP bonded sheets as flexural or shear repairing systems. Even the few studies conducted have shown abnormal trends of the natural frequencies regarding repair effectiveness. Future studies are required to investigate the use of modal testing and modal parameters as a tool for assessing the effectiveness of using CFRPs as a flexural and shear system. Additionally, there is a need to investigate the effect of different parameters (i.e., different pre-repair damage levels, maximum and minimum flexural steel ratios, different shear stirrups ratios and damage at different locations from the supports) on the use of modal testing as an assessment tool. Moreover, efforts should be directed towards overcoming the shortcomings highlighted by the previous researchers regarding the use of the modal parameters.

5- Although many studies have been conducted to calculate the contribution of FRP bonded plates to the flexural and shear capacity of strengthened or repaired beams, research is still ongoing on this matter. Moreover, the work of the ACI is continually updated regarding the use of externally bonded FRP plates according to the findings of new studies. Based on previous studies, further research is needed for a better understanding of the interaction between the internal stirrups/flexural steel and external FRP plates.

6- The contribution of FRP plates to the ultimate shear of strengthened beams depends on the ratio between the steel stirrup and the FRP plates. The ACI-440-2R (2002) guideline was more conservative in predicting flexural capacity. The ACI-440R (1996) guideline predicted lower shear load capacity values than the experimental results. Based on the aforementioned conclusions, future studies have to evaluate the equations of the ACI code in predicting the ultimate flexural and shear capacities of repaired RC beams affected by different parameters; i.e., different pre-repair damage levels, maximum and minimum flexural steel ratios, different shear stirrups ratios and damage at different locations from the supports.

Conflict of Interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

REFERENCES

Abdessemed, M., Kenai, S., Bali, A., and Kibboua, A. (2011). "Dynamic analysis of a bridge repaired by CFRP: Experimental and numerical modelling". Construction and Building Materials, 25, 1270-1276.

ACI-440.1R-06. (2006). "Guide for the design and construction of structural concrete reinforced with FRP bars". American Concrete Institute, Farmington Hills, Mich.

ACI-440.2R-08. (2008). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures". American Concrete Institute, Farmington Hills, Mich.

ACI-440.3R-04. (2004). "Guide for test methods for fiber-reinforced polymers (FRPs) for reinforcing and strengthening concrete structures". American Concrete Institute, Farmington Hills, Mich.

ACI-440.4R-04. (2004). "Prestressing concrete stuctures with FRP tendons". American Concrete Institute, Farmington Hills, Mich.

ACI-440.5-08. (2008). "Specification for construction with fiber-reinforced polymer reinforcing bars". American Concrete Institute, Farmington Hills, Mich.

ACI-440.6-08. (2008). "Specification for carbon and glass fiber-reinforced polymer bar materials for concrete reinforcement". American Concrete Institute, Farmington Hills, Mich.

ACI-440.7R-10. (2010). "Guide for the design and construction of externally bonded FRP systems for strengthening unreinforced masonry structures". American Concrete Institute, Farmington Hills, Mich.

ACI-440-2R-0. (2000). "Design guidance for strengthening concrete structures using fiber composite materials". American Concrete Institute, Farmington Hills, Mich.

ACI-440-2R-02. (2002). "Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures". American Concrete Institute, Farmington Hills, Mich.

ACI-440R-07. (2007). "Report on fiber-reinforced polymer (FRP) reinforcement for concrete structures". American Concrete Institute, Farmington Hills, Mich.

ACI-440R-96. (1996). "State-of-the-art report on FRP for concrete structures: Manual of concrete practice". American Concrete Institute, Farmington Hills, Mich.

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, 235-244.

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, 163-183.

Alexander, J.G.S., and Cheng, J.J.R. (1996). "Shear strengthening of small-scale concrete beams with carbon fibre-reinforced plastic sheets". Proceedings of the First Structural Speciality Conference, Edmonton (Alberta, Canada), 29 May-1 June, 167-177.

Alhawamdah, M., and Alqam, M. (2020). "Behaviour assessment of reinforced concrete columns externally rehabilitated with carbon fiber-reinforced polymers (CFRPs) subjected to eccentric loadings". Jordan Journal of Civil Engineering, 14.

Al-Khafaji, A., and Salim, H. (2020). "Flexural strengthening of RC continuous T-beams using CFRP". Fibers, 8, 41.

Al-Kharkhi, H., and Aziz, A. (1998). "Shear strengthening of reinforced self-compacted concrete hammer head beams using warped CFRP strips: Experimental and theoretical study". Jordan Journal of Civil Engineering, 12.

Almakt, M.M., Balazs, G.L., and Pilakoutas, K. (1998). "Strengthening of RC elememts by CFRP plates' local failure". 2nd International PhD Symposium in Civil Engineering, Budapest.

Al-Saidy, A.H., Al-Harthy, A.S., Al-Jabri, K.S., Abdul-Halim, M., and Al-Shidi, N.M. (2010). "Structural performance of corroded RC beams repaired with CFRP sheets". Composite Structures, 92, 1931-1938.

Al-Sulaimani G.J., Sharif, A., Basunbul, I.A., Baluch, M.H., and Ghaleb, B.N. (1994). "Shear repair for reinforced concrete by fiberglas plate bonding". ACI Structural Journal, 91, 458-464.

An, W., Saadatmanesh, H., and Ehsani, M.R. (1991). "RC beams strengthened with FRP plates. II: Analysis and parametric study". Journal of Structural Engineering-ASCE, 117, 3434-3455.

Anil, Ö. (2006). "Improving shear capacity of RC T-beams using CFRP composites subjected to cyclic load". Cement and Concrete Composites, 28, 638-649.

Araki, N., Matsuzaki, Y., Nakano, K., Kataka, T., and Fukuyama, H. (1997). "Shear capacity of retrofitted RC members with continuous fibre sheets: Non-metallic (FRP) reinforcement for concrete structures". Proceedings of the Third International Symposium, Japan, 512-522.

Arduini, M., D'Ambrisi, A., and Di Tommaso, A. (1994). "Shear failure of concrete beams reinforced with FRP plates: Infrastructure, new materials and methods of repair". Proceedings of the Material Engineering Conference 804, ASCE, New York, 123-130.

Arduini, M., and Nanni, A. (1997). "Behavior of precracked RC beams strengthened with carbon FRP sheets". Journal of Composite for Construction-ASCE, 1, 63-70.

Badawi, M., and Soudki, K. (2009). "Flexural strengthening of RC beams with prestressed NSM CFRP rods: Experimental and analytical investigation". Construction and Building Materials, 23, 3292-3300.

Baghiee, N., Esfahani, M.R., and Moslem, K. (2009). "Studies on damage and FRP strengthening of reinforced concrete beams by vibration monitoring". Engineering Structures, 31, 875-893.

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- ASCE, 6, 73-87.

Barros, J.A., and Fortes, A.S. (2005). "Flexural strengthening of concrete beams with CFRP laminates bonded into slits". Cement and Concrete Composites, 27, 471-480.

Barros, J.A.O., Ferreira, D.R.S.M., Fortes, A.S., and Dias, S.J.E. (2006). "Assessing the effectiveness of embedding CFRP laminates in the near surface for structural strengthening". Construction and Building Materials, 20, 478-491.

Benachour, A., Tounsi, A., and Adda-Bedia, E.A. (2007). "Interfacial stress analysis of steel beams reinforced with bonded prestressed FRP plate". Engineering Structures, 30, 3305-3315.

Bencardino, F., Spadea, G., and Swamy, R.N. (2007). "The problem of shear in RC beams strengthened with CFRP laminates". Construction and Building Materials, 21, 1997-2006.

Benjeddou, O., Ouezdou, M.B., and Bedday, A. (2007). "Damaged RC beams repaired by bonding of CFRP laminates". Construction and Building Materials, 21, 1301-1310.

Benrahou, K.H., Adda-Bedia, E.A., Benyoucef, S., Tounsi, A., and Benguediab, M. (2006). "Interfacial stresses in damaged RC beams strengthened with externally bonded CFRP plate". Materials Science and Engineering: A, 432, 12-19.

Bonacci, J.F., and Maalej, M. (2000). "Externally bonded fiber-reinforced polymer for rehabilitation of corrosion damaged concrete beams". ACI Structural Journal, 97, 703-711.

Bonfiglioli, B., and Pascale, G. (2006). "Dynamic assessment of reinforced concrete beams repaired with externally bonded FRP sheets". Mechanics of Composite Materials, 42, 1-12.

Buyukozturk, O., and Hearing, B. (1998). "Failure behavior of precracked concrete beams retrofitted with FRP". Journal of Composites for Construction- ASCE, 2, 138-144.

Büyüköztürk, O., and Yu, T.Y. (1998). “Understanding and assessment of debonding failures in FRP-concrete systems”. Seventh International Congress on Advances in Civil Engineering, Yildiz Technical University, Istanbul, Turkey.

Capozucca, R. (2009). “Static and dynamic response of damaged RC beams strengthened with NSM CFRP rods”. Composite Structures, 91, 237-248.

Capozucca, R., and Cerri, M.N. (2002). “Static and dynamic behaviour of RC beam model strengthened by CFRP sheets”. Construction and Building Materials, 16, 91-99.

CEB-FIB-14. (2002). “The international federation for structural concrete: Technical report”. Bulletin 14.

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, 692-704.

Chaallal, O., Nollet, M.J., and Perraton, D. (1998). “Shear strengthening of RC beams by externally bonded side CFRP strips”. Journal of Composites for Construction-ASCE, 2, 111-114.

Chajes, M.J., Januszka, T.F., Mertz, D.R., Thomson Jr, T.A., and Finch Jr, W.W. (1995). “Shear strengthening of reinforced-concrete beams using externally applied composite fabrics”. ACI Structural Journal, 92, 295-303.

Chajes, M.J., Thomson Jr, T.A., Januszka, T.F., and Finch Jr, W.W. (1994). “Flexural strengthening of concrete beams using externally bonded composite materials”. Construction and Building Materials, 8 (3), 191-201.

Chajes, M.J., Finch W.W., Jansuzka, T.F., and Thomosh, T.A. (1996). “Bond and force transfer of composite material plates bonded to concrete”. ACI Structural Journal, 93, 231-244.

Chen, J.F., and Teng, J.G. (2001). “Anchorage strength models for FRP and steel plates bonded to concrete”. Journal of Structural Engineering, 127, 784-791.

Chen, J.F., and Teng, J.G. (2001). “Anchorage strength models for FRP and steel plates bonded to concrete”. Journal of Structural Engineering-ASCE, 127, 784-791.

Chen, J.F., and Teng, J.G. (2003). “Shear capacity of fiber-reinforced polymer-strengthened reinforced concrete beams: Fiber-reinforced polymer rupture”. Journal of Structural Engineering-ASCE, 129, 615-626.

Chen, J.F., and Teng, J.G. (2003). “Shear capacity of FRP-strengthened RC beams: FRP debonding”. Construction and Building Materials, 17, 27-41.

Choo, C.C., Zhao, T., and Harik, I. (2007). “Flexural retrofit of a bridge subjected to overweight trucks using CFRP laminates”. Composites - Part B: Engineering, 38, 732-738.

Colalillo, M.A., and Sheikh, S.A. (2011). “Seismic retrofit of shear-critical reinforced concrete beams using CFRP”. Construction and Building Materials, doi:10.1016/j.conbuildmat.2010.12.065.

Colotti, V., and Spadea, G. (2001). “Shear strength of RC beams strengthened with bonded steel or FRP plates”. Journal of Structural Engineering-ASCE, 127, 367-373.

Colotti, V., and Swamy, R.N. (2011). “Unified analytical approach for determining shear capacity of RC beams strengthened with FRP”. Engineering Structures, 33, 827-842.

Cromwell, J.R., Harries, K.A., and Shahrooz, B.M. (2011). “Environmental durability of externally bonded FRP materials intended for repair of concrete structures”. Construction and Building Materials, 25, 2528-2539.

Dawood, M., Guddati, M., and Rizkalla, S. (2007). “Bond and splice behavior of a CFRP strengthening system for steel structures”. Asia-Pacific Conference on FRP in Structures, Hong Kong.

Decker B.R. (2007). “A method of strengthening monitored deficient bridges”. M.Sc. Thesis, Kansas State University.

Dias, S.J.E., and Barros, J.A.O. (2010). “Performance of reinforced concrete T-beams strengthened in shear with NSM CFRP laminates”. Engineering Structures, 32, 373-384.

El-Ghandour, A.A. (2011). “Experimental and analytical investigation of CFRP flexural and shear strengthening efficiencies of RC beams”. Construction and Building Materials, 25, 1419-1429.

El-Mihilmy, M., and Tedesco, J.W. (2000). “Analysis of reinforced concrete beams strengthened with FRP laminates”. Journal of Structural Engineering- ASCE, 126, 684-691.

El-Mihilmy, M.T., and Tedesco, J.W. (2000). “Analysis of reinforced concrete beams strengthened with FRP laminates”. Journal of Structural Engineering-ASCE, 126, 684-691.

Erki, M.A., and Meier, U. (1999). "Impact loading of concrete beams externally strengthened with CFRP laminates". Journal of Composites for Construction-ASCE, 3, 117-124.

Etman, E.E., and Beeby, A.W. (2000). "Experimental programme and analytical study of bond stress distribution on a composite plate bonded to a reinforced concrete beam". Cement & Concrete Composites, 22, 281-291.

Fam, A., MacDougall, C., and Shaat, A. (2009). "Upgrading steel-concrete composite girders and repair of damaged steel beams using bonded CFRP laminates". Thin-walled Structures, 47, 1122-1135.

Fanning, P., and Kelly, O. (1999). "Shear strengthening of reinforced concrete beams: An experimental study using CFRP plates". Eighth International Conference of Structural Fault and Repair, London (UK).

Fanning, P.J., and Kelly, O. (2001). "Ultimate response of RC beams strengthened with CFRP plates". Journal of Composites for Construction-ASCE, 5, 122-127.

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, 21-31.

Fayyadh, M.M., and Razak, H.R. (2012). "Assessment of adhesive setting time in reinforced concrete beams strengthened with carbon fibre-reinforced polymer laminates". Material & Design, 37, 64-72.

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.

Ferracuti, B., Savoia, M., and Mazzotti, C. (2007). "Interface law for FRP–concrete delamination". Composite Structures, 80, 523-531.

Funakawa, I. (1997). "Experimental study of shear strengthening with continuos fiber reinforcement sheet and methyl metaacrylate resin". Non-Metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third Symposium, Japan, 465-482.

Garden, H.N., and Hollaway, L.C. (1998). "An experimental study of the influnce of plate end anchorage of carbon fibre composite plates used to strengthen reinforced concrete beams". Composite Structures, 42, 175-188.

Gergely, I., Pantelides, C.P., Nuismer, R.J., and Reaveley, L.D. (1998). "Bridge pier retrofit using fiber-reinforced plastic composites". Journal of Composites for Construction-ASCE, 2, 165-174.

Ghosh, K.K., and Karbhari, V.M. (2007). "Evaluation of strengthening through laboratory testing of FRP-rehabilitated bridge decks after in-service loading". Composite Structures, 77, 206-222.

Hag-Elsafi, O., Lund, R., and Alampalli, S. (2002). "Strengthening of a bridge pier capbeam using bonded FRP composite plates". Composite Structures, 57, 393-403.

Heffernan, P.J., and Erik, M.A. (1996). "Equivalent capacity and efficiency of reinforced concrete beams strengthened with carbon fibre-reinforced plastic sheets". Canadian Journal of Civil Engineering, 23, 21-29.

Hoque N., and Jumaat M.Z. (2018). "Debonding failure analysis of prestressed FRP-strengthened RC beams". Structural Engineering and Mechanics, 66, 543-555.

Hosen, M.A., Jummat, M.Z., Alengaram, U.J., Sulong, N.H.R., and Saiful-Islam, A.B.M. (2019). "Structural performance of lightweight concrete beams strengthened with side-externally bonded reinforcement (S-EBR) technique using CFRP fabrics". Composites-Part B: Engineering, 176, 107323.

Huang, H., and Chen, G. (2005). "Bonding and anchoring characterization between FRP sheets, concrete and viscoelastic layers under static and dynamic loading". International Symposium on Bond Behaviour of FRP in Structures.

Hudson, J.L., and Darwin, D. (2005). "Evaluation and repair of blast-damaged reinforced concrete beams". University of Kansas Center for Research.

Hutchinson, R.L. (1999). "The use of externally bonded CFRP sheets for shear strengthening of I-shaped prestressed concrete bridge girder". PhD Thesis, University of Manitoba.

Jeevan, N., and Reddy, H.N.J. (2018). "Strengthening of RC beams using externally bonded laminate (EBL) technique with end anchorages under flexure". Asian Journal of Civil Engineering, 19, 263-272.

Jeevan, N., Reddy, H.N.J., and Prabhakara, R. (2019). "Flexural strengthening of RC beams with externally bonded (EB) techniques using prestressed and non-prestressed CFRP laminate". Asian Journal of Civil Engineering, 19, 893-912.

Jumaat, M.Z., Rahman, M.M., and Alam, M.A. (2010). "Flexural strengthening of RC continuous T-beam using CFRP laminate: A review". International Journal of Physical Sciences, 5, 619-625.

Jumaat, M.Z., and Alam, M.A. (2007). "Plate-bonded strengthened R.C. beams with end and intermediate anchors". International Journal of Engineering and Technology, 4, 185-193.

Jumaat, M.Z., Rahman, M.A., Alam, M.A., and Rahman, M.M. (2011). "Premature failures in plate-bonded strengthened RC beams with an emphasis on premature shear: A review". International Journal of Physical Sciences, 6, 156-168.

Jumaat, M.Z., and Alam, M.A. (2011). "Optimization of intermediate anchors to eliminate premature shear failure of CFRP laminate-flexurally strengthened R.C beams". International Journal of Physical Sciences, 6, 182-192.

Jumaat, M.Z., and Ashraful-Alam, M.D. (2006). "Problems associated with plate bonding methods of strengthening reinforced concrete beams". Journal of Applied Sciences Research, 2, 703-708.

Kage, T., Abe, M., Lee, H.S., and Tomosawa, F. (1997). "Effect of CFRP sheets on shear strengthening of RC beams damaged by corrosion of stirrup". The Third International Symposium on Non-metallic (FRP) Reinforcement for Concrete Structures, Japan, 443-450.

Karbhari, V.M., and Zhao, L. (1998). "Issues related to composite plating and environmental exposure effects on composite-concrete interface in external strengthening". Composite Structures, 40, 293-304.

Khalifa, A., and Nanni, A. (2000). "Improving shear capacity of existing RC T-section beams using CFRP composites". Cement and Concrete Composites, 22, 165-174.

Khalifa, A., De Lorenzis, L., and Nanni, A. (2000). "FRP composites for shear strengthneing of RC beams". 3rd International Conference on Advanced Composites Materials in Bridges and Structures, Ottawa, 137-144.

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-ASCE, 2, 195-203.

Kim, Y.J., and Brunell, G. (2011). "Interaction between CFRP-repair and initial damage of wide-flange steel beams subjected to flexure". Composite Structures, 93, 1986-1996.

Klaiber, F.W., Wipf, T.J., and Kempers, B.J. (2003). "Repair of damaged prestressed concrete bridges using CFRP". Mid-Continent Transportation Research Symposium, Ames, Iowa.

Kutarba, M.P. (2004). "Durability of carbon fiber-reinforced polymer (CFRP) strengthening system used to repair corrosion damage in reinforced concrete". Master of Engineering Thesis, University of Florida.

Lam, L., and Teng, JG. (2001). "Strength of RC cantilever slabs bonded with GFRP strips.". Journal of Composites for Construction-ASCE, 5, 221-227.

Lee, H.K., Cheong, S.H., Ha, S.K., and Lee, C.G. (2011). "Behavior and performance of RC T-section deep beams externally strengthened in shear with CFRP sheets". Composite Structures, 93, 911-922.

Lee, L.K., and Al-Mahaidi, R. (2008). "An experimental investigation on shear behaviour of RC T-beams strengthened with CFRP using photogrammetry". Composite Structures, 82, 185-193.

Leung, C.K.Y., and Pan, J. (2005). "Effect of concrete composition on FRP/concrete bond capacity". International Symposium on Bond Behaviour of FRP in Structures.

Li, A., Assih, J., and Delmas, Y. (2001). "Shear strengthening of RC beams with externally bonded CRRP sheets". Journal of Structural Engineering-ASCE, 127, 374-380.

Lu, X.Z., Chen, J.F., Ye, L.P., Teng, J.G., and Rotter, J.M. (2009). "RC beams shear-strengthened with FRP: Stress distributions in the FRP reinforcement". Construction and Building Materials, 23, 1544-1554.

Maeda, T., Asano, Y., Ueda, T., and Kakuta, Y.A. (1997). "Study on bond mechanism of carbon fiber sheet, non-metallic (FRP) reinforcement for concrete structures". Proceedings of the Third International Symposium, Sapporo, Japan 1, 279-286.

Malek, A.M., and Patel, K. (2002). "Flexural strengthening of reinforced concrete flanged beams with composite laminates". Journal of Composites for Construction-ASCE, 6, 97-103.

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.

Masoud, S., Soudki, K., and Topper, T. (2001). "CFRP-strengthened and corroded RC beams under monotonic and fatigue loads". Journal of Composites for Construction- ASCE, 5, 228-236.

Meftah, S.A., Tounsi, A., Megueni, A., and Adda-Bedia, E.A. (2006). "Lateral stiffness and vibration characteristics of RC shear walls bonded with thin composite plates". Composite Structures, 73, 110-119.

Meftah, S.A., and Tounsi, A. (2007). "Lateral stiffness and vibration characteristics of damaged RC coupled shear walls strengthened with thin composite plates". Building and Environment, 42, 3596-3605.

Meier, U. (1995). "Strengthening of structures using carbon fiber/epoxy composite". Construction and Building Materials, 9, 341-351.

Meier, U. (1992). "Carbn fiber-reinforced polymers: Modern materials in bridge engineerig". Structural Eineeering International, 2, 7-12.

Miller A.D. (2006). "Repair of impact-damaged prestressed concrete bridge girders using carbon fiber-reinforced polymer (CFRP) materials". M.Sc. Thesis, North Carolina State University.

Mohamed-Ali, M.S., Oehlers, D.J., and Seracino, R. (2006). "Vertical shear interaction model between external FRP transverse plates and internal steel stirrups". Engineering Structures, 28, 381-389.

Monti, G., and Liotta, M.A. (2007). "Tests and design equations for FRP-strengthening in shear". Construction and Building Materials, 21, 799-809.

Nanni, A., Di-Ludovico, M., and Parretti, R. (2004). "Shear strengthening of a PC bridge girder with NSM CFRP rectangular bars". Advanced Structural Engineering, 7, 97-109.

Nanni, A., Focacci, F., and Cobb, C.A. (1998). "Proposed procedure for the design of RC flexural members strengthened with FRP sheets". The Second International Conference on Composites in Infrastructure, Tucson, Arizona, 187-201.

Newhook, J., Ghali, A., and Tadros, G. (2002). "Cracking and deformability of concrete flexural sections". Journal of Structural Engineering-ASCE, 128, 1195-1201.

Nezamian, A., and Setunge, S. (2004). "Comparison between ACI 440 and FIB 14 design guidelines in using CFRP for strengthening of concrete bridge headstock". 4th International Conference on Advanced Composite Materials in Bridges and Structures, Calgary, Canada.

Nguyen, D.M., Chan, T.K., and Cheong, H. (2001). "Brittle failure and bond development length of CFRP-concrete beams". Journal of Composites for Construction-ASCE, 12-17.

Niu, J., and Wu, Z. (2001). "Prediction of debonding failure load due to flexural cracks in concrete for FRP-strengthened structures". FRPRCS-5, Cambridge, 361-370.

Obaidat, Y.T., Heyden, S., and Dahlblom, O. (2010). "The effect of CFRP and CFRP/concrete interface models when modeling retrofitted RC beams with FEM". Composite Structures, 92, 1391-1398.

Obaidat, Y.T. (2018). "The effect of beam design on behaviour of retrofitted beam using CFRP". Jordan Journal of Civil Engineering, 12, 149-161.

Pellegrino, C., and Modena, C. (2002). "Fiber-reinforced polymer shear strengthening of reinforced concrete beams with transverse steel reinforcement". Journal of Composites for Construction-ASCE, 6, 104-111.

Pellegrino, C., Boschetto, G., Tinazzi, D., and Modena, C. (2005). "Progress on understanding bond behaviour in RC elements strengthened with FRP". International Symposium on Bond Behavioure of FRP in Structures, 63-68.

Plevris N. (1995). "Reliability of RC members strengthened with CFRP laminates". Journal of Structural Engineering- ASCE, 121, 1037-1044.

Qiao, P., and Chen, Y. (2008). "Cohesive fracture simulation and failure modes of FRP-concrete bonded interfaces". Theoretical and Applied Fracture Mechanics, 49, 213-225.

Qu, Z., Lu, X.Z., and Ye, L.P. (2005). "Size effect of shear contribution of externally bonded FRP U-jackets for RC beams". International Symposium on Bond Behaviour of FRP in Structures, Hong Kong, China, 371-380.

Quantrill, R.J., Hollaway, L.C., and Thorne, A.M. (1996). "Experimental and analytical invetigation of FRP-stregthened beam response: Part I. 177". Magazine of Concrete Research, 48, 331-342.

Rahimi, H., and Hutchinson, A. (2001). "Concrete beams strengthened with externally bonded FRP plates". Journal of Composites for Construction- ASCE, 5, 44-56.

Ritchie, P.A., Thomas, D.A., Lu, L.W., and Connely, G.M. (1991). "External reinforcement of concrete beams using fiber-reinforced plastics". ACI Structural Engineering, 88, 490-500.

Ross, C.A., Jerome, D.M., Tedesco, J.W., and Hughes, M.L. (1999). "Strengthening of reinforced concrete beams with externally bonded composite laminates". ACI Structural Journal, 96, 212-220.

Saadatmanesh, H., and Ehsani, M.R. (1991). "RC beams stregthened with GFRP plates- I: Experimental study". Journal of Structural Engineering- ASCE, 117, 3417-3433.

Saadatmanesh, H., and Malek, A.M. (1998). "Design guidelines for flexural strengthening of RC beams with FRP plates". Journal of Composites for Construction-ASCE, 2, 158-164.

Saafan, M.A.A., Shear strengthening of reinforced concrete beams using GFRP wraps". Acta Polytechnica, 46 (2006), 24-32.

Sato, Y., Katsumata, H., and Kobatake, Y. (1997). "Shear strengthening of existing reinforced concrete beams by CFRP sheets". Non-metallic (FRP) Reinforcement for Concrete Structures, Proceedings of the Third Symposium, Japan, 507-514.

Shaker, Q.M., and Kamonna, H.H. (2016). "Nonlinear analysis of reinforced concrete beams strengthened by prestressess CFRP sheets under static loads". Jordan Journal of Civil Engineering, 10, 93-106.

Sharif, A., Al-Sulaimani, G.J., Basunbul, I.A., Baluch, M.H., and Ghaleb, B.N. (1994). "Strengthening of intially loaded reinforced concrete beams using FRP plates". ACI Structural Journal, 91, 160-168.

Sharma, S.K., Mohamed-Ali, M.S., Goldar, D., and Sikdar, P.K. (2006). "Plate-concrete interfacial bond strength of FRP and metallic plated concrete specimens". Composites-Part B: Engineering, 37, 54-63.

Silva, M.A.G., and Biscaia, H. (2008). "Degradation of bond between FRP and RC beams". Composite Structures, 85, 164-174.

Spadea, G., Bencardino, F., and Swamy, R.N. (1998). "Structural behavior of composite RC beams with externally bonded CFRP". Journal of Composites for Construction, 2, 132-137.

Stallings, J.M., Tedesco, J.W., El-Mihilmy, M., and McCauley, M. (2000). "Field performance of FRP bridge repairs". Journal of Bridge Engineering-ASCE, 5, 107-113.

Swamy, R.N., Jones, R., and Charif, A. (1986). "Shear adhesion properties of epoxy resin adhesives". International Symposium on Adhesion between Polymers and Concrete, Aix-en Provnce, Rilem, Chapman & Hall, London, 741-755.

Täljsten, B. (1994). "Plate bonding strengthening of existing concrete structurers with epoxy bonded plates of steel or fibre reinforced plastics". Doctoral Thesis, Luleå University of Technology, ISSN 0348-8373, 308.

Tan, K.H. (1999). "Towards a cost-effective application of FRP reinforcement in structural rehabilitation". Seventh East Asia-Pacific Conference on Structural Engineering & Construction, Kochi, Japan, 1, 65-73.

Teng, J.G., Chen, J.F., Smith, S.T., and Lam, L. (2001). "FRP-strengthened RC structures". England: John Wiley & Sons, Ltd.

Teng, J.G., Chen, J.F., Smith, S.T., and Lam, L. (2000). "RC structures strengthened with FRP composites". Research Center for Advanced Technology in Structural Engineering, The Hong Kong Polytechnic University, Hong Kong, China.

Teng, J.G., Yuan, H., and Chen, J.F. (2006). "FRP-to-concrete interfaces between two adjacent cracks: Theoretical model for debonding failure". International Journal of Solids and Structures, 43, 5750-5778.

Tounsi, A., and Benyoucef, S. (2007). "Interfacial stresses in externally FRP-plated concrete beams". International Journal of Adhesion & Adhesives, 27, 207-215.

Toutanji, H., and Ortiz, G. (2001). "The effect of surface preparation on the bond interface between FRP sheets and concrete members". Composite Structures, 53, 457-462.

Triantafillou, T.C. (1998). "Shear strengthening of reinforced concrete beams using epoxy-bonded FRP composites". ACI Structural Journal, 95, 107-115.

Triantafillou, T.C., and Plevris, N. (1992). "Strengthening of RC beams with epoxy-bonded fiber-composite materials". Materials and Structures, 25, 201-211.

Triantafillou, T.C., and Antonopoulos, C.P. (2000). "Design of concrete flexural members strengthened in shear with FRP". Journal of Composites for Construction-ASCE, 4, 198-205.

Triantafillou, T.C., and Fardis, M.N. (1997). "Strengthening of historic masonry structures with composite materials". Materials and Structures, 30, 486-496.

Van Gemert, D. (1980). "Force transfer in epoxy-bonded steel-concrete joint". International Journal of Adhesion and Adhesives, 1, 67-72.

Varastehpour, H., and Hamelin, P. (1997). "Strengthening of concrete beams using fiber reinforced plastics". Materials and Structures, 30, 160-166.

Vuković, N.K., Jevrić, M., and Zejak, R. (2020). "Experimental analysis of RC elements strengthened with CFRP strips". Mechanics of Composite Materials, 56, 75-84.

Wang, J. (2006). "Debonding of FRP-plated reinforced concrete beam: A bond-slip analysis- I. Theoretical formulation". International Journal of Solids and Structures, 43, 6649-6664.

White, T.W., Soudki, K.A., and Erki, M.A. (2001). "Response of RC beams strengthened with CFRP laminates and subjected to a high rate of loading". Journal of Composites for Construction-ASCE, 5, 153-162.

Wu, Z.J., and Davies, J.M. (2003). "Mechanical analysis of a cracked beam reinforced with an external FRP plate". Composite Structures, 62, 139-143.

Xiao, J., Li, J., and Zha, Q. (2004). "Experimental study on bond behavior between FRP and concrete". Construction and Building Materials, 18, 745-752.

Xie, H.B., and Wang, Y.F. (2019). "Reliability analysis of CFRP-strengthened RC bridges considering size effect of CFRP". Materials, 12, 2247.

Xue, W., Zeng, L., and Tan, Y. (2008). "Experimental studies on bond behaviour of high-strength CFRP plates". Composites-Part B: Engineering, 39, 592-603.

Yaun, H., and Wu, Z. (1999). "Interfacial fracture theory in structures strengthened with composites of continuous fibre". Symposium of China and Japan: Science and Technology of 21st Century, Tokyo, Japan, 142-155.

Yuan, H., Wu, Z.S., and Yoshizawa, H. (2001). "Theoretical solutions on interfacial stress transfer of externally bonded steel/composite laminates". Journal of Structural Mechanics and Earthquake Engineering, 675/1-55, 27-39.

Zirab, Y.N., Baluch, M.H., Basunbul, I.A., Azad, AK., Al-Sulaimani., G.J., and Sharif, A.M. (1995). "Combined experimental-numerical approach to characterization of steel-gle-concrete interface". Materials and Structures, 28, 518-525.