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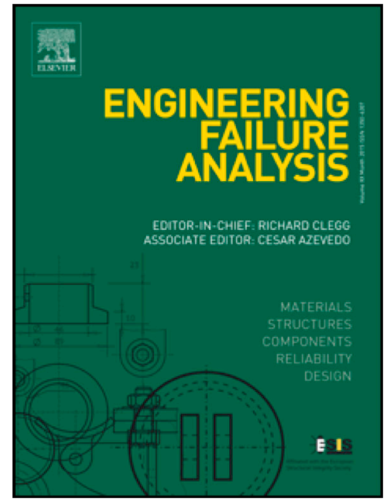

Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs - A state-of-the-art review

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RESEARCH PAPER

Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs - A state-of-the-art review

(Title contains 15 words)

by

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Performances, challenges and opportunities in strengthening reinforced concrete structures by using FRPs - A state-of-the-art review

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Abstract: Structures are often subjected to extreme loading conditions that lead to their premature deterioration, and replacement of those structures before the end of their design lives is very expensive. The rehabilitation of deteriorated structures by using externally bonded fibre-reinforced polymer (FRP) composites is gaining popularity in the construction sector owing to its high strength, optimum durability and compatibility with concrete structures during application. This paper aims to review the current state-of-the-art on the performances, challenges and future opportunities of FRP-strengthened reinforced concrete (RC) structures under different loading scenarios. FRP strengthening leads to satisfactory performances under static, dynamic and extreme environmental conditions. Debonding and FRP rupture are the common types of failure observed, however, the failure mechanisms operating under the combined action of service loads and environmental exposures are still unclear. The acceptance and application of FRPs in strengthening RC structures will further increase upon developing techniques for utilising the full FRP strength, reducing the brittleness, risk of fires and accidental damage, minimising the energy consumption as well as carbon emission during production, and reducing the high initial cost. This paper also identifies the gaps in the present state of knowledge and the potential research directions for FRP-strengthened structures that lead to better understanding and establishment of design guidelines.

Keywords: FRP; strengthening; performance; modelling; challenges; future opportunities.

1. Introduction

Strengthening of existing structures has emerged as a major construction activity to meet the upgraded design codes and strength requirements and because of environmental deterioration over time. Structures are required to sustain critical loads under challenging environmental conditions such as heavy traffic density, heavy blasts from terror attacks, impact from debris flow and highly corrosive environments. Therefore, strengthening is frequently required in reinforced concrete (RC) structures to meet the adequate strength requirements and extend the service life. The conventionally practiced strengthening techniques of RC structures may include the application of an external layer of a metallic plate, textile fibre sheet, wire mesh, post tensioning, concrete or steel jacketing, and injection of epoxy [1–3]. Strengthening of RC members by using fibre-reinforced polymers (FRPs) results in superior performance, compared to those realised through the techniques that have generally been practiced recently [4]. The typical FRP systems are shown in Fig. 1. FRPs may consist of carbon, glass, aramid and basalt fibres that are bonded together by the matrix of a polymer such as epoxy, vinyl ester or polyester to form CFRP, GFRP, AFRP and BFRP, respectively [5–10]. FRP materials are being used in the forms of laminates, rods, dry fibres or sheets in concrete structures. FRPs are gaining popularity as strengthening materials because of their high longitudinal tensile strength, non-corrosive nature, high stiffness and strength-to-weight ratio, high resistance to insect and fungal growth, high resistance to chemical attack, low thermal transmissibility and ease of installation [1,10–18]. Fig. 2 compares the stress-strain behaviours of different FRP materials with that of mild steel, which is clear evidence of the high strength of FRPs relative to those of other conventional materials.

Being lightweight with high stiffness and strength, FRPs require less equipment and minimum resources and, therefore, can be fabricated fast with reasonable life cycle costs and low waste productions [19]. The use of FRPs is considered an effective technique in terms of strength and economy for both strengthening and repairing of RC structures [20]. Currently, the use of FRPs in bridge repair, strengthening and maintenance is most pronounced owing to its efficient and economical nature [8].

(a) Slab strengthening (b) Bridge strengthening

Fig. 1 Real-life FRP strengthening of RC structures [9,21,22]

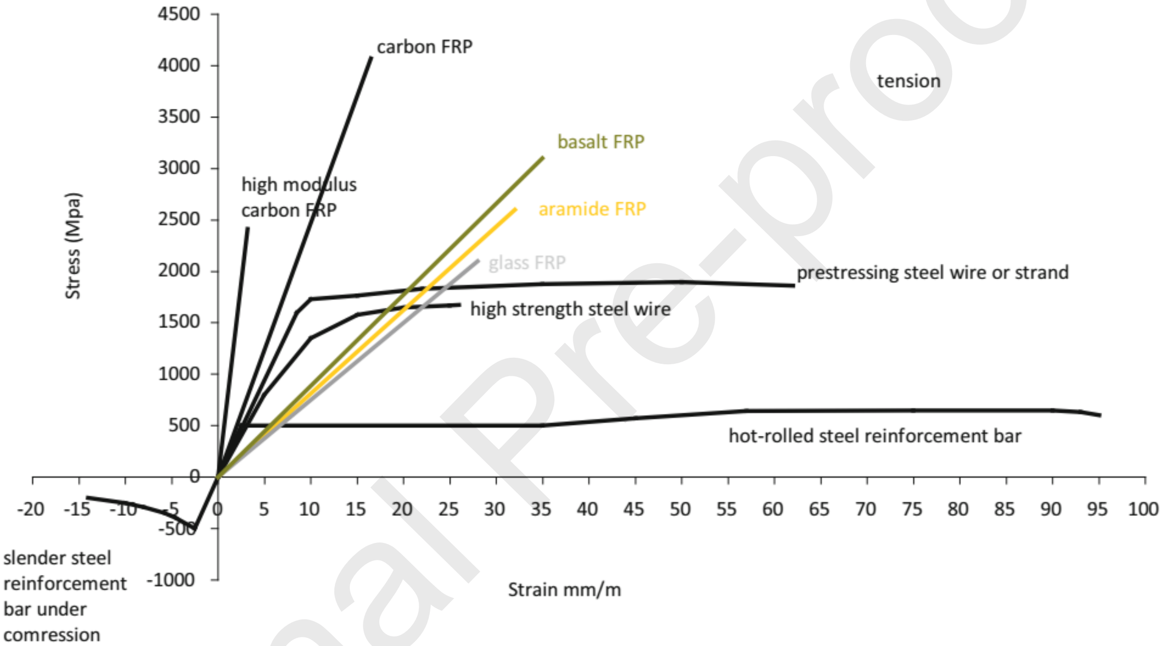


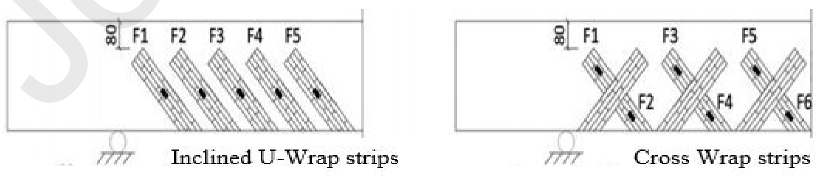
Fig. 2 Comparison of typical FRP materials with mild steel [23]

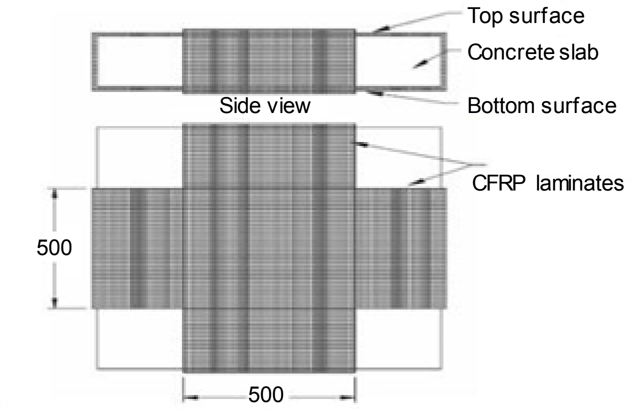
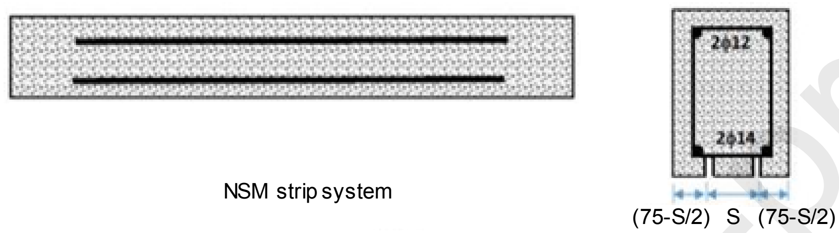
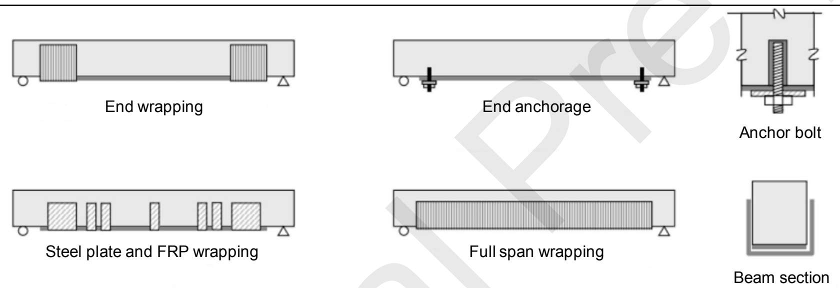
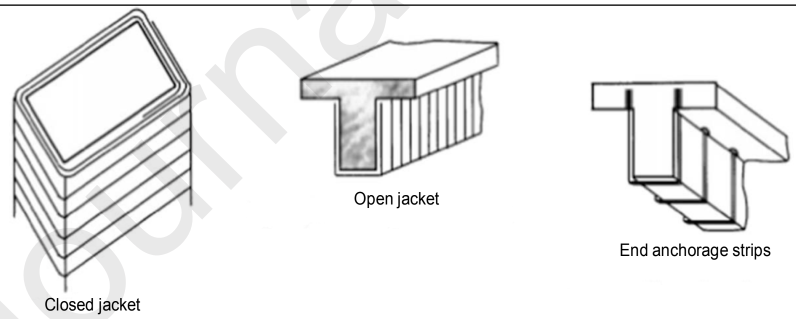
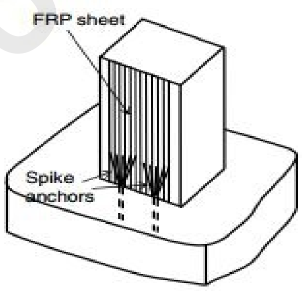
Despite the significant progress in FRP strengthening, several issues related to their long-term performance remain unresolved. It is therefore necessary to understand the dynamic and durability performances of FRP-strengthened structures and their critical issues. Indeed, if the strengthening techniques become ineffective over the expected design life, the rehabilitation will be compromised. This paper comprehensively reviews the performances, failure modes, modelling techniques, common challenges and future opportunities of FRP-strengthened RC structures. The outcomes of this study will benefit researchers and engineers through deep understanding of the strengthening of RC structures by using FRPs.

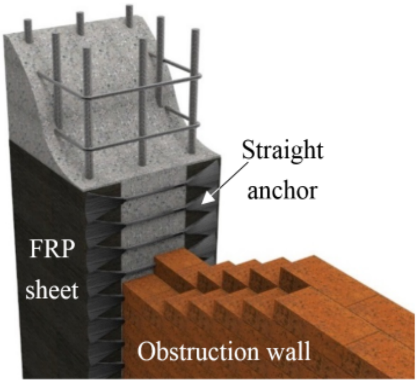
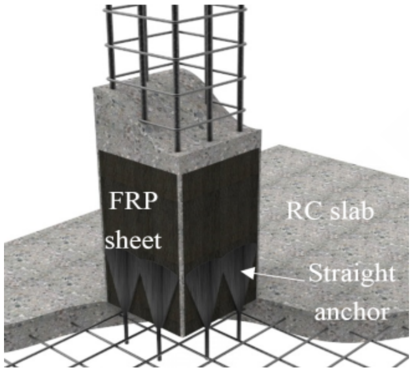
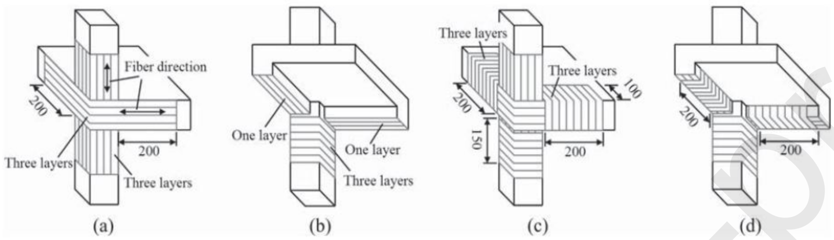
2. Types of strengthening techniques

RC structures can be strengthened by using FRPs as externally bonded (EB) laminates, near-surface mounted (NSM) bars/strips with or without adhesives and anchorage systems [16,24–26]. Generally, epoxy resins are used as the adhesive in FRP application. The different configurations of FRP strengthening systems are shown in Table 1. EB FRP-strengthening can be carried out in any configuration, such as side-bonding, partial or full-wrapping, inclined or vertical. Instead, NSM strips could be inserted into grooves made in concrete and covered with sufficient adhesives. Provision of anchorage system can effectively increase the efficiency of strengthened structures. A wide range anchorage system can be applied in FRP strengthening, for example FRP anchors, mechanical fasteners, spike anchors, powder-actuated fasteners, straps, or any other suitable configurations [1,26–28]. Koutas and Triantafillou [27] and Ekenel et al., (2006) [29] illustrated that spike anchors are more practical and advantageous anchor system. Selection of the strengthening technique depends on the structural configuration, loading and exposure conditions.

Table 1. FRP strengthening techniques

Strengthening technique	Type of strengthening	Ref.
	Flexural and shear	[16]
	Shear	[13]

 U-Wrapped slab in both directions	Flexural and shear	[30]
 NSM strip system	Flexural	[31]
	Flexural	[8]
	Shear	[32]
 	Axial	[1]

 (a)  (b)	(a) Shear and (b) flexural strengthening of column	[33]
	(a) Shear (joint) (b) Seismic (column) (c, d) Shear (beam)	[34, 35]

3. Performances of FRP-strengthened structures

In general, the strengthening of existing RC beams, slabs, columns, bridge components, as well as prestressed structural components can be carried out to enhance the flexural strength, shear strength, strain control capacity and ductility under different types of loading conditions [4,16,26,36]. For designing FRP systems, the generally applied codes are ACI 440.2R, FIB 14 and CECS 146 [37]. FRP-strengthened structures may experience different types of loading and exposure conditions, therefore its sustainability needs to justify accordingly.

3.1 Static loading

3.1.1 Axial strengthening

Structural members may act as columns which may predominantly experience direct compression and require strengthening to increase the strength and service life and prevent spalling during brittle failure in concrete crushing [38]. Wrapping of an EB-FRP sheet along the perimeter of the column is a common strengthening technique which results in increased compressive strength [39]. EB-FRP partial-wrapping systems are less effective when used under direct compression [40]; full-wrapping is required to provide confinement to the column in order to resist lateral deflection [39] and obtain a higher compressive strength, ductility and strain control capacity [41]. An improvement in strength of 66% was observed for a hollow column through research [42] after wrapping it with one layer of a CFRP sheet, whereas 123%

increment was obtained by using three-layer CFRP. EB-FRP wrapping is considered an effective technique under axial loading. Only 8% strength improvement was realised by applying the NSM system and around 42% improvement was noticed in the EB-FRP system in the same column [38]. A hybrid of NSM strips with EB-FRP system has been proven to be the most effective technique of column strengthening.

The compressive strength of FRPs is generally 20-50% of the tensile strength [40], and the risk of local layer instability and buckling failure cannot be ignored under compression [43]. FRPs with fibres in the circumferential direction, as spiral or tie reinforcement, are very effective [44,45]. Wrapping of a rectangular section shows very little flexural rigidity along its flat side, with non-uniform distribution of the axial stress under compression; on the other hand, a circular section exhibited pronounced rigidity [46]. Sometimes, a rectangular section may need to be rounded to prevent tearing or debonding of the FRP along sharp corners [38,47]. The ductility of a FRP-wrapped RC member is more than that of an ordinary member and increases with the eccentricity. The hybrid-FRP system displayed high ductility and energy dissipation capacity of the column under compressive loadings [44]. FRP-wrapped structures under direct axial loading are shown in Fig. 3.

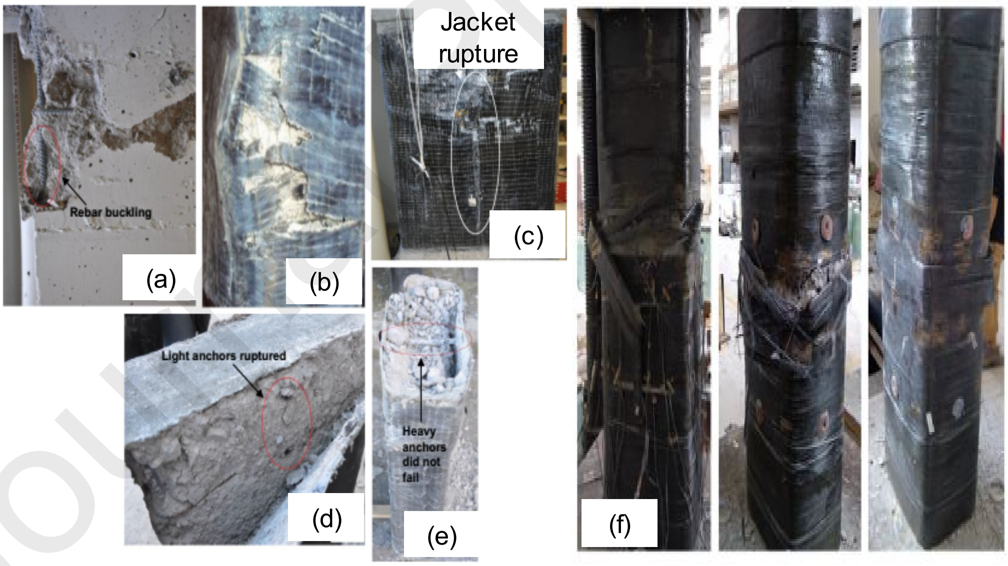


Fig. 3 A typical FRP-wrapped column under axial compression: (a) Concrete crushing in the control specimen, (b, c, f) FRP rupture and (d) anchor rupture [46,48,49]

3.1.2 Flexural strengthening

Structural members may repeatedly undergo bending action, therefore, there is a need to increase the flexural strength. The performance of a flexurally strengthened member depends on the type of strengthening system, properties of the FRP and adhesives and additional anchorages provided. An EB-FRP sheet aligned along the tension face of a concrete structure is the most common and provides excellent performance under bending [5,41,50–52], whereas the fibres in FRP laminates need to be arranged along the length of the member.

Furthermore, the performance of NSM-strip strengthened beams has proven to be better than that of the widely practiced EB laminate system under bending, which may enhance the overall strength by more than 200% [38,41,53]. This is sometimes argued as being attributable to the stiff character of NSM strips, compared to the FRP laminates with two-dimensional fibres [54]. FRP wrapping reduces the deflection and width of cracks under bending, thus enhancing the ductility [55]. The RC beam u-wrapped by a carbon-glass fibre hybrid sheet reveals a 114% increase in the flexural strength, which is equivalent to strengthening with one layer of CFRP sheet in the longitudinal direction and another in the direction perpendicular to the beam [56]. Researchers [55] retrofitted a concrete beam which had lost 31% steel mass due to corrosion by CFRP wrapping and observed 73% increase in the flexural strength. A 60-year old 8 m long prestressed concrete bridge deck girder was strengthened by using a EB CFRP plate along the soffit, and 10% increase in the serviceability load along with 54% increase in the ultimate strength were observed [37]. Another similar girder was also strengthened by using a GFRP I-beam anchored along the soffit of the deck and finally adhesively bonded CFRP laminates. These strengthened girders performed excellently, with 105% increased ultimate strengths. Increasing the thickness of the FRP layer resulted in a great improvement of strength [42]. As reported in [42], combined strengthening are more beneficial in terms of ultimate strength gaining, when they applied the combined flexure-shear strengthening, the beams have shown more strength.

Strengthening of RC slabs by using FRP strips was found to be very effective and may improve the strength by around 40-90% when the fibres of the FRP are oriented at zero degrees and bonded along the maximum bending zone [8,57]. Haddad and Almomani [58] found a 154% increase in the flexural strength and 85% improved rotational ductility by using a FRP NSM strip in a RC beam. The concrete cover and embedment length are important in a NSM strengthening system [58,59]. The wrapping of a column with an EB-FRP sheet may have little impact in improving the flexural performance during bending, but the NSM strip technique of strengthening has been proven to be effective [44]. The common failure mode of FRP-strengthened RC structures under bending is debonding, which reduces the effectiveness of the strengthening [5,8,20], as shown in Fig. 4 [5].

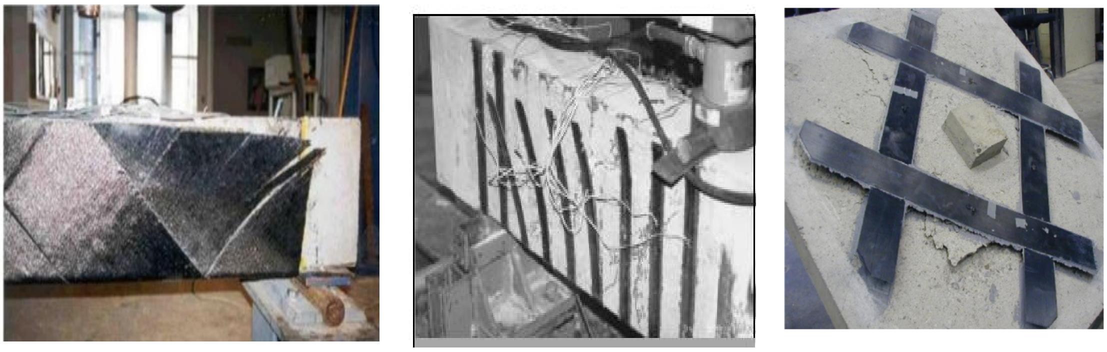
(a) Compression crushing with FRP rupture (b) Cover separation (c) IC debonding

Fig. 4 Typical failure modes of flexurally strengthened beams and panels [5,56,57]

3.1.3 Shear strengthening

Externally bonded FRP web reinforcements can be used as shear reinforcements to strengthened the shear deficit RC beams, where vertical, inclined, side-bonded, U-wrapped or anchored configurations can be applied [26]. The performance of strengthened structures depends upon the quality and quantity of fibers, orientation and distribution of FRP, interaction between internal steel stirrup and FRPs [60,61]. Among all the wrapping systems, the inclined wrapping system was found to be the most effective technique for increasing the shear capacity. In the study by Singh [62], around 11.9% and 7.7% increased load capacities were observed after wrapping a RC beam with a 45° oriented CFRP sheet and bidirectional CFRP sheet, respectively. As found from the literature, FRP wrapping along the 45° direction could resist diagonal cracks, whereas 0° and 90° fibre-oriented strengthened beams could not [63]. Researchers [64] also repaired the shear cracks developed in a damaged beam by externally applying a prestressed force and strengthened it by using a U-wrapped CFRP system, which resulted in a 57% increase in the load carrying capacity. With an anchorage system, the increase in the capacity could be more pronounced, can be 75-82.2%, as reported in previous researches [65,66].

In addition, the interaction between the internal stirrup and the EB-FRP also affects the strength [67]. In order to achieve highest effectiveness in strengthening a moderate shear span-to-depth ratio and closely spaced FRP stirrups are useful, where the negative effect of transverse reinforcement can be eliminate by ignoring their uses [63]. It was proven that, the ultimate shear capacity of strengthened beam can be effectively increased by 82.2%, when no internal stirrup used in critical shear span [66]. The expected failure mode in strengthened structures is ductile, which is a result of flexural failure of the beam [66]. Therefore, there is a need to provide a higher shear capacity than flexural capacity while designing for the purpose of strengthening. The typical shear-strengthened systems are displayed in Fig. 5.



(a) FRP rupture with debonding (b) Debonding of FRP strips (c) Punching shear cracks in a FRP-strengthened slab

Fig. 5 Typical shear-strengthening techniques of beams and panels [5,62]

3.2 Dynamic behaviour

3.2.1 Impact behaviour

The impact forces developed in structures due to moving loads, falling ice, accidental falling loads, explosion and tornados [68], which have loading rates of up to 10 s^{-1}, may concentrate as point loads on structures [41] for very short durations with strain rates higher than those of static and seismic loadings [68]. Under impact loading, shear failures occur very often and are critical in RC elements [13], therefore, structures need to be strengthened with respect to their shear capacities in order to improve the overall impact resistance [69]. An EB-FRP sheet strengthened system significantly increases the impact strength of RC structures and decreases the deflection and crack width [41,68]. It was reported that 15% [68] increase in impact strength and 96% increase in shear strength [13] are observed in a FRP-strengthened RC beam which was shear-deficient. Strengthening can be carried out by using uni/cross directional fibres, especially cross directional carbon and aramid sheets having high capacity to resist orthogonal impact forces [70]. Though the choice of the FRP material for increasing the impact capacity is still a matter of argument, in some cases, the impact resistance of AFRP is considered as being higher than those of other FRPs. Around 20% and 33% increments in the impact load capacity were observed from the study [70] after strengthening a RC slab by using CFRP and AFRP bidirectional sheets. Therefore, the impact strength of a FRP-strengthened RC structure greatly depends on the material characteristics, impact energy, stiffness, loading rate, and strengthening configuration [68].

Impact loading may produce vibrations and progressively negative bending in a structure, which should be accounted for in the strengthening design [41]. Therefore, the FRP must be applied in both the tension and compression directions when impact forces are applied. Inclined shear cracks in the diagonal direction are observed in most of the impact tests, due to excessive diagonal shear. That is why 45° inclined wrapping of FRP sheets yields better performance than U-wrapped RC members [69]. Impact loading changes the strain distribution, which has a wide gradient, and the loading rate greatly influences the bond strength of the FRP-concrete interface [70,71]; however, the failure mode and ductility of the strengthened structure do not directly depend on the loading rate.

Flatter punching shear cones and bidirectional yielding are observed in a FRP-strengthened slab upon impact, which is a positive sign that suggests increased rigidity [70]. A FRP-strengthened RC beam under impact loading develops inclined shear cracks and diagonal cracks, which lead to debonding in the high stress concentration zone [13,68]. The U-wrapped beam shown in Fig. 6 was tested under a static load and found to display 43% increased capacity, compared to that of a control beam [69]. Shear cracks and debonding of the FRP were noticed at the failure load. However, in the impact load test, the beam failed during concrete crushing, with full debonding of the FRP. These phenomena may be caused by the generation of negative bending under a direct impact force [41]. However, while strengthening applied for any structure that would subject any impact loading, the designers should accounts these negative bending actions.

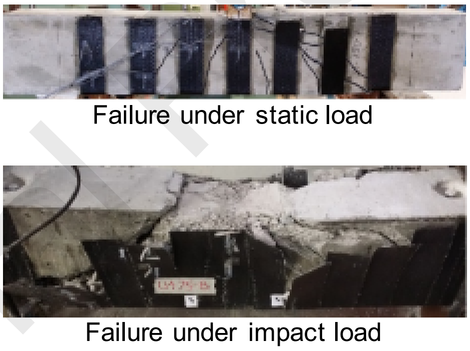


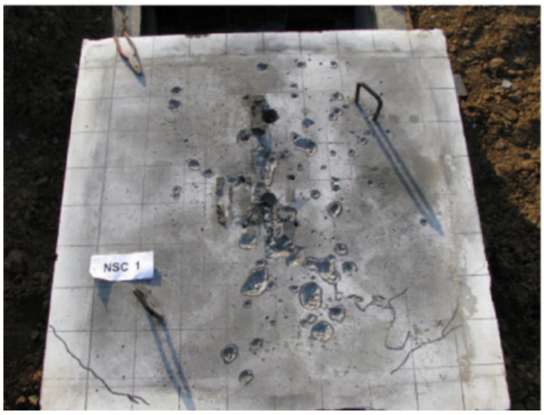
Fig. 6 Typical failure of FRP-strengthened RC beams under impact loading [69]

3.2.2 Blast resistance

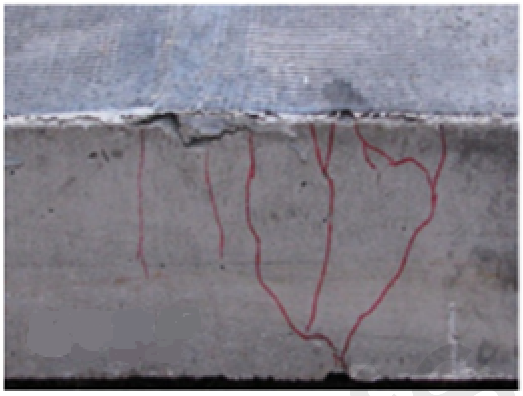
Blast is a kind of sudden load which may be generated by a heavy explosion, in which energy is released very rapidly on a large scale to scatter heavy debris and cause destructive fragmentation of RC structures; these structures therefore need to resist such high loads for safety reasons. In the modern world, blasts occur in different places due to terror attacks, nuclear explosions or accidental explosions. Ensuring a sufficient standoff distance is very effective way of protecting structures from blasts [72,73].

A FRP is a lightweight high-strength material which may exhibit resistance to bending, tension and combined action of tension-compression that may be produced during a blast. The performances of FRP-strengthened systems depend on the stiffness, energy absorption capacity and debris-capturing ability of the overall system [72–74]. A FRP could be used as a strip, wrap or spray in RC structures to increase its blast resistance by enhancing the ductility, shear and flexural capacity [72,73]. Blast damage can be minimized and spall and fragmentation can be completely prevented through AFRP strengthening of RC structures, because this material exhibits a high energy absorption capacity [30]. It is considered that the blast resistances of CFRP- and GFRP-strengthened RC structures are nearly identical, but hybrid aramid/glass fibre composites are more reliable and provide improved flexibilities under blast loadings [72]. Ha et al. [75] used a combination of CFRP with sprayed polyurea to strengthen RC structures by enhancing the ductility, stiffness and overall resistance under blast loading. The authors represented a better blast resistance for hybrid FRP system, where the retrofitting effect is improved by 63.7% for residual displacement in hybrid CFRP and polyuria system compared to the non-strengthened specimens.

Generally, strengthening is needed for the back face of a RC member, where tension and bending actions take place during and after a blast. However, the blast resistance of a RC panel strengthened with an EB-FRP sheet along the directions of tension and compression (i.e. both faces) was found to be higher than that of a panel strengthened only on the tension face or compression face for small to large standoff distances. NSM technique is considered less effective in increasing the blast resistance, as reported through research for up to 6 kg of explosive charge [73]. FRP strips and EB wrapping are simultaneously applied in some cases to strengthen columns and significant increases in blast and deflection resistances have been observed. Around 30% increase in the energy absorption capacity and 85% decrease in the displacement were observed after strengthening a RC panel by using a CFRP sheet under a blast of 15.88 kg explosive charge with 1.5 m standoff distance [75]. Even the post-blast static strength could be improved by up to 70% by FRP strengthening [30]. While designing a strengthening system for provide resistance against blast loading, the bond strength and the requirement of an anchorage system need to be analysed first [74,76]. It is clearly observed in Fig. 7 that the control specimen experiences several damages, which the FRP-strengthened specimens do not.



(a) Blast damage of a control specimen



(b) Blast damage of a FRP-retrofitted specimen

Fig. 7 Typical blast damage in RC panels [75]

3.2.3 Fatigue resistance

When a structure is subjected to cyclic loading, it starts losing its overall stiffness and the ductility of its members, leading to permanent deformation. If strengthened by using a high tensile strength FRP system, redistribution of the stresses takes place and a lower concentration of stress is developed in the cracked portion, and the overall fatigue resistance is improved [77,78]. The stress transfer occurs through the FRP-concrete bonds, therefore, the fatigue performance is controlled by the FRP-adhesive-concrete bond strength, which is dependent on the strength of concrete, confinement rate, thickness and elastic modulus of the FRP and development length of the FRP laminates available for load transfer [79]. An EB-FRP along the lateral and bottom faces of a RC beam enhances the rigidity, ultimate strength and first crack load, and shortens cracks under fatigue loading [80]. On the other hand, a FRP U-wrapping system increases the shear capacity and ductility under repeated loading, thus, the overall fatigue performance is improved. RC beams which were spliced along their mid-spans strengthened for different FRP wrapping conditions and concrete cover thicknesses under fatigue loading [79,81–83], and up to 62% improvement in the fatigue strength was observed. Further, 70% reduced deflection and 24.7% increased first crack load were observed for a GFRP diagonally strengthened beam [80]. Researchers concluded that the tension-tension fatigue loading capacities of FRP-strengthened RC structures are unquestionable, but exhibit the worst loading capacities under tension-compression or reversed axial fatigue loading [43]. Flexural strengthening by using FRP laminates may enhance the fatigue resistance of steels in RC members, because an elastic material which does not yield in the tension zone increases the resistance to stiffness of a structure under fatigue loading [84]. The functioning of a FRP-strengthened beam under impact is shown in Fig. 8(a). Most experiments [25,78] reveal that

FRP-strengthened beams fail owing to the tensile rupturing of the steel, primarily at the early stage of the loading cycle, when fatigue loading is applied. Therefore, during design, the stress limit should be kept well below the yield limit of the steel to resist steel failure [84]. The main factors influencing steel rupturing under fatigue are the geometry and ultimate strength of the flexural steel and the stress applied to the structure [79]. Therefore, the stress limit of the steel is very important for determining the fatigue life of a FRP-strengthened structure; the upper limit of fatigue loads is increased up to 60% [84] of the yield strength. The stress distributions of both the steel and FRP should be considered to increase the fatigue life of a strengthened structure. The upper limit of the stress in CFRP laminates is generally kept at 55% of the rupture strength of the whole composite when designing the fatigue strength of RC structures strengthened by using FRPs [85]. The FRP-strengthened beam and control beam under fatigue loading are shown in Fig. 8(b).

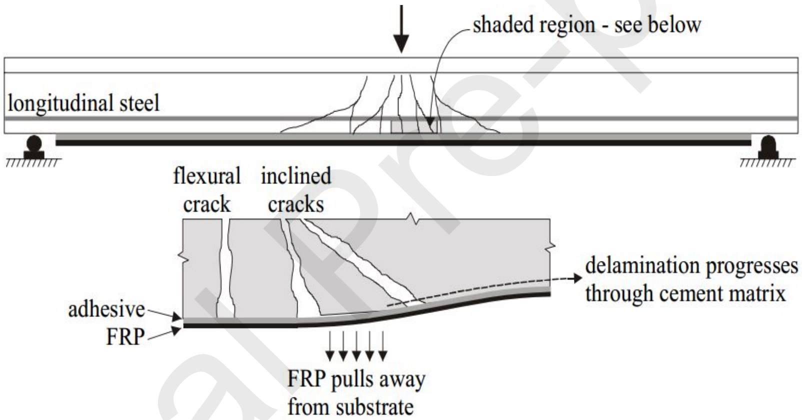


Fig. 8 A typical FRP-strengthened beam under fatigue loading [78]

3.2.4 Seismic behaviour

RC structures sometimes experience hazardous failure under moderate to severe earthquakes, when the capacity is exceeded. RC columns are frequently found to be shear-deficient, and their failure is in brittle mode and severe [33]. These shear- and flexural-deficient columns are the major reason for the failure of RC buildings during earthquakes, and therefore, need to be strengthened. Wrapping of a column by using a FRP sheet is a widely recommended solution for seismic retrofitting, because the FRP jacket activate the confinement of concrete columns and increases the axial strength [8], which improves the ductility and strength and reduces spalling. Highly ductile structures are more resistive to seismic action; the resistance can be enhanced by wrapping a RC column with a FRP sheet [86,87]. FRP strengthening reduces the stiffness degradation of columns under cyclic loading, which may happen during earthquakes, decreases the slenderness of columns through enhanced stiffness [86], and improves the deformation capacity through an increase in the lateral load carrying capacity [47,88]. The wrapping of a column by using a hybrid FRP by applying both NSM and EB techniques increases the load capacity and ductility under seismic events. Iacobucci et al. [87] revealed that FRP wrapping of a shear-deficient RC column may help to provide at least 54% better strength than an un-strengthened column. Wrapping may be carried out either partially or up to the full height of the column, including the plastic hinge zone. Research reveals that the FRP-concrete debonding moment and FRP rupture moment are two critical considerations when a flexurally strengthened column is tested under seismic loading conditions, although the strength is not very dependent on the tension-compression cycle [33]. Higher energy absorption capacity, viscous damping and lateral drift without damage are observed in FRP-strengthened columns [88], which are dependent on the confinement level of the FRP wrapped, axial load ratio and aspect ratio of the column section [89].

Shear walls are the most important elements in buildings located in seismically vulnerable areas, and could be effectively strengthened by using lateral FRP strips to enhance their ductile flexural behaviour under cyclic loading [90]. RC shear walls strengthened by using BFRP lateral strips may increase the viscous damping and energy dissipation capacity by up to 40% and 175%, respectively, which could be more pronounced by altering the arrangement and FRP proportion [90]. A RC beam-column joint fails during shear in a brittle manner due to the imposed seismic load, and could be strengthened up to a certain limit with a FRP sheet that is U-wrapped from the top of the beam [35,91]. Such strengthened RC joints can enhance the shear strength capacity of the beam and the ductility of the column. The strengthening of this joint should be carried out in such a way that the column exhibits adequate ductility and the beams start to fail during flexure [34] in order to avoid shear failure of the joint and allow flexural yielding of the column [92]. Fibres should be placed in both the directions to satisfy the shear requirement under reversed cyclic loading [5]. It was proven that a hybrid carbon-basalt FRP jacket can improve the ductility of a concrete column significantly under seismic loads [88]. The strengthening of beams under reverse seismic events requires tension-only reinforcements in both 90°-θ and 90°+θ directions (angles measured with respect to the beam axis) [92]. The ultimate objective of these strengthening processes is to transform the brittle shear failure into ductile failure mode, which was observed in several studies [33,47]. However, partial wrapping along the joint area may cause early debonding failure under transverse cyclic loading; a typical debonding pattern is shown in Fig. 9.

(a) (b)

Fig. 9 A typical FRP-wrapped beam-column joint under loading (a) before and (b) after the removal of the FRP sheet [35]

3.3 Durability

3.3.1 Moisture conditions

Though externally applied FRP laminates act as low-permeable barriers to the ingress of moisture into concrete [55], when FRP-strengthened RC structures are exposed to cyclic moisturization, they may greatly affect the material properties and the bonds within the adhesive and at the FRP-concrete interface [93,94]. Because, if polymers are exposed to moisture conditions for a long time, their properties may be changed to some extent, which may or may not be possible to recover after drying. Generally, plasticization, swelling, hydrolysis and differential stress may develop owing to moisture uptake [95,96]. Swelling of a polymer is proportional to its moisture content and increases with increasing relative humidity [97]. The swelling of a polymer matrix and the plasticization of its structure may be recovered after drying; the recovery depends on the constituents and quality of adhesives. Micro-cracks are formed due to capillary pressure in the adhesive as a result of the increase in moisture, which is irreversible and causes degradation in the overall strength. This phenomenon may also occur within the polymeric matrix of FRPs.

Another change may occur in the chemical structure of a polymer after reaction with a water-repelling agent. The fibre integrity and matrix-fibre bonding within a FRP can also degrade and cause reduction in the glass transition temperature (T_g), due to the ingress of moisture [6,98]. AFRP, and GFRP are more susceptible to moisture and high humidity conditions, whereas CFRP exhibits sufficient resistance [9,96]. In GFRP, moisture extracts the ions from the glass fibres and a change in the fibre structure takes place and fibrillation increases when aramid fibres absorb moisture [99]. High moisture absorption is noticed in BFRP, which causes huge diffusion of ions inside, leading to a greater loss in the tensile strength. Surface pitting and roughness may arise in fibres due to hydroxylation under moisture conditions, which worsen the fibre properties. Concrete uptake moisture as soon as the freezing temperature is reached, and the volume increases and micro-cracks are formed inside the concrete to generate tensile stresses, which may lead to severe damage under loading or debonding from the FRP. Moisture absorption in humid environments may result in excess shrinkage when dried at elevated temperatures, and micro-cracks are formed inside polymer composites due to the generation and degeneration of stresses [100]. These cracks act as desorption paths for moisture uptake. During the drying of these moisture-laden specimens, the outer part of their bonding interface released more water than the inner part as part of the evaporation process, which is why the outer bond interface exhibited cohesive failure while the inner part displayed adhesive failure [97]. Therefore, the debonding failure mode transformed to adhesive separation of the FRP from the concrete substrate as a result of cohesive concrete fracture [94]. These debonding mechanisms are complex and FRP cannot withstand the designed strength, leading to premature failure and the purpose of strengthening cannot be achieved.

The higher interfacial damage observed owing to the difference in the thermal coefficients of the fibres and the resin matrix generated a differential stress when cyclic wetting-drying took place [101]. Shrestha et al. [94] observed 12% bond strength loss of a FRP-strengthened concrete element after 24 months of continuous immersion in water. Amidi and Wang [97] concluded that degradation of the interface of FRP-concrete completed within three months of immersion in water, after which no significant loss in the properties was observed. They found that the fracture toughness was only 22% of the initial fracture toughness at the interface after three months of immersion in water. A FRP used with a cover of concrete is comparatively safe in moisture and moderate temperature conditions. Therefore, the NSM technique of FRP strengthening is advantageous because it prevents the direct exposure of FRPs to any environmental change [31]. Treatment of the FRP-concrete bonds or using a protective covering for the moisture uptake can reduce its vulnerability. Silane treatment can also enhance the bond interface durability in moisture conditions by increasing the fracture toughness [97]. However, in spite of these risks and challenges, the FRPs were proven as effective and advantageous in many applications including the fabrication of water retaining structures [102].

3.3.2 Freeze-thaw effect

Freeze-thaw cycle is one of the common environmental conditions in cold regions that adversely affects concrete structures. These structures, after strengthening by using FRP composites, should be clearly investigated for their durability against the freeze-thaw cycle.

Some experimental results showed that for less than 80 freeze-thaw cycles, there is negligible effect on the properties of FRP laminates, whereas above that number, there can be a loss of strength; beyond 200 cycles, FRP laminates lost around 10% of the tensile strength [103]. BFRP and GFRP composites display negligible strength reductions in freeze-thaw condition, but around 16% reduction in the tensile strength of CFRP composite was reported in the literature [104]. The most important factor is the bonding between the FRP and concrete under the freeze- thaw condition. EB-FRP laminates can resist the freeze-thaw condition up to certain limit. Even these materials reveal an increase in the bond strength for a small number of freeze-thaw cycles, which is due to an increase in the compressive strength of concrete as a post-curing benefit, which enhanced the ductility of the specimen. However, for increased number of freeze-thaw cycles, deterioration in the FRP-concrete bond strength is observed, and the failure shifted to the adhesive-FRP interface from the FRP-concrete interface [105]. It was reported that stiffness, shear strength and fracture energy decreased significantly during the debonding stage when subjected to freeze-thaw cycling [106]. Reductions of 35% interfacial fracture energy, 17% ultimate load capacity and 17% shear stress during debonding were reported after testing a concrete specimen over 300 freeze-thaw cycles [107]. Therefore, the bond development length should be sufficient to increase the resistance against the freeze-thaw condition [106].

When a concrete cylinder is wrapped by using CFRP and GFRP sheets and exposed to 300 freeze-thaw cycles, around 2-16% strength loss is observed relative to the unconditioned specimen [108]. On the other hand, the cylinder without FRP wrapping lost its full strength after 150 freeze-thaw cycles under similar conditions. Further, 6.25% of pre-existing bond defected CFRP-strengthened concrete specimens were tested under freeze-thaw cycling and less than 4% degradation in the ultimate strength was observed after 50 cycles, even though the bond degradation increased [109]. Additionally, around 36% higher flexural strength was noticed in FRP-wrapped beams than in unstrengthened beams, when both were tested under freeze-thaw cycling [104]. These stresses generated from the cyclic freeze-thawing effect are not very destructive, but produce micro-cracks and delaminations in the fibre matrix [93,106]. If the freezing temperature is reached after water ingresses into concrete, which may lead to an increase in the volume of water and the concrete experiencing a stress, which result in micro-cracks; these cracks propagate towards the FRP laminates and concrete interface, and finally, debonding takes place [105]. Continuous freeze-thaw cycling produces permanent scaling and spalling in concrete specimens, which could certainly be minimized by FRP wrapping, as claimed by Marby et al. [109]. After 50 freeze-thaw cycle the researchers claimed that the performance of strengthened specimens were found satisfactory as long as the defect sizes are within the standard limits. However, the presence of any defects are not desirable, because these could negatively affects the strengthening purpose.

3.3.3 Acidic-alkaline conditions

The concrete in highly alkaline materials and acid attack can damage FRP-strengthened concrete structures in different ways [110]. Acid attack may arise from different sources such as acid rain, chemical exposure and industrial, clinical and domestic wastes. Different types of acidic media may be produced as a result of the moisture content and gases and liquids present in the surroundings, which may attack the adjacent structures. It was reported that carbon fibres showed excellent resistance to acid attack, but other fibres are considered weak against acid attacks [110]; glass fibres display very low resistance to alkaline environments compared to other fibres [7]. Besides, upon exposure to an acidic or alkaline solution, polymeric resins are most degraded and their T_g may be reduced [93,111]. Long-term acid exposure decreases the overall load carrying capacity, energy dissipation capacity and strain softening owing to the chemical damage to the resin-fibre interface within the FRP [111]. These degradations are dependent on the exposure time, concentration of chemicals during the exposure and temperature. The use of FRPs is not recommended for exposures where the structure may come in contact with 80-90% sulphuric acid [110]. Therefore, the use of FRPs in chemical plants, treatment plants and power plants requires additional protection to provide resistance to acid-alkali conditions, because fibres exchange ions with the acidic or alkaline solution and corrosive solutions ingress into concrete by diffusion or infiltration through cracks.

Degradation of CFRP occurs due to the accelerated chemical response of alkene, alkyne and amine groups in the presence of carbon fibres in resins and after the decomposition of the resins and the chemical by-products generated by the reaction between the fibre and the epoxy [111]. The T_g of FRPs decreased by 10% after 6 weeks of exposure to an acid solution [111]. Environmental exposure conditions have less effect on the stress-strain relationship of FRPs, which is found to be linear in most of the cases [98]. However, when the stress level increases, the degradation of FRPs increases in such acidic or alkaline media. Therefore, the stress level is limited to 25% of the ultimate design strength for GFRP, 30% for AFRP and 40% for CFRP composites [99]. A critical condition may arise from disintegration of the resin matrix through acid or alkali attack, which can finally result in debonding due to a reduction in the shearing strength of the adhesive-concrete interface. Sometimes, decomposition of hydrated concrete may also occur and progress to decrease the strength and weaken the bonding within FRP-strengthened concrete structures [110]. The typical phenomena occurring during the penetration of a corrosive solution into the FRP-concrete bond interface which lead to degradation of the strength are shown in Fig. 10. As the corrosive solution ingress into or diffused through molecular transformation, the reaction products can be removed by abrasion or dissolution.

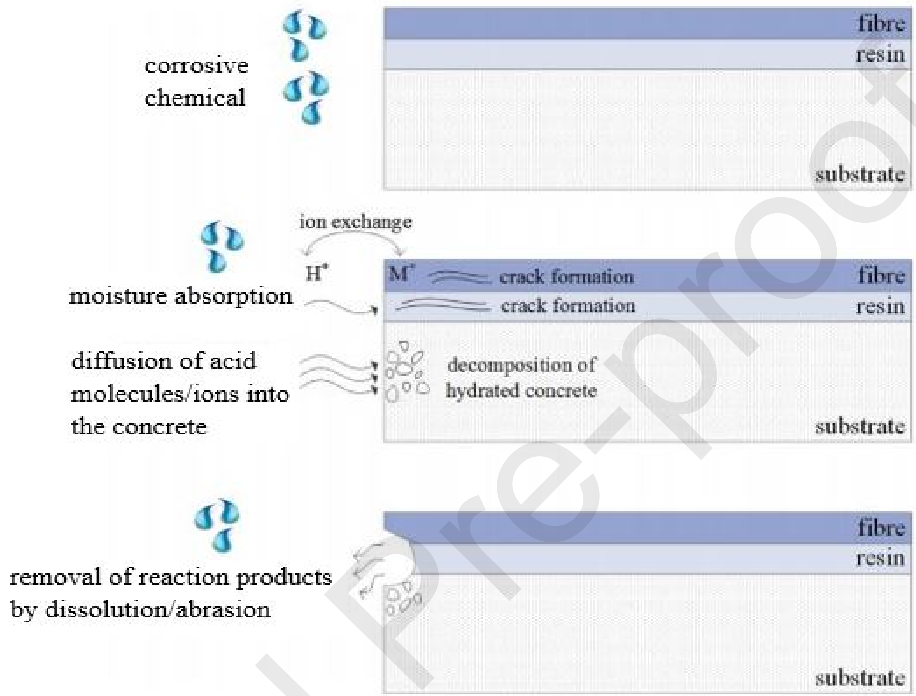


Fig. 10 Penetration of a corrosive medium into the FRP-concrete interface [110]

3.3.4 Temperature variation

Variations in temperature may adversely affect FRP-strengthened concrete structures. Because, although fibres are relatively less aggressive at high temperatures, the polymer inside a FRP is highly vulnerable to temperature changes. The usable temperature range of carbon fibres is -50 to +500 °C, whereas glass fibres can be used from -60 to +450 °C and basalt fibres from -200 to +700 °C [103]. However, above the T_g, the stiffness, viscosity and mechanical properties of the polymeric matrix decrease due to the change from the brittle state into the plastic state, which may lower the strength of the strengthened structure [6,93,112]. Furthermore, most of the polymers show a great loss in the ductility below their T_g [100]. The value of the T_g of epoxy polymers may vary between 15 and 20 °C above the curing temperature, which is generally 45-82 °C [6,113]. The critical temperature of exposure is generally considered as the temperature at which FRP composites lose 50% of their strength [113,114]. Therefore, a polymeric matrix should be chosen for strengthening purpose such that it exhibits a T_g that us at least 30 °C higher than the expected maximum environmental temperature [99].

During the period of curing of the adhesive which is applied to the FRP-strengthened structure, a high temperature is beneficial to increase the T_g of the bonding interface. On the other hand, when cured at a lower temperature (<10 °C), the bond quality is highly inferior [115]. High-temperature exposure immediately after the curing of the adhesive is beneficial in terms of post-curing activities [98,116]. However, thereafter, about 50% of Poisson's ratio, elastic modulus and bond strength of the adhesive layers are lost at a temperature 15 °C higher than the T_g [116]. Moreover, accelerated diffusion of moisture and chemicals may occur in a FRP-strengthened system at elevated temperatures [117,118]. In addition, CFRP laminates lose 30% of their tensile strength when the temperature changed from 20 to 70 °C with the relative humidity being 65% [103]. This is a very negative result for a strengthening system. The techniques of strengthening and the loading conditions also have great effects on the strength loss of FRPs at elevated temperatures [119]. In this case, the NSM technique is superior to the EB-FRP wrapping system [113]. This is possible owing to the generation of a frictional stress at the FRP-matrix interface which subjected the FRP to tension at a highly elevated temperature. A small protective cover of concrete may be helpful in controlling the temperature of the FRP bar/strip inside the concrete even when the outside temperature is raised to a high level.

The most critical problem is that the coefficient of thermal expansion of FRPs in the transverse direction is nearly 20×10^{-6} m/m.°C, whereas that of concrete is around 14.5×10^{-6} m/m.°C [10]. As a result of this difference, a small rise in temperature causes a great variation between the expansions of the FRP and concrete, leading to the development of stress due to swelling of the FRP in the transverse direction. When the stress exceeds the limit of the tensile strength of the concrete, debonding or cracks may be heavily produced [100]. This can happen in-between the fibres or resin in the FRP composites, owing to their different thermal expansion coefficients, which results in differential stress generation [101]. The typical variations in the bond strengths of FRPs at different temperatures as percentages of the strengths at room temperature are found in the literature, and shown in Fig. 11. This suggests that the working temperature ranges of FRP composites should below 250 °C.

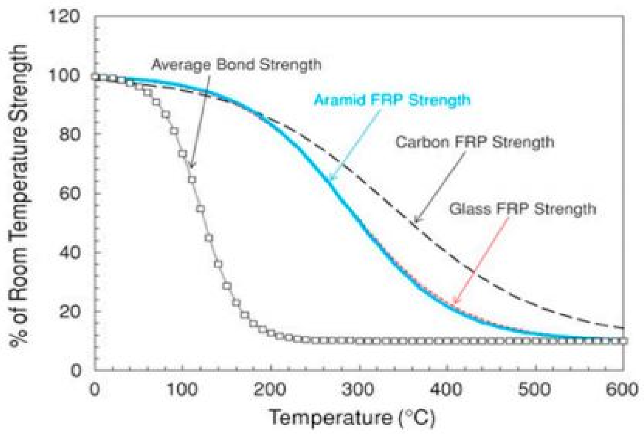


Fig. 11 Variations in FRP bond strengths with temperature [8]

3.3.5 Ultraviolet (UV) radiation

The effect of UV radiation on FRP composites is very limited, but it can change the overall performance of polymeric resins. Extreme brittleness and successive micro-cracking may arise in polymer composites after the reaction with UV photons. Aramid fibres lose their strength and change colour, but carbon and glass fibres display sufficiently stable properties, when exposed to UV light [6,7,9]. This radiation has reduced effect on the properties when fibres are combined with a polymeric matrix to form composites of FRPs [7]. The polymeric coating on FRP laminates does not directly inhibit the degradation of the FRP, but acts as a self-sacrificing layer which prevents direct attack of the fibres by the UV radiation [99]. The addition of fly ash to a resin system can reduce the effect by blocking UV rays [120]. The UV degradation rate increases when FRP composites experience several freeze-thaw cycles or moisture exposure or heat [98,121]. These conditions make the polymeric matrix weak in ionic-bond, thus quickly transferred into other forms of products in the presence of UV, which causes degradation in strength and stability.

Table 2. Summary of the performances of FRP-strengthened structures

Loading type	Strengthening material	Wrapping system	Capacity improvement	Failure mode	Ref.
Axial	CFRP	Full-wrap	66%	Detachment of concrete cover at the end of the FRP system	[42]
	CFRP	Full-wrap with a NSM strip	54%	Rupture of EB-FRP, with delamination of the FRP strip	[38]

	CFRP	Full-wrap	81%	Rupture of FRP jacket	
Flexure	Hybrid CFRP-GFRP	U-wrap	114%	Concrete crushing, then FRP rupture	[56]
	CFRP	NSM strips	154%	End cover separation	[58]
	BFRP	EB strip along soffit with inclined U-wrap	55%	Rupture of FRP strips	[50]
Shear	Hybrid CFRP-GFRP	U-wrapped EB strip with mechanical anchorage	113%	Detachment of concrete cover	[66]
	CFRP	U-wrapped EB strip with CFRP anchorage	75%	Flexural failure	[65]
	GFRP	U-wrapped EB strip	50%	Shear failure with FRP debonding	[65]
Impact	CFRP	EB sheet along soffit	15%	Bond splitting	[68]
	CFRP	U-wrapped EB strip	9%	Local concrete crushing with shear failure	[122]
	CFRP	Inclined U-wrap	43%	Shear failure with FRP debonding	[69]
Fatigue	CFRP	U-wrap along midspan	123%	Bond splitting	[79]
	GFRP	U-wrap along midspan	71%	Bond splitting	[79]
	CFRP	NSM-strip	30%	Steel rupture	[25]
Seismic	CFRP	Full-wrap with longitudinal strip	54%	Flexural failure	[87]
	CFRP	Full-wrap	86%	Anchorage pull-out	[123]

Moisture (6-18 months of immersion)	CFRP	EB sheet along soffit	15%	Adhesive failure	[94]
Freeze-thaw (300 cycles; -27 to +6 °C)	CFRP	EB sheet along soffit	36%	Concrete crushing, Delamination	[104]
Acidic-alkaline condition	CFRP and BFRP	EB wrapping	Reliable improvement	Adhesive failure	[110]

Table 2 summarises the performances of FRP-strengthened structures. It can be seen that CFRP is the most common strengthening material which has proven to be the most effective. The common and widely practised technique of FRP strengthening is the EB-FRP system, where the configuration of the wrapping system depends on the structural geometry and loading, along with the exposure conditions. Most of the studies reveal that U-wrapped FRP systems are reliable in terms of strength gain under shear, impact and fatigue loadings, while inclined wrapping of EB-FRP is also beneficial under impact and fatigue loadings. Moreover, full-wrapped techniques are found to be effective in terms of durability. Alternatively, the NSM technique is impressive in resisting the early debonding and increasing the axial and flexural capacities. Further, the NSM technique is also suitable for elevated temperature and fire conditions. Additionally, provision of anchor can effectively increase the capacity of strengthened elements.

4. Common failure modes of RC members strengthened with FRPs

The failure mode of a FRP-strengthened structure is indicative of the effectiveness of the strengthening. The generally observed failure modes in FRP-strengthened systems are debonding of the FRP, rupture of the FRP, concrete crushing and shear or flexural failure with steel yielding [56]. Some of the typical failure modes are shown in Fig. 12.

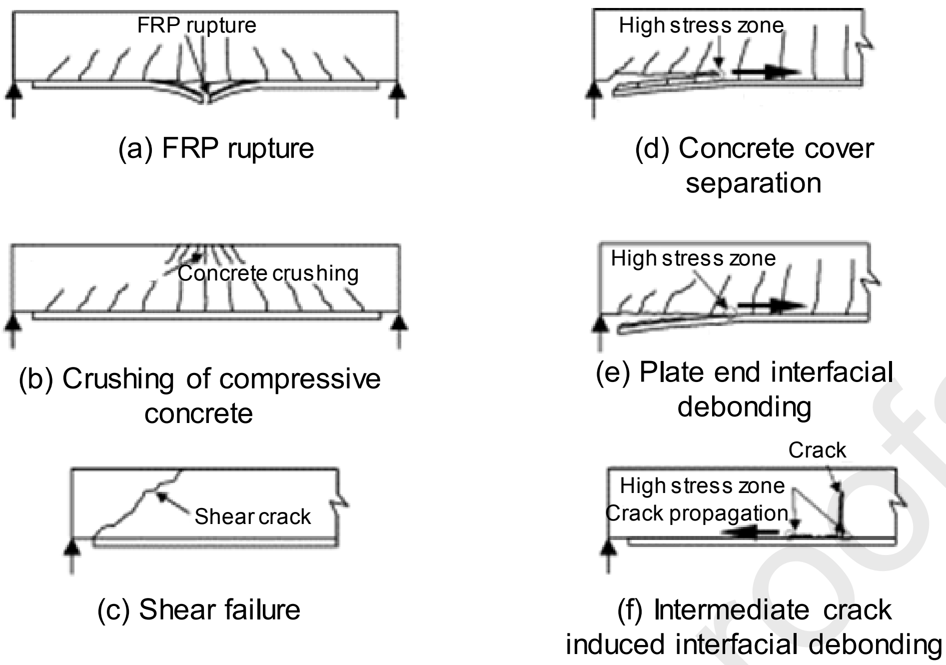


Fig. 12 Typical failure modes of FRP-strengthened structures [124]

Camata et al. [125] described that the weak linkages at the interfaces of all the components are the potential zones of failure (Fig. 13), so that the whole system may fail when any of the components fail.

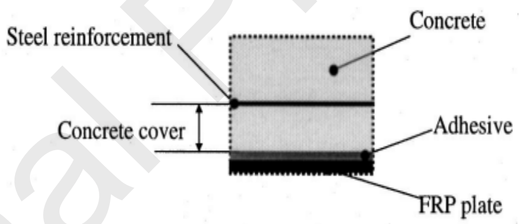


Fig. 13 Potential failure zones in FRP-strengthened concrete systems [125]

4.1 Debonding failure

The most common failure mode of FRP-strengthened systems is debonding failure, which may be classified as concrete cover separation, plate end debonding and flexure- and shear-induced debonding (Fig. 14) [124,126]. In an EB system, debonding at the concrete-adhesive interface occurs due to the low adhesion between the concrete and the adhesive, which may be caused by ineffective surface preparation [127]. As the interface bond strength was found to be much higher than the tensile strength of concrete, concrete cover separation takes place. Both the failure modes are shown in Fig. 15. Intermediate crack-induced interfacial debonding starts from the region corresponding to the maximum bending moment or high tension and propagates towards the ends [57,58,78]; it also originates from the ends of flexural- or shear-induced cracks, where a large moment to shear ratio is observed, and propagates towards the low-moment regions [128].

On the other hand, end interfacial debonding occurs due to high interfacial shear and normal stresses near the ends and propagates towards the mid span. These interfacial stresses highly fluctuate and rapid variations are noticed when the applied load is close to the yield limit [129]. Frequently, both types of debonding lead to cover separation [53]. A structures cannot realise its ultimate strength and the full tensile strength of a FRP cannot be utilised when debonding failure initiates [5,33], which is brittle failure. This debonding can be delayed by using intermediate anchorage of FRP laminates to reduce the interfacial stresses [50,126,129,130], or through a high embedment length of a NSM strip [58], but their effectiveness should be justified appropriately [45].

FRP strengthened elements without any provision of end anchorage exhibit lower strength capacity due to the premature failure through plate end (PE) debonding [131]. Baggio et al., (2014) [65] showed that the uses of anchor can prevent the debonding failure in partially wrapped GFRP strengthened beam. These anchors may provide continuous load paths between the FRP and the concrete to increase the bond strength, which prevents debonding up to a certain load level [132]. The uses of fibres in both the horizontal and vertical directions could be effective in resisting debonding failure [133].

Similarly, the most common debonding failure observed in NSM systems is cover separation [134] (Fig. 14). A side-NSM strengthened beam fails through concrete crushing with intermediate crack-induced debonding, which is ductile, compared to the concrete cover separation observed in a bottom NSM system [134]. The smooth surfaces of the NSM strips can result in lower adhesion between the strip and adhesives. This will cause longitudinal cracks in the adhesive layer due to the radial component of the bond stress and, eventually, failure occurs at the FRP-adhesive interface [135]. For stiffer concrete, when the adhesive stress exceeds the tensile strength limit, cohesive shear failure within the adhesive can occur. However, cohesive shear failure within concrete is the most common debonding failure mode of NSM systems. Therefore, the thickness of the adhesive layer should be sufficient to resist this type of debonding. The debonding generally starts from the ends of the FRP strips where flexural cracks are most prominent; these cracks produce a great variation in the strain level of the FRP strips [136]. Additionally, the strain capacity limit of concrete and adhesive layers are not much satisfactory along with the high strain capacity of FRP strips, thus debonding initiates and propagates rapidly. However, debonding is less prominent in the case of low-rate loading system.

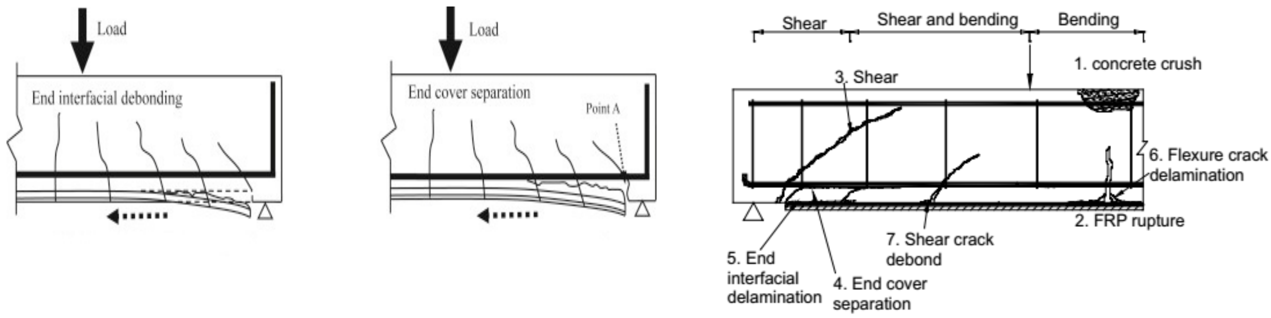


Fig. 14 Debonding failure of FRPs: (a) NSM technique [53] and (b) EB system [137]

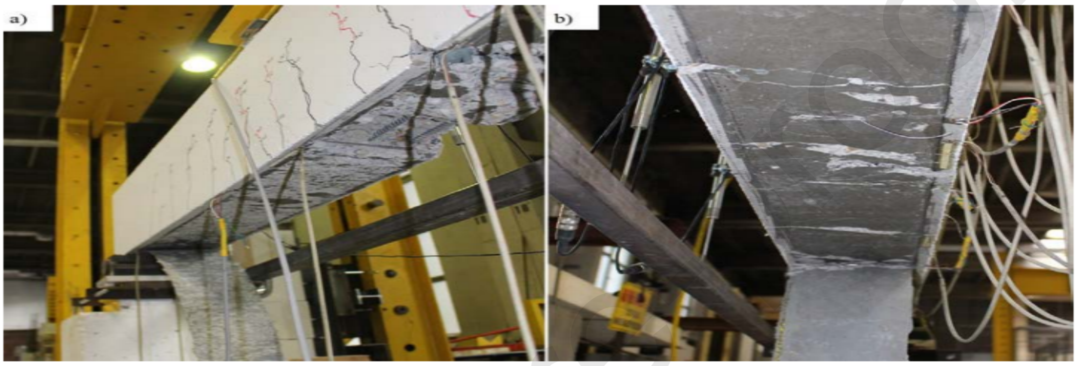


Fig. 15 Debonding failure at the (a) FRP-concrete (b) concrete-adhesive interfaces [138]

In addition, modification of the concrete surface proved to be an effective technique which prevented debonding. In the study by Pham [122], it was revealed that a U-wrapped FRP system in a rectangular section could not generate a resistance to the peeling stress in the adhesive, as shown in Fig. 16. However, when the section is significantly modified in a radial manner, the peeling stress is resisted by the total tensile stress in the adhesive and the confining stress from the FRP U-wraps. Therefore, the stress at the adhesive-concrete interface is lowered and debonding is delayed to a significant level. Thus, the efficiency of the FRP-strengthened system could be improved.

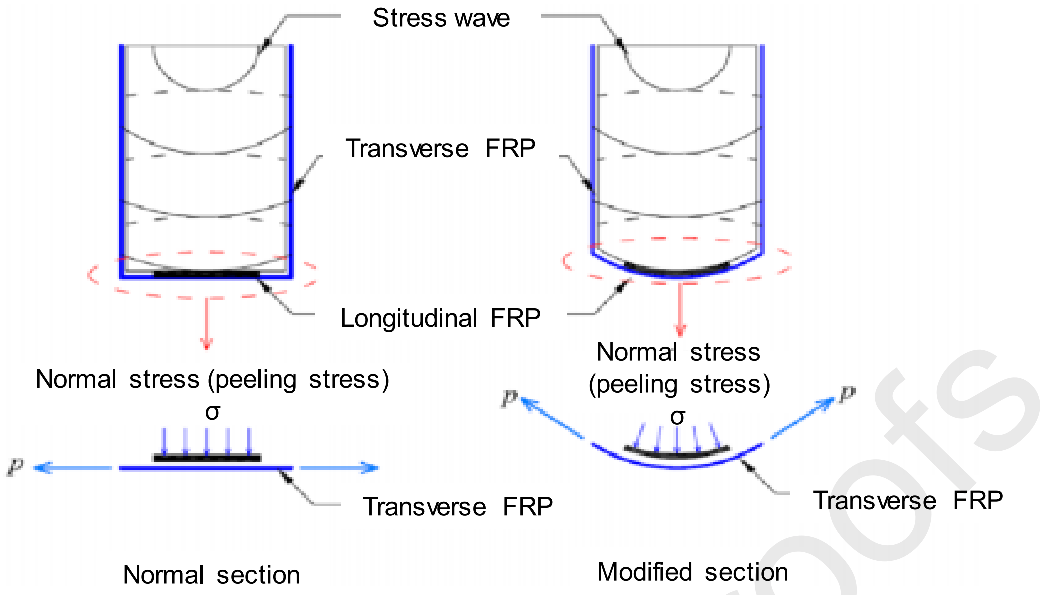
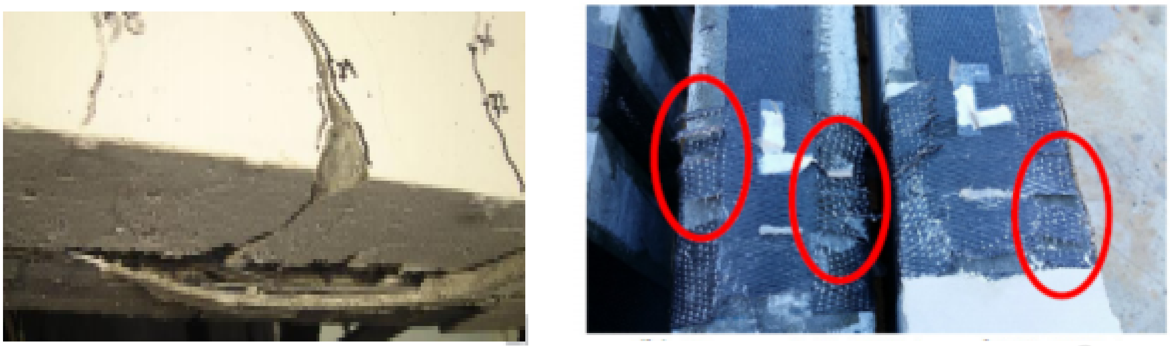


Fig. 16 Debonding mechanism under impact [122]

4.2 Rupture of FRP strips

The most common failure mode of strengthened RC beams and columns with full wrapping is FRP rupture after localized debonding (Fig. 3), which may be explained in terms of achieving peak strain level in the FRP [8,126]. A FRP-wrapped column fails in an explosive manner as the failure generally occurs due to rupture of the FRP sheet along the hoop direction [46]. Though EB-FRP with fibres in both the horizontal and vertical directions showed a higher strain utilisation in the vertical direction, debonding occurred with fibre tears at the failure load. When a partially side-wrapped shear-strengthening system was used in a RC beam with the aim to achieve shear failure, FRP rupture takes place due to excess diagonal shear cracks at the peak load. These ruptures occurred in the stronger direction, which is generally parallel to the fibre alignment direction [133]. The maximum FRP rupture strain was obtained in the horizontal direction for the beam strengthened with a single layer of CFRP sheet instead of a double-layer sheet. Generally, the allowed strain in FRPs is considered to be about 10-25% of the rupture strain [126]. Using multiple layers of FRPs can reduce the possible utilisation of strain, and brittle rupture of the FRP layers occurs at stresses below their effective stress. Anchors are an effective measure for preventing premature fracture through effective bond stress distribution along the length of concrete. However, rupture was noticed in a FRP anchor zone, instead of in a region corresponding to the maximum applied load, because of the high stress concentration in the anchor zone [1,132]. Additionally, when NSM strips are used in strengthened systems, rupture of the strips takes place with local concrete cover separation, as shown in Fig. 17. Moreover, sometimes, surface preparation and section modification have been proven to be effective in increasing the strength at FRP rupture [122].



(a) (b)

Fig. 17 Rupture of (a) NSM FRP strips and (b) EB sheets [122,139]

4.3 Splitting of concrete

According to most of the literature, concrete crushing occurs in the compression zone along with FRP rupture or shear failure in FRP-strengthened structures [56,122]. The brittle concrete failure mechanism depends on the proportion of reinforcement used in the strengthened structure. Flexural failure is initiated by flexural cracks in concretes, which may cause delamination of the EB-FRP system or crushing of concrete when the compressive stress limit crosses the ultimate strength. Moreover, under impact loading, most of the FRP-strengthened beam suffers from diagonal shear cracks and negative bending effects, which cause concrete crushing along with debonding of the wrapped FRP [13,41]. When the steel ruptures under any type of fatigue or impact loading, all the stress is redistributed in the FRP and, eventually, the FRP ruptures and cracks originate in the concrete [77,140]. Controlled use of the FRP layer is suggested in the literature to resist the concrete crushing before the tensile yielding of steel takes place due to a change in the stress distribution [141]. The concrete crushing modes of FRP-strengthened structures are shown in Fig. 4(a) and Fig. 5.

Therefore, the most common failure mode of EB-FRPs is debonding-type failure. This could be characterized according to the study of Gribniak et al. [142] as FRP debonding in the anchorage zone due to bond shear fracture through the concrete, FRP debonding at shear or flexural cracks and debonding with concrete cover separation. FRP ruptures occur in the case when reached at highest strain level [126]. Additionally, most of the fully wrapped FRP systems fail through FRP rupture instead of through debonding in the side or U-wrapped system [16]. Other types of failure could be characterised by failure occurring in the material.

5. Modelling of RC members strengthened with FRPs

Modelling is an essential part for designing structures. Currently, there is no systematic review on the modelling of strengthening RC structures using FRP. Therefore, a comprehensive review on currently available models with typical and wide boundary conditions of strengthening are important. Since the behaviour of FRP strengthening are highly dependent on loading and environmental conditions, thus a verity of models were developed through several investigations. The fundamental assumptions, degradation mechanisms, reliability and serviceability characteristics of FRP strengthened structures were reviewed.

5.1 Degradation model

Arrhenius equation (equation 1) can be applied to predict the parameters such as the strength and modulus of FRP systems which are exposed to any specific condition:

$$100\frac{P(t)}{P_0} - B = A.\ln(t) \quad \text{for } t > 0 \tag{1}$$

where $P(t)$ and P_0 are the performance attributes at times t (days) and 0 (i.e. corresponding to the unexposed condition), respectively, A and B denote the degradation rate and a material constant which reflects the early effect of post-cure progression, respectively. Other models were described in different studies, such as moisture diffusion into the FRP-concrete interface as a function of relative humidity, cycle of moisturization and moisture diffusivity of concrete, epoxy and FRP [143,144]. Temperature-degradation model is based on the variation of the T_g in terms of the residual bond strength [145]. On the other hand, the residual bond strength at a temperature T is given by the following equation (2) [145], which is dependent on the T_g and degree of cross linking (C_r).

$$\tau^*(T) = 0.5 \cdot (1 - \tau_r^*) \cdot \tan\{-\frac{0.02}{C_r}[T - \left(T_g + \frac{k_1}{0.02}C_r\right)]\} + 0.5 \cdot (1 + \tau_r^*) \tag{2}$$

The normalized residual bond strength, τ_r^* , can be completely neglected for a temperature higher than 250 °C.

5.2 Debonding model

The ultimate limit is controlled by the failure mode of a FRP-concrete system. Debonding at the mid span occurs due to flexural or flexural-shear cracks, and is a function of the maximum strain developed in the FRP [146]. The model developed by Chen and Teng [147] describes the strain at debonding in terms of α, an empirical factor that depends on the element type of the RC; b_c, the beam width; b_f, t_f, and E_f,, FRP plate width, thickness and elastic modulus, respectively; L, the actual bond length; and f'_c, the compressive strength of concrete, which is given by equation (3).

$$\varepsilon_{f,\,debonding} = \alpha\beta_f\beta_l\sqrt{\frac{\sqrt{f'_c}}{t_f E_f}} \tag{3}$$

where

$$L_e = \sqrt{\frac{t_f E_f}{\sqrt{f_c'}}}$$

$$\beta_f = \sqrt{\frac{2 - b_f/b_c}{1 + b_f/b_c}}$$

$$\beta_l = \begin{cases} 1, \; L > L_e \\ \sin{(L/2L_e)}, \; L < L_e \end{cases}$$

In the study by Pham and Mahaidi [137], the suggested limit for the strain level in EB-FRPs is in the range 0.005-0.008. Moreover, a limit to the tensile stress acting at the location of the flexural crack debonding was observed for beams strengthened by using FRP sheets. This is given by equation (4):

$$f_f \leq \sqrt{\frac{2G_f E_f}{n_f t_f}} \quad (4)$$

where n_f is the number of FRP layers and G_f is the interfacial fracture energy, which was either considered to correspond to a double bond stress or taken as 0.5 N/mm.

In the same study [137], the shear capacity of a FRP-strengthened shear-deficient beam was also determined as follows (equation 5):

$$V_R = kbd(1.2 + 40\rho_l)\tau_{RK} \quad (5)$$

where $\rho_l = (A_s + A_f \frac{E_f}{E_s})/bd$

Here, k takes the size effect into account: k = 1.6 – d ≥1, where d is the effective depth of the section in metres and b is the width of the section.

The shear stress is dependent on the cylindrical strength of concrete, as follows (equation 6):

$$\tau_{RK} = 0.18(\sqrt[3]{f_{cm}}) \quad (6)$$

Conversely, bond-slip model is used to generalize the debonding failure of NSM strip strengthened elements. The study of Zhang et al. [148] revealed that cohesion failure in concrete near to the adhesive-concrete interface depends on the concrete cylinder strength (f_c) and the groove height (h_g) to width (w_g) ratio (Υ), as follows (equation 7):

$$Bond\ strength, \tau = A(\frac{2B - s}{B})^2 \sin{(\frac{\pi}{2} \times \frac{2B - s}{B})} \quad (7)$$

where slip s ≤ 2B

with $B = 0.37\Upsilon^{0.284} f_c^{0.006}$ and $\Upsilon = \frac{h_g}{w_g}$.

$$A = 0.72\gamma^{0.138} f_c^{0.613}$$

$$B = 0.37\gamma^{0.284} f_c^{0.006}$$

Some other significant bond-slip models were developed based on the compressive strength of concrete, quality of substrate aggregates, groove size and concrete cover strength of NSM strips [148–150]. All these bond-slip models could be helpful in analysing the debonding failures of strengthened structures.

5.3 Fatigue prediction model

The general fatigue life prediction model yields the formula as follows (equation 8):

$$\log N = A - B\ \sigma_r \tag{8}$$

where σ_r refers to the stress range of a steel bar and N is the number of cycles to failure. The values of A and B depend on the stress and number of cycle curves, respectively. The maximum permissible fatigue stress range could be found from the equation (9) presented by Charalambidi et al. [84]:

$$\sigma_r \leq 166 - 0.20\left(\frac{\sigma_{min}}{f_y}\right), MPa \tag{9}$$

where σ_{min} is the minimum fatigue stress on steel and f_y is the yielding strength of the steel.

Furthermore, equation (10) is suggested [8] as the best distribution fit of fibres in FRP composites for evaluating the fatigue life and 95% confidence intervals, based on previous research.

$$f(x) = \frac{1}{0.5987\sqrt{2\pi x}}\left[-\frac{(Lnx - 4.202)^2}{0.7169}\right] \tag{10}$$

Some other significant bonding models under fatigue loading were also developed by researchers based on static bond strength, monotonic shear stress, number of fatigue cycles, crack growth parameters and elastic-plastic strain [82,151,152].

5.4 Reliability index model

Considering the concrete crushing, FRP rupture and debonding failure modes of FRP-strengthened structural components, the reliability index β was fitted within a minimum target value in the study by Ali et al. [146]. The relationship is given by equation (11).

$$G = \gamma_m R(t) - S(t) = \gamma_m R(X_1, X_2, \ldots\ldots X_n) - (\gamma_{DL} DL + \gamma_{LL} LL) \tag{11}$$

where γ_m is the model error which reflects the uncertainty in the theoretical evaluation of element resistance, and was considered here as a random variable, R is the random section resistance, which is a function of the random variables X_i (geometric and material properties). S is the applied dead (DL) and live (LL) loads. γ_{DL} and γ_{LL} are random variables representing the uncertainties of the dead and live loads, respectively. Alternatively, the reliability index β can be determined from a solution of the constrained optimization equation (12).

$$Maximise\ \beta = (u^{*T} u^{*})^{1/2}\ under\ G = 0 \tag{12}$$

where u is a vector of basic variables in the standard normal space, u^* is the vector of the most probable design point and u^{*T} is the transposed vector of u^*. The resistance reduction factor and reliability greatly depend on the failure modes of structures [128].

5.5 Serviceability model

The toughnesses of fibres, resin and composite matrix of FRPs are the properties which have direct effects on the crack generation and propagation within the composite under loading and adverse environmental conditions. The toughness (G_c) of a composite is the amount of energy captured per unit area of a crack, which could be evaluated by using equation (13) [121].

$$G_c = f_f G_c^f + f_m G_c^m \qquad (13)$$

where the critical fibre length (l_c), volume fraction of fibres (f_f) and f_m=1 $- f_f$ control the G_c. For fibre lengths < l_c, the system will not fracture.

Moreover the crack width in a FRP composite could be calculated by using equation (14) by incorporating the bond quality coefficient (k_b), which is recommended as 1.4 through research [8].

$$\text{Crack width, } w = 2\frac{f_f}{E_f}\beta_r k_b \sqrt{d_c^2 + (\frac{s}{2})^2} \qquad (14)$$

where β_r is the ratio between the distance from the neutral axis to the fibre experiencing extreme tension and the distance from the neutral axis to the centroid of the tensile reinforcement, d_c is the concrete cover and s is the spacing of longitudinal bars.

Several significant models are available to predict the degradation, failure or service life of FRP-strengthened RC structures under specific conditions. The FRP-concrete bond is a very important factor which generally controls the debonding failure under specific exposure or loading condition, as described in section 4.1. The reliability index, resistance factor in design and service life of FRP-strengthened RC structures are also functions of the bond strength at the FRP-concrete interface. The FRP-concrete bond-slip relation is very important for the prediction of debonding failure. With increased interfacial slip and stress, the bond strength of the FRP-concrete interface decreased. Under peak stress, large slip debonding may result, along with negligible shear stress. The mechanics-based approach to evaluate the deflection behaviour of adhesively bonded FRP plate to RC beams were modelled in previous research, which accounts the slip between reinforcement and adjacent concrete [153]. Alternatively, the degradation observed under specific exposure conditions could be generalized by using the primary equation and adopting the appropriate coefficients. Moreover, predictions of the service life, failure mode, fatigue life and applicable temperature range are required to assess the sustainability and effectiveness of the application of FRP-strengthened RC structures.

6. Challenges with using FRP-strengthened structures

The usage of FRP strengthening systems is challenging owing to the high processing and material costs, susceptibility to fires, damage experienced when installed for brittleness and low bonding with concrete in the absence of treatment [9]. FRP production requires chemicals which may cause environmental degradation [19]. To lower the risk associated with FRPs and increase the service life, maintenance of FRP-strengthened RC structures should be carried out. Particular attention should paid to the regions of anchorage, overlapping and adhesive layers, and periodical checks must be carried out for local delamination.

6.1 Partial utilisation of strength capacity

FRP composites display high tensile strengths, but, in designing, the full strength has not been utilised. As recommended in the literature, the effective strength of a FRP should be less than the uniaxial ultimate strength while designing a column which is subjected to cyclic bending and axial loading [44]. When structures are strengthened by using FRPs, the design stresses of CFRP, GFRP and AFRP are maintained at up to 55%, 20% and 30%, respectively, of their ultimate strengths to sustain the dead and live loads [85]. Moreover, while investigating the creep rupture behaviour, the stress limits for the application of CFRP, GFRP and AFRP are 90%, 30% and 45% of their short term tensile strengths, respectively [154]. The stress of a FRP at failure depends on the strength of the concrete and the arrangement, strength and amount of the reinforcement used in RC structures. Higher utilisation of the tensile strength is observed in FRP-strengthened systems when using NSM technique, compared to that of EB systems [53]. In addition, the strain in the FRP at failure may be well below its ultimate strain, being in excess of 1% [15]. Lower failure strains are observed because of the debonding failure initiated by relatively small cracks. The GFRP strengthening design is generally limited to 0.4% effective strain for adverse environmental and loading conditions [93,155], which is considered a very conservative value for a RC member [35].

Debonding may arise in both EB and NSM FRP systems of strengthening, and is the main barrier to FRP achieving its ultimate strength [5]. In an EB CFRP strengthened structure, maximum utilisation of the strain is realised for 30-35% of the ultimate tensile strength [156]. On the other hand, in NSM technique, the strain in the FRP is considered to be 70% of the ultimate value for monotonic loading [85]. By using NSM technique, columns were strengthened and tested by Yao and Wu [44]. They selected strength utilisation factors ranging from 0.38 to 0.80 for modelling the seismic performances of strengthened columns. They pointed out that pull-out failure of a FRP strip resulted in lower utilisation of the strength. The challenges of partial strength utilisation of a material may increase the material cost, prevent the realisation of the target strength, and result in the material exhibiting uncertain behavior under adverse conditions, which may adversely affect the overall benefits of strengthening.

6.2 Brittleness

Structures with sufficient ductilities always perform better under both static and dynamic loadings and fail only after revealing appropriate signs. Concrete is a brittle material which fails catastrophically under service loads. When these structures are strengthened by using FRP laminates, the brittleness is increased. Brittleness is a major weakness of a FRP-strengthened RC structure, and is due to the brittle natures of the hardened polymer, concrete and the interfacial bond between the FRP and concrete [157]. Hardened FRPs display excessive brittleness compared to those of conventional steel materials [158]. This brittleness changes the stress distribution drastically and, therefore, the conventional method of designing RC cannot be applied to FRP structures. The limited rotational capacity of these brittle composites restricts their widespread structural application [157]. By moderating the strengthening system and fibre direction and adding steel reinforcing materials, the brittleness of FRP-strengthened RC structures can be reduced. Generally, a strong FRP-concrete bond leads to brittle failure of the whole RC structure, whereas a weak bond may cause debonding and ductile failure of FRP-strengthened structures [43]. An EB-FRP plate frequently shows debonding which is very brittle, while NSM strip strengthening can slips widely and provide higher rotational capacity [157,159]. FRP rupture is also a brittle failure mode, as is concrete crushing, therefore, traditional steel yielding is not possible in EB-FRP-strengthened systems [5]. The fibre direction of a strengthening system can influence the brittleness of a FRP-reinforced structure.

6.3 Risk of fires

Owing to the combustible nature of FRPs and production of toxic substances during combustion (except in the case of BFRP [8]), their use in building structures, especially in confined spaces, requires additional safety requirements [6]. EB-FRPs are less effective in terms of imparting fire resistances to RC elements than NSM technique [113], because of concrete cover protection. Ignition of FRP NSM strips with sufficient concrete cover is not frequent in fires occurring at elevated temperatures. Therefore, a fire-prone structure should be strengthened by using NSM technique [38]. Failure is mainly governed by the loss in the bond strength of the FRP-concrete system when exposed to a fire. As a result, the interfacial stress acting along the bond between FRP-concrete and FRP-resin matrix is crucial for strengthening at high temperatures or for direct fires. Failure may be delayed by providing sufficient anchorage to prevent pull-out of the internal FRP bars, and is governed by the strength limit. Because of the presence of sufficient concrete, the temperature of the FRP reinforcement inside the concrete is well below the environmental temperature.

A fire-protective polymeric coating which acts as a thermal barrier or flame retardant may be a protective measure against fire hazards [160]. GFRP bars with thermoset resins derived from halogen groups produce low rate flames under fires. Gypsum or a cementitious mix which is sprayed can also be a fire insulator in FRP-strengthened structures. By providing sufficient concrete cover and unexposed anchorage zones, fire endurance can be increased up to a reasonable limit in FRP RC structures. The protective coating helps to reduce the temperature of the internal elements such as steel, FRPs and adhesives under identical fire conditions, compared to that of an unprotected coating. For the same fire condition, a 25 mm thick cementitious coat can reduce the temperature 200-300 °C in the adhesive and steel present inside a RC element [113]. Additionally, the ceram powder can be a solution to improve the fire performance of GFRP, which can effectively increase the glass transition temperature by 32°C after adding 50% powder (by weight of resin) with the polymer matrix [161].

Besides these risks, strengthened RC structures exhibit reliable resistances against fires. Jiangtao et al. [113] found that a RC beam with NSM CFRP strips displayed more than 3 h resistance under standard fire conditions with high loading. They used a thick cementitious coat for fire protection because fire-unprotected CFRP is vulnerable and may fail before an unstrengthened beam.

6.4 Risk of accidental damage

The use of FRPs can be relatively challenging owing to the abrasive character of fibres and brittleness of the composite (especially CFRP) after bonding with the adhesive material [158]. Drilling of CFRP is required for anchoring and fastening the overall strengthening system, which always has the risk of fibre pull-out or breakage, crack formation in the matrix or thermal degradation and delamination [12]. A typical failure surface is shown in Fig. 18.

Delamination is frequently observed in FRPs, and may reduce the overall strengthening performance, resulting in a loss of the integrity of the composite. The static and fatigue strengths of laminates decrease greatly after the occurrence of delamination [162]. Additionally, temperature rise may cause deteriorations of the polymer matrix and adhesive properties.

Reducing the point angle of the drill bit may reduce the push-down delamination and help prevent intralaminar failure [158]. Then again, a poor bond interface between the smooth surface of concrete and the FRP may result in the risk of accidental damage through sudden impacts or when seismic loads are applied at values much lower than the ultimate strength. These accidental risks could be minimized by using primers or by treating the concrete and FRP surface before use [163]. As mentioned in the literature, accidental damage is highly probable through impact of over-height vehicles on the soffit of a FRP-strengthened bridge and strengthened columns in parking zones [164]. Therefore, warnings should be placed in such zones where accidental damage can occur, and structurally, additional supports should be provided in these zones. Sometimes, anticipated mechanical damages may occur during high-risk usage of strengthened structures, or the protection may be uncovered from a portion of the FRP.

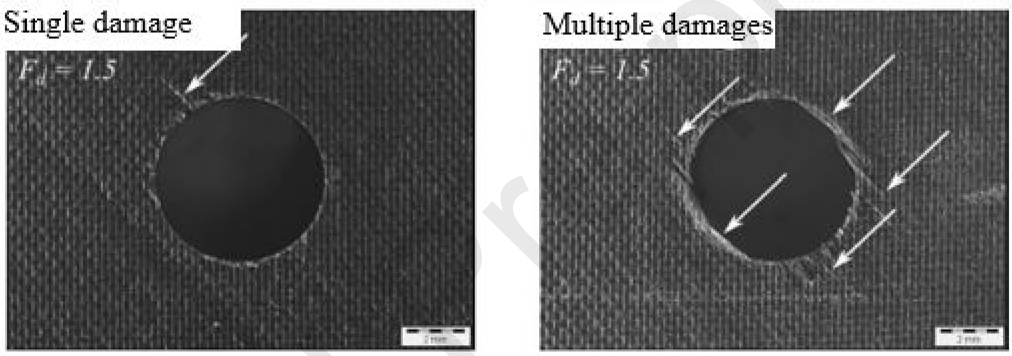
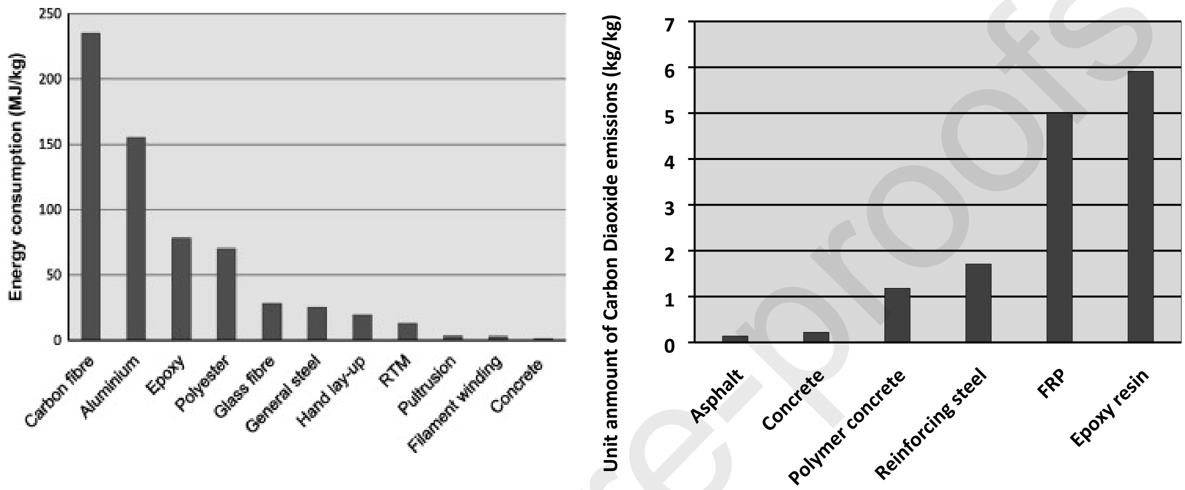


Fig. 18 Fibre damage during drilling of holes in CFRP [162]

6.5 High energy consumption and carbon emission

The energy consumed during the production of a material is a major factor which governs the cost sustainability of that material. Fig. 19(a) shows the energies consumed in the production of different construction materials; it clearly reveals that FRP production requires a very large amount of energy, compared to those of other conventional materials. The higher energy requirements may result in higher initial investments for a construction system. By considering the whole life cycle, including service and the amount of material required, FRP fabrication may be regarded as being sustainable and requiring low maintenance.

Additionally, carbon emission during FRP production is higher than those during conventional steel and concrete productions. Nevertheless, when considering the entire service life, construction process and maintenance requirement of a FRP-reinforced structure, the carbon emission is lower than that of a steel constructed structure. A 20% reduction in carbon emission may be possible across the entire life of a 12 m long bridge deck, the superstructure of which was constructed by FRP surfacing instead of concrete in the study of Mara et al. [165]. They also mentioned that, when a FRP is used for surfacing purpose, it emits 13% more carbon than conventional asphalt surfacing. The amounts of CO_2 emitted during the entire life cycles of different materials are shown in Fig 19(b). The figure reveals that, compared to traditional steel, FRP emits around 192% more CO_2 during its entire life cycle. Therefore, significant reductions in carbon emission during the production, use and life cycle of FRPs are required, which can be challenging.



(a) Energy consumption (b) Carbon emission

Fig. 19 Energy consumptions and carbon emissions of composite materials [165]

6.6 High material costs

FRP strengthening requires high initial investments. The cost of the FRP strengthening material is more than that of a conventional strengthening material such as ordinary steel plate, wire mesh or aluminium plate. Based on recent market trends [166], the prices of the materials used for strengthening RC structures are listed in Fig. 20. Around 16-17 times higher material cost will be involved for using a similar amount of CFRP instead of a conventional steel plate; this difference in cost is around 8 times for AFRP. From the trend of the price per unit weight of material, it can be understood that strengthening by using any type of FRP material is challenging.

In comparison, AFRP is cheaper than both CFRP and GFRP. Among all of them, E-GFRP is the cheapest [8]. Carbon fibres are 10-30 times more expensive than glass fibres [9]. Ouyang et al. [88] retrofitted square RC columns with BFRP and CFRP sheets and observed higher strength to weight ratios for BFRP than for CFRP. Therefore, the use of BFRP is suitable, considering both the cost and strength, although CFRP may exhibit longevity. The reason for the high costs of FRP materials is the requirement of highly specialized operating systems. The lack of specifications, standards and proper guidelines for obtaining desired properties of FRPs has resulted in the production of FRPs with varying characteristics across different industries. This issue should be appropriately taken into consideration in order to overcome the production difficulties and fulfil the growing demand for FRPs. Furthermore, if production increases, the cost will be consequently optimized.

By considering not only the materials, energy and resources needed for the production of FRPs but also the beneficial uses of FRPs, based on life cycle assessment, FRPs can be considered as sustainable materials for construction in terms of cost and environment [10,19]. The positive aspects of FRP strengthening are it requires less labour and lighter equipment and supporting arrangements, which may be considered to be cost effective in construction and with respect to long-term maintenance, compared to the use of traditional steels in construction [167]. Analysis of the life-cycle costs of FRP-strengthened structures reveals their economic sustainability. Therefore, the overall outlook is positive: the production level will increase with increasing demand, and, once they become locally available, the cost of FRP construction will be optimized and well accepted. The strength gained to cost ratios of retrofitted RC structures give us a better idea on the cost optimization of FRP systems.

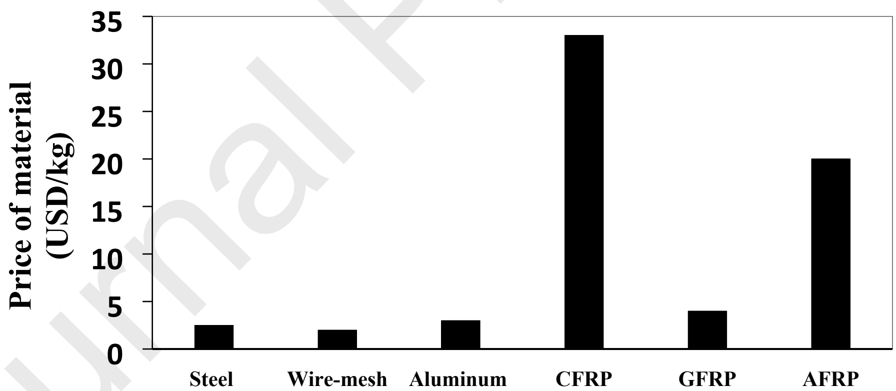


Fig. 20 Prices of different strengthening materials (Price source: ref. [166])

Table 3. Summary of the challenges and the techniques used to overcome those challenges

Challenges	**Techniques to overcome the challenges**	**Ref.**
Partial utilisation of strength	Development of standard design guidelines for FRP strengthening	Suggestion
Uneven bonding surface	Concrete surface preparation by grinding, mechanical abrading, bush hammering and applying air or water pressure to ensure good	[24,163,168]

	balance between bond strength and surface unevenness.	
Brittleness	Hybridization of a CFRP sheet by swapping it with a flexible fibre	[8]
Risk of fires	Using fire resistant polymers, thermoset resins consisting of halogen molecules, cementitious covers	[8,113,160]
Accidental damage	Additional supports, protective covers and warnings should be provided	[164]
High energy consumption	Innovative techniques must be used to optimize the energy consumption rate during FRP production	Suggestion
High carbon emission	Reduce on-site activities; the use of appropriate polymeric resins could also reduce CO_2 emission	[165]
High initial cost	Increased production of FRPs of appropriate grades	Suggestion

The techniques to overcome the challenges described in section 6 are listed in Table 3. The most challenging feature related to FRP strengthening is the lower utilisation of stress in the design capacity, which can sometimes be very conservative and lead to excess material requirement and associated costs. The current practiced guidelines must be reanalysed to address the deficiencies. Preparation of the concrete surface and FRP before application in a suitable manner and protection against fires and high temperatures are required. The effectiveness and acceptance of FRPs in strengthening RC structures will significantly increase by designing for the full FRP strength, protecting against fires and accidental damage, enhancing the ductility and minimising the energy consumption as well as carbon emission during production, all of which will lead to reductions in the initial cost.

7. Future opportunities

FRPs are gaining popularity ever since they began to be used in practical applications. Some examples of rehabilitation of large structures are shown in Fig. 21. The present practice of FRP strengthening of RC structures is increasing because of its effectiveness and sustainability.

(a) Rehabilitation of a RC superstructure by using CFRP wraps; Muddy Creek Bridge, Preston County, WV (October 2000) [169]

(b) Structural upgrade of a football stadium in Ukraine, 2009 [170]

(c) Strengthening of a floor diaphragm at Midas Place, Christchurch (March 2013) [170]

Fig. 21 Rehabilitation of RC structures by using FRPs

7.1 Future market

The demand for FRPs in the overall construction and material areas is increasing tremendously [8]. FRPs are being used and manufactured by the most developed countries. In the USA, Middle East, UK and Europe, the use of FRP composites in the strengthening and construction of buildings and bridges is noticeable. According to a current available report [8], the share of the USA market is almost 21% in the construction area, which is increasing with time. It is recently predicted that [171,172] the FRP market will increase around 47% by 2021, with further increases predicted up to 2025, as shown in Fig. 22. Based on current market trends, it can be easily predicted that the FRP market will rise significantly in the construction area. The main obstacle to FRP production is the lack of specifications and guidelines for the required properties and grades of FRPs. Recently, only a very few countries have adopted FRP-strengthening systems in their construction sectors. The production of FRPs to fulfil the requirements of different sectors may be a challenge in the future owing to the higher raw material requirement [15]. Manufacturing guidelines and production standards should be established for the effective utilisation of FRPs.

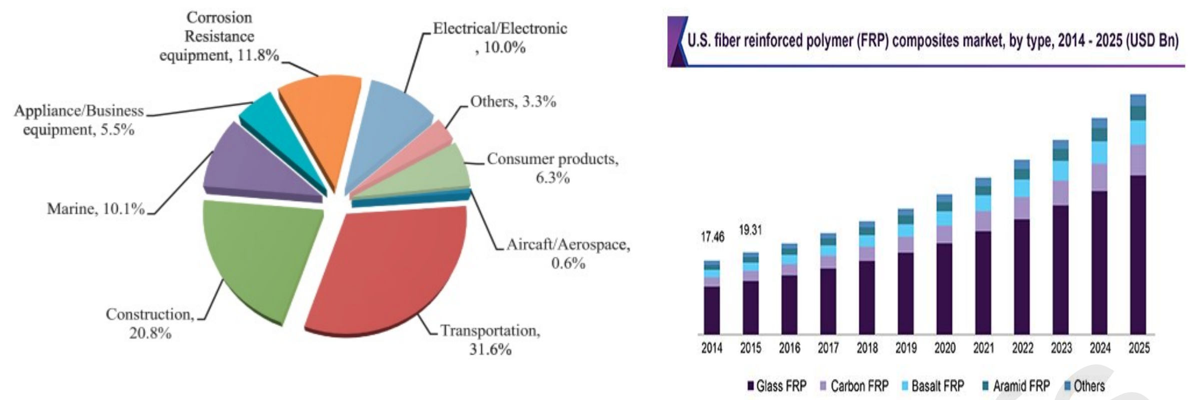


Fig. 22 Current applications and markets of FRPs across different sectors [8,172]

7.2 Future research directions

The strengthening systems of RC structures which employ conventional materials are being replaced day-by-day with those which utilise FRPs. Investigations on the behaviour of FRP-strengthened RC structures were performed by researchers under specific loading and environmental conditions. This study identified the potential areas of FRP strengthening, in which further investigations are required.

- Although most of the studies reveal short-term performances under specific conditions, their long-term behaviour and performance under extreme conditions have not been investigated broadly.
- The stress-strain relationship of conventional concrete cannot be directly applied to the FRP-strengthened concrete [173], therefore, appropriateness of the stress-strain relationship for FRP-strengthened RC structures needs to be established.
- The stress limit of the FRP during the designing of FRP-strengthened members is considered to be very conservative [35], and requires further investigation to establish the standard.
- The durability of FRPs under particularly unfavourable environmental conditions has been researched in several studies [93,94,104,110], but the most vulnerable conditions may arise in wastewater treatment plants, chemical plants and nuclear plants, which were not studied in combination. In these plants, cyclic moisturisation, direct UV exposure, temperature variation, freeze-thawing cycles and acidic-alkaline environments may be encountered simultaneously. The durability of FRP-strengthened RC structures under all these conditions should be investigated.
- Most of the studies were based on prototype structural elements, but the application of FRPs in practical structures which are repaired and retrofitted are very few. Therefore, full-

scale testing, along with practical application, is required, and practical cases should be studied to evaluate the performances.

- The uncertainties associated with the application of FRPs in RC structures under extreme conditions need to be investigated experimentally and their remedies established in accordance with scientific concepts.
- FRPs are being used in prestressing and anchorage systems to strengthen RC structures [21,174]; these require further investigation owing to the lack of information. Composite FRP skins can be effectively used to enhance the flexural capacity [175], which require further investigation to increase the utilizations.
- Most of the current degradation models are based on specific exposure conditions, therefore, further investigations based on the most critical combinations of exposure and loading conditions are needed.

8. Conclusions

This study aimed to provide the current state-of-the-art on FRP-strengthened RC structures, particularly focusing on their performances, failure modes, modelling, challenges and opportunities. The following conclusions were drawn:

- Reinforced concrete structures are commonly strengthened by using FRPs as externally bonded laminates with or without adhesives and anchorage systems. CFRP is the most common strengthening material owing to its high strength. Both U-wrapping and inclined wrapping FRP techniques are reliable under shear, impact and fatigue loadings, whereas the full-wrapping techniques are effective in improving the ductility and durability.
- Debonding is the most common failure mode for side-wrap and u-wrap strengthened systems, whereas rupture of the FRP is the typical failure mode for full-wrapping systems which occurs due to confinement effect. FRP strengthening also helps a structure transform from the brittle mode to a flexible mode of failure.
- Theoretical models are available to predict the environmental degradation, debonding failure, fatigue damage, reliability index and serviceability of FRP-strengthened structures. However, the reliability of these models needs to be investigated experimentally for different combinations of environmental conditions, wrapping materials and wrapping systems.
- The acceptance and application of FRPs in strengthening RC structures will further increase upon developing techniques which utilise the full FRP strength, reduce the

brittleness, risk of fires and accidental damage, minimise the energy consumption as well as carbon emission during production and reduce the high initial cost.

- Currently, there are no standard specifications available for strengthening RC structures by using FRPs. To establish the design guidelines, future studies should be focused on the performances of full-scale FRP-strengthened structures under combined and extreme loading conditions.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Highlights

- Identified the common mode of failures for FRP strengthen RC structures
- Accumulated theoretical models for different failures
- Suggestions provided to increase the acceptance of FRPs in strengthening RC structures
- Identified the research gaps for future investigations