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Repair, retrofitting and rehabilitation techniques for strengthening of reinforced concrete beams - A review

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Abstract. Structural strengthening of reinforced concrete (RC) beams is becoming essential to meet the up-gradation of existing structures due to the infrastructure development. Strengthening is also essential for damaged structural element due to the adverse environmental condition and other distressing factors. This article reviews the state of the field on repair, retrofitting and rehabilitation techniques for the strengthening of RC beams. Strengthening of RC beams using various promising techniques such as externally bonded steel plates, concrete jacketing, fibre reinforced laminates or sheets, external prestressing/external bar reinforcement technique and ultra-high performance concrete overlay have been extensively investigated for the past four decades. The primary objective of this article is to discuss investigations on various strengthening techniques over the years. Various parameters that have been discussed include the flexural capacity, shear strength, failure modes of various strengthening techniques and advances in techniques over the years. Firstly, background information on strengthening, including repair, retrofitting, and rehabilitation of RC beams is provided. Secondly, the existing strengthening techniques for reinforced concrete beams are discussed. Finally, the relative comparisons and limitations in the existing techniques are presented.

Keywords: RC beams; strengthening; retrofitting; rehabilitation; flexural capacity; shear strength

1. Introduction

In developing infrastructure, the premature disintegration of RC elements causes many problems in terms of strength and durability of the structure. The deterioration or degradation of RC structures could be evident by its poor serviceability causing excessive deflection, cracking, strength and stiffness degradation, etc. This could be mainly due to the design faults, poor construction practices, durability issues and unplanned increment in the service loading conditions. Hence, it is essential to strengthen the reinforced structural element to encounter the associated distresses. The awareness of the strengthening of RC structures has garnered prominence from the 1960s to the researchers (L'Hermite and Bresson 1967). Numerous research works have been carried out to develop different comprehensive strengthening materials and techniques over the years (Vesmawala and Kodag 2017, Marijana *et al*. 2018). However, those methods have several advantages and disadvantages relatively. The prime limitations of those methods are low strength to weight ratio, compatibility between the parent and repair material, corrosion and durability issues and failure modes. These limitations play a vital role to choose appropriate material and technology for strengthening.

The maintenance of RC structures components throughout its life span and its up-gradation are the crucial situations for the construction sector, especially maintaining and upgrading of RC beams in the structure. (Alaee and Karihaloo 2003a, b). An RC beam is an integral part of the structural systems are more prone to damage during their service life due to various distressing factors. Therefore, these existing RC beams have to be strengthened to carry higher permissible loads and increasing service loading conditions, especially strengthening techniques for bridges are significant when the demand increases due to increased traffic loads and earthquake conditions. The primary objective of strengthening is life safety and serviceability in addition to the time, cost, and environmental restrictions behind the construction of new structures. For instance, the bridge structures are always desirable to strengthen instead of rebuilding it. Hence, the available promising strengthening techniques should be effectively identified to choose for suitable structural strengthening requirement and make use of its environmental and economic benefit.

To address these problems, several researchers in the past have worked on various RC beam strengthening techniques and development of new repair materials. ACI Committee-224 suggests various repair procedures like resin injection, stitching, drilling and plugging, chemical grouting, epoxy sealing etc., (ACI 1993). The treatment for repairing of damaged RC beams varies with the nature of deterioration. For instance, the repair of RC structure for the damage due to corrosion of rebar is significantly varied from the damage due to the fire accident. The losses incurred due to fire accident are strength and stiffness

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degradation, cracking, concrete spalling, unpleased serviceability, change in colour etc., (Allen *et al.* 1992, Jumaat *et al.* 2006). On the other hand, the damage caused by corrosion of rebar is observed with the appearance of a longitudinal crack along the beam and rust stains on the surface. Hence, the material for strengthening is supplemented with suitable techniques tend to satisfy the required criteria for strength restoration or up-gradation. Also, there is a due consideration in cost and material available for the strengthening techniques.

A different structural strengthening technique has been developed over the past four decades. The popular strengthening techniques are external steel plate attached with epoxy or anchorage bolts, concrete jacketing, wrapping with fiber reinforced plastics (FRP), external bar reinforcements, external prestressing and bonding of ultra high performance concrete strip or overlay (Jones *et al.* 1980, Meier 1987, Crains and Zhao 1993, Diab 1998, Alaee and Karihaloo 2003a, Yaman 2016, Vesmawala and Kodag 2017). The severity and level of damage of RC structures could be determined from the available technical parameters like compressive strength, elastic modulus etc., to choose the suitable strengthening technique required for the distressed structural member. This paper reviews the popular and promising techniques developed for the strengthening of RC beams, along with their implications and key findings. This paper is divided into three main sections: (i) definitions of repair, retrofitting and rehabilitation of RC beams, (ii) existing strengthening techniques and its outcomes, and (iii) relative comparison over the existing techniques and its limitations.

2. Strengthening terminologies and reinforced concrete beams

2.1 Repair, retrofitting and rehabilitation: definition

Strengthening is a collective term used to refer repair, retrofitting and rehabilitation. These terminologies differ with respect to their own functions and attributes. Typically, repair is a process where the performance of the structure is minimally increased from their original performance or to meet the requirement provides aesthetic appearance without increasing the performance much. Typical repair works such as patching up of defects like cracks and fall of plastering, checking and repairing pipes and plumbing services. These repair works have been carried out by using resin injection, stitching, epoxy bonding, drilling and sealing, and chemical grouting (ACI 1993, CPWD 2011). On the other hand, retrofitting is the process intended to improve the performance of the structures like flexure, shear, ductility, service life, fatigue life etc.,. The improved performance by retrofitting is significant than the initial performance of the structural members for which the members were designed (Alaee and Karihaloo 2003a, Bhattacharjee 2011, Kyriaki *et al.* 2013, Murthy *et al.* 2018). Rehabilitation is the process explained by the name itself "Rehab" which is intended for restitution and restoration of strength or performance lost in the structures due to various distressing factors (Bruhwiler and Denarie

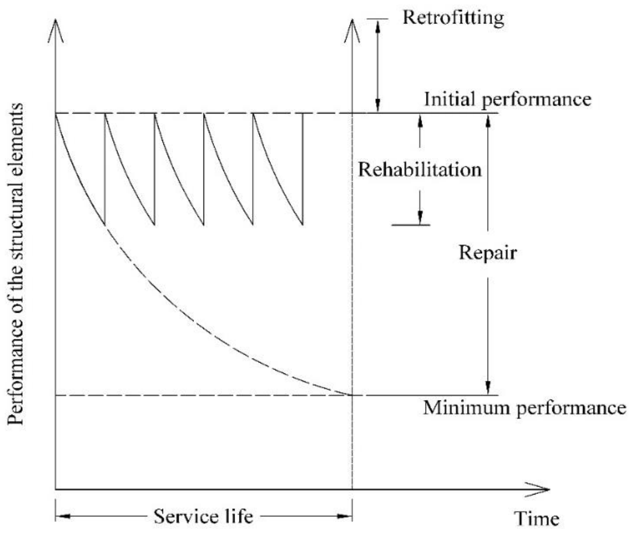

Fig. 1 Strengthening performance of structural components over the service life

2008, Varghese 2014, Gulsan *et al.* 2018). The promising strengthening techniques for retrofitting and rehabilitation are externally bonded steel plates, concrete jacketing, fibre reinforced plastic (FRP) laminates or sheets, external prestressing/external bar reinforcement technique and ultra high performance concrete (UHPC) overlay. Strengthening of structural components by means of repair, retrofitting, and rehabilitation is essential throughout its service life for which the members were designed. Fig. 1 shows the performance of the structural elements for different strengthening terminology over the service life.

2.2 Strengthening of reinforced concrete veam

A reinforced concrete beam is an integral part of the RC structural element which transfers the loads from the adjacent slabs and walls and the imposed live loads safely to the adjacent columns. Hence, a beam should be designed for significant safety and serviceability against the flexural and shear stresses developed in the structure at service conditions. In reality, the typical RC beams are subjected to various distressing factors like as design errors, construction errors, material deficiencies, operational errors and adverse environmental factors. Therefore, in some cases, a typical ultimate limit state of the structure is attained which leads to the complex stresses of shear and flexure induced in the RC beams. These complex stresses could be a problem to the RC beams due to the exceeded resistance capacity which may initiate the tensile cracks. The initiation of tensile cracks could be contributed mainly due to the tensile capacity of concrete which is comparatively lesser than its compressive strength. The behaviour of RC beams subjected to adverse distresses mentioned above causing failure in flexure and shear by means of tensile cracks. Hence, it is essential to strengthen those critically damaged and damage prone beam elements to improve load carrying capacity and in-service performance in which it is designed (Meier 1987, Cairns and Zhao 1993, Alaee and Karihaloo 2003a).

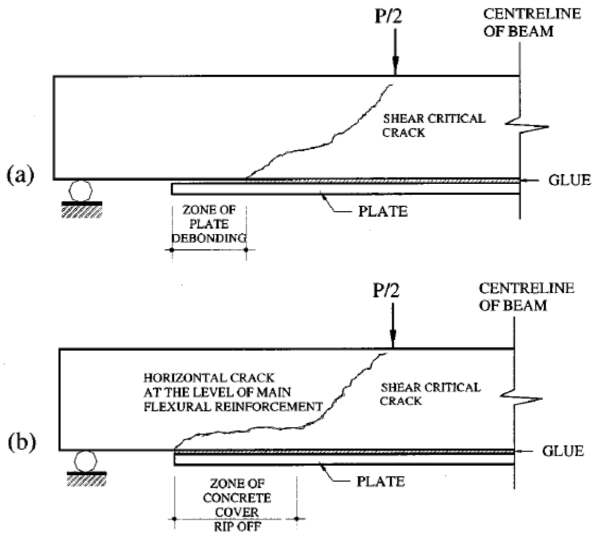

Fig. 2 Distresses on RC beams strengthened using steel plate: Plate debonding and concrete rip off (Ziraba *et al.* 1994)

3. Review on the existing beam strengthening techniques

Different strengthening methods for structural components are evolved over the past four decades are (i) externally bonded steel plates, (ii) concrete jacketing, (iii) fibre reinforced plastic (FRP) laminates or sheets, (iv) external prestressing/external bar reinforcement technique and (v) ultra high performance concrete (UHPC) overlay.

3.1 Steel plate bonding

Steel plate bonding is the oldest technique used to strengthen the RC structures. Steel plates and confined reinforcements were used as a retrofit with various configurations to withstand the flexural and shear capacity. Bonding of steel plates using epoxy was first pioneered by L'Hermite and Bresson (L'Hermite and Bresson 1967). The external bonding of steel plates in RC structure is precise and straightforward, which does not significantly reduce the clear storey height, and it can be done under service condition of the structures (Parkinson 1978, Gemert 1981). The flexural behaviour of distressed RC beams was studied by Jones *et al.* using the steel plates bonding (Jones *et al.* 1980). Based on the studies, it was found that the epoxy resin used for bonding the distressed RC beams and steel plate had maintained the composite action till failure. Strengthening by external steel plate bonding significantly improved the structural performance of the cracked beams efficiently by restoring the stiffness and strength values compared to the original unplated beams. The under reinforced and over reinforced RC beams are studied by strengthening with a glued steel plate (Jones *et al.* 1982). It was concluded that the thick plate improves the ultimate strength drastically. However, thick plates are more prone to failures by separation due to the increase of self-weight of the section. The improvement in flexural strength is above 100% for the under reinforced beams with respect to control beams. The Rotherham Bridge was strengthened by Davis and Powell using this technique to improve its load carrying capacity (Davis and Powell 1984). The bridge was initially designed for maximum vehicle load of 100 tonnes and later to meet the increased demand, the strength was enhanced to 456 tonnes using this technique.

Strengthening of RC structure with externally bonded steel plate has become famous and widespread due to its quick, less site disturbance while bonding, and versatile in dimension. However, this method has certain limitations such as, handling of heavy steel plates, corrosion of bonded steel plate, undesirable shear failure, and mainly debonding of steel plates (Jones *et al.* 1988, Swamy *et al.* 1989, Ziraba *et al.* 1994). The debonding is one of the crucial problems which can lead to abrupt brittle failure. These debonding could be due to the high interfacial shear or normal stresses induced in the RC elements by the transfer of tensile stresses from the bonded steel plate. These transfer of tensile stresses results in debonding of plate or ripping of the adjacent concrete cover as shown in Fig. 2. The generic and common problem associated with the steel plate is the corrosion due to the aggressive environmental conditions. Corrosion of steel plates adversely affects the bonding between the steel-concrete interfaces.

Many researchers investigated to address the debonding of steel plate from the RC structures and suggested to use anchorage bolts and angle sections bonded over the side of the RC beams (Hussain *et al.* 1995, Adhikary and Mutsuyoshi 2002, Su and Zhu 2005, Wang and Su 2013). Performance of strengthened RC members is improved significantly by the addition of anchorage bolts in the bonded steel plates (Hussain *et al.* 1995). It was observed that the pattern of bolt arrangement influences the failure behaviour of strengthened RC elements. The failure behaviour of RC beams is not significantly changed due to the anchorage of bolts at the end plate. However, it helps in delaying the failure by debonding (Adhikary and Mutsuyoshi 2002). The flexural strength and ductility of coupling beams are sufficiently maintained after strengthening by the bolt anchorage techniques (Su and Zhu 2005, Su and Siu 2007, Su *et al.* 2010).

Su *et al.* investigated the influence of bolt-plate configuration on strengthened RC beams as shown in Fig. 3. Four different bolt side-plated (BSP) combinations were studied including 'Strong Bolt Strong Plate' (SBSP), 'Weak Bolt Strong Plate' (WBSP), 'Weak Bolt Weak Plate' (WBWP) and 'Strong Bolt Weak Plate' (SBWP). From the BSP studies, it was evaluated the post-elastic strength enhancement and displacement ductility for the different configuration of bolt plate arrangement. It was concluded that "Strong bolt weak plate" configuration enhances the strength and ductility significantly, whereas "Strong bolt strong plate" effects in abrupt brittle failure. It was suggested to limit the steel plate dimensions to avoid brittle mode of failure of RC beams. The moderately reinforced RC beams were strengthened using deep steel plates bolted at sides (BSP) significantly improved the flexural strength and energy absorption (Li *et al.* 2013, Li *et al.* 2015).

It was also observed that the strengthening could be completely achieved by enhancing the shear in addition to flexural capacity. In general, strengthening of structural

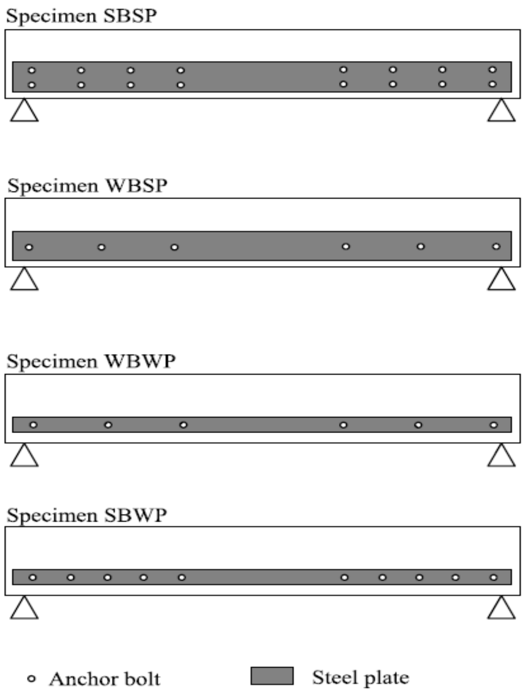

Fig. 3 Different Bolt-Plate configurations on Strengthened RC Beam (Su *et al*. 2010)

beams used to enhance the flexural capacity which may cause the shear deficiency in it. Hence, it is essential to handle the strengthening technique by considering both the shear and flexural stability. Later 90s, researchers worked on the shear strengthening of RC beams using steel plates (Swamy *et al*. 1996, Subedi and Baglin 1998). Suitable external bonded side plate technique can improve the serviceability and ultimate shear capacity. Steel jacket plates and small steel strips are used to strengthen RC beams by entirely encasing the shear zone to develop shear resistance and thereby failure was induced in flexural mode (Sharif *et al*. 1995). The web bonded steel plate is efficiently enhancing the ultimate shear strength with respect to the depth and thickness of the plate (Adhikary *et al*. 2000). Even 2 mm thin steel plate could enhance the shear capacity of the beam substantially if it provided with sufficient depth and anchorage bolt arrangements (Barnes *et al*. 2001). Also, it was observed that the depth of the bonded steel plate is an important criterion for shear strength enhancement of RC beams and the shear strength does not prominently rely on the thickness of the plate. Shear strength is improved by providing maximum depth of steel plate instead of its thickness (Adhikary and Mutsuyoshi 2006). Fig. 4 shows the typical strengthening scheme of RC beams using bonded steel and strength development over various schemes of steel plate techniques. From Fig. 4, it was observed that bolted plates show significant strength enhancement than the unbolted steel plates, especially the BSP resulted in 162% enhancement compared to control beams. RC beams strengthened with BSP technique was found to be nearly double the time of anchored plate at the soffit of the beams.

3.2 Concrete jacketing/section enlargement

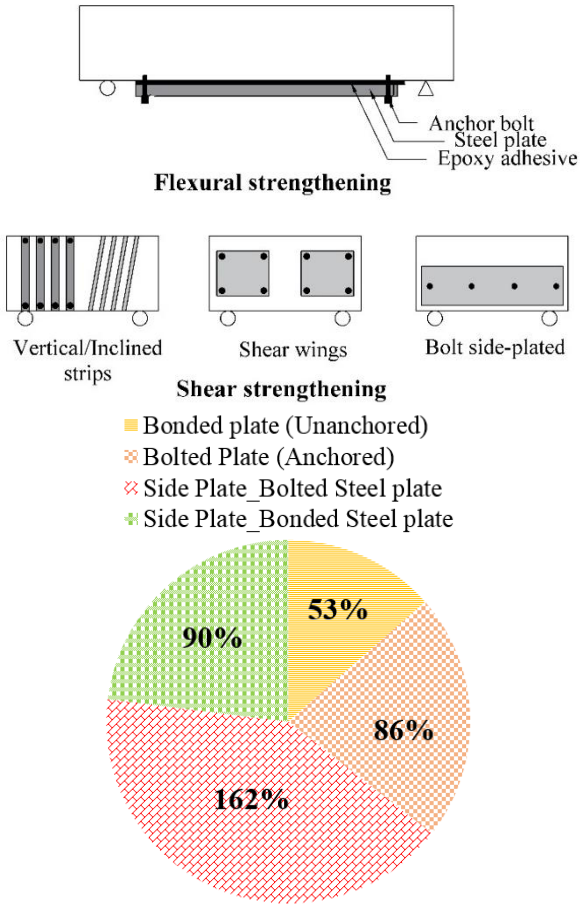

Fig. 4 Strengthening scheme of RC beams using bonded steel and strength development over various schemes (Adhikary and Mutsuyoshi 2006)

Concrete jacketing is the traditional technique used for strength restoration or up-gradation of damaged or poorly designed RC elements. Concrete jacketing is typically involved with the addition of encasing steel reinforcement over a parent structural member with a concrete jacket as shown in Fig. 5. Jacketing is mainly intended to improve the flexural and shear capacity of the damaged RC beams by increasing the percentage of tensile reinforcement. Jacketing could enhance the ductility which leads to strength recovery and restoration and changing the failure behaviour. The concrete section is enlarged by sprayed concrete which is the most common enlargement method. The load carrying capacity and stiffness of the strengthened RC beams by sprayed concrete has been improved significantly with respect to parent RC beam (Diab 1998). The additional concrete used for jacketing is preferably a pre-placed aggregate (PA) concrete since at cast in situ placing of concrete is extremely difficult. Also, PA concrete is essential for concrete jacketing because it keeps the drying shrinkage relatively low (50% than the normal concrete) which results in effective aggregate contact (ACI 1992).

The surface treatment between the parent concrete and the PA concrete could be either partially or fully roughened using impact tools to ensure the interfacial bonding between them. However, there is no significant variation in the

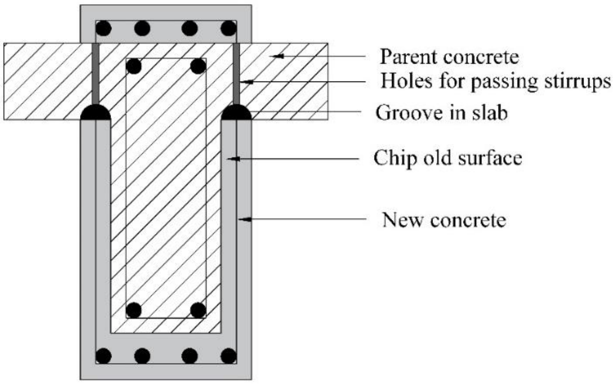

Fig. 5 Typical strengthening by section enlargement/ concrete jacketing (Cheong and MacAlevey 2000)

results with respect to surface treatment by partial and fully roughening (Cheong and MacAlevey 2000). The flexural behaviour of severely damaged RC beams and RC jacketed beams have a similar trend with a significant change in ultimate strength. Welding interlocks the connection between longitudinal reinforcement of the damaged beam and the jacketed beam with Z bars which have a positive impact on strength enhancement (Altun 2004). In general, the interface surface is roughened significantly with the use of a bonding agent or an epoxy resin. Also, it is an essential requirement to perform jacketing technique using high skilled workmanship and the effective utilization of cost and time.

In concrete jacketing, the effective thickness could be reduced appreciably with the usage of concrete grout which is either self-compacting or high strength concrete (Julio *et al*. 2005). The main objective of this technique is to change the unusual premature failure modes which could then be succeeded in the structural element with the reversal of cyclic loading conditions. These loading conditions could stimulate the primary reinforcement to yield by flexure (Thermou *et al*. 2007). Partial jacketing techniques by the addition of concrete and steel reinforcement along the tension face of the RC beams with the use of shear connectors are the easiest and quickest method for strengthening (Shehata *et al*. 2009). The application of dowel connectors and micro concrete using bonding agent in RC jacketing beams improves the flexural capacity of beam significantly (Raval and Dave 2013).

The strengthening by means of the addition of thick concrete layer at the tensile zone improves the performance of RC beams in terms of stiffness and ultimate capacity. However, the technique of adding a thick concrete layer is monolithically effective only if the interface is appropriately prepared by sufficient roughening or chipping the surface to ensure the bond between the parent and strengthening layer (Raval and Dave 2013, Tsioulou *et al*. 2013). The performance of thin reinforced concrete jacketing with the use of self-compacting concrete is enhanced remarkably under monotonic and cyclic loading conditions than the conventional RC jackets (Chalioris *et al*. 2014). The enhancement could be due to its reduced thickness (Ultra thinner jacket and ease in placing), better microstructure, aesthetics, and certainly no serviceability

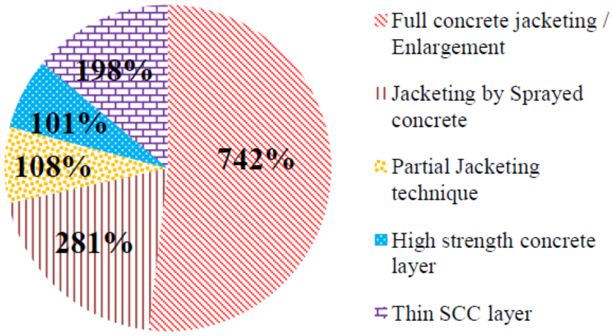

Fig. 6 Strength development over various schemes of section enlargement / concrete jacketing

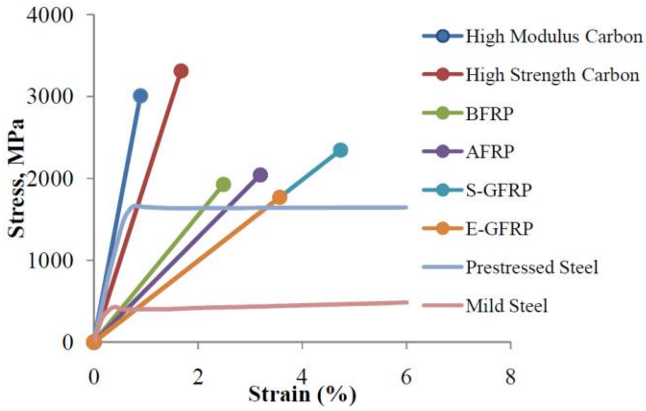

Fig. 7 Typical tensile strength and stress-strain relationship of FRP and steel reinforcement (Taerwe 1995)

issues. However, a marginal reduction in flexural strength of RC jacketed beam was observed when the member is subjected to a repeated cyclic loading in caparison to the strengthened beam subjected to monotonic loading. Fig. 6 shows strength development over various schemes of section enlargement/concrete jacketing. From Fig. 7, it was observed that full concrete jacketing shows tremendous strength development; however, poor serviceability leads to go for other partial jacketing techniques. From the results, strengthening by thin SCC layer found to be a feasible choice in terms serviceability with a strength development of around 200% compared to the control beams.

3.3 Fiber reinforced polymers

Fiber reinforced polymer (FRP) is a versatile material, contains composite polymers reinforced with uni or multi-directional fibres. Initially, these FRPs were used in the fields of automotive sectors and aerospace industries in European countries. For the past three decades, it becomes popular in the field of civil engineering. FRP is first pioneered in the repair work of a bridge element to restore the original cross-sectional strength (Meier 1987). Various types of FRP materials are available in the construction sector, suitable for the strengthening of concrete elements. The FRP types are broadly classified based on the fiber composites; namely, carbon fibre reinforced polymer (CFRP), glass fibre reinforced polymer (GFRP) and aramid fibre reinforced polymer (AFRP). These FRP composite

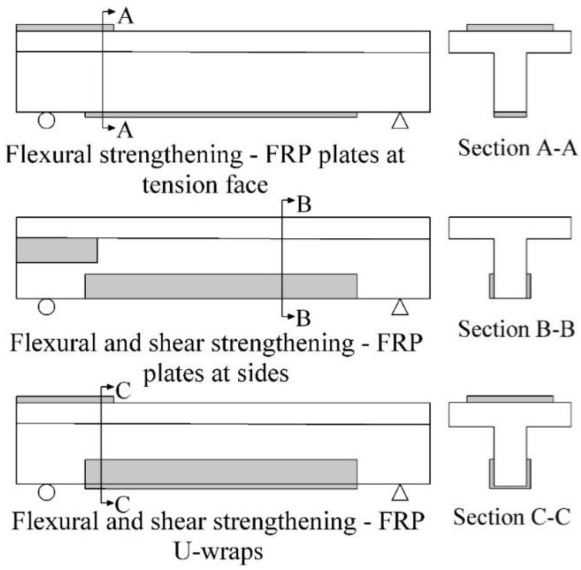

Fig. 8 Strengthening by externally bonded FRP laminates/ plates/U-wraps (Oehlers 2001)

laminates or sheets are bonded with the use of polymer matrix like adhesive epoxy, vinyl ester, polyester, etc. Extensive studies on the different FRP composites for the strengthening of RC elements were reported in the literature. This method became a promising technique due to their superior material properties like significant mechanical properties, high strength to weight ratio, corrosion resistance, easiness in handling, weathering resistance, better fatigue performance, versatile in size and shape, etc., (Ritchie 1988, Saadatmanesh and Ehsani 1990, An *et al*. 1991, Meier and Kaiser 1991, Karam 1992, Soheil and Javad 2016). Fig. 7 shows the typical tensile strength and the stress-strain relationship of various FRP and steel reinforcement.

The method of attaching FRP in the strengthening of RC elements is classified into two types. Wet lay-up is the first method which involves epoxy resin applied as cast in situ over the FRP sheets bonded with RC beams and slabs. The second method is pultrusion for producing plates by means of fabrication in factories and bonded to beams and slabs at the site using epoxy resin. Various RC structural elements strengthened using FRP composite plate or laminate bonding to enhance or restore the performance has been reported (Triantafillou and Deskovic 1991, Ross *et al*. 1994, Chakrabortty and Khennane 2014, Mesbah and Benzaid 2017, Hammad *et al*. 2018). Fig. 8 shows the typical strengthening of RC T-beam with the externally bonded FRP plates or laminate. The use of CFRP and GFRP composites enhanced the stiffness and the flexural capacity of the RC beams by about 118 and 97%, respectively (Ritchie *et al*. 1991). It was observed that there is no flexural failure in the maximum moment region for most of the beams, but debonding failure was observed at the plate ends.

Saadatmanesh and Ehsani investigated the GFRP strengthening RC beams with various adhesive epoxy which exhibits significant improvement in strength and ductility (Saadatmanesh and Ehsani 1990). The ductile adhesive epoxy was not responsible for the ultimate capacity because it is too flexible to influence the shear transmission between the parent material and the GFRP laminate. Though, the ultimate flexural strength is enhanced by about 110% with respect to the use of rubber-roughened epoxy with viscosity and consistency relatively similar to cement paste. The thickness of the laminates is also an important parameter studied and typically 1.0 mm thick CFRP laminate found to enhance the flexural capacity by 22% (Meier and Kaiser 1991). The deflection of the CFRP strengthened beams is found to be comparatively less than the control beams, but it is significant to predict the impending failure. However, the laminate is peeled off suddenly from the concrete surface due to the formation of shear cracks.

In the early 1990s, studies showed that the application of FRP laminates significantly enhanced the flexural capacity of RC beams with very less weight to strength ratio than the steel plate jacketing. Nearly, 2 kg of CFRP laminate was used for the repair of Ibach Bridge instead of 175 kg steel plate (Meier 1987). Eventually, all the works on FRPs were carried out using merely a mobile platform instead of expensive scaffolding (Raghavachary 1992, Triantafillou and Plevris 1992, Ghaleb 1992). Also, a composite fabric made of AFRP, E-GFRP, and graphite fabrics were attached with RC beams by two-component epoxy resin which enhanced flexural capacity by about 57% and flexural stiffness by about 53%. The RC beams strengthened with E-GFRP and graphite fibres were failed due to tensioning of fabrics in maximum moment section, whereas the failure due to the reinforcement with aramid was by crushing of concrete at compression zone (Chajes *et al*. 1994).

Hence, FRP plates or laminates used for strengthening of RC structural component known to be very popular with the significant increase in rigidity and strength along with easiness in fixing and quick polymerization in the site. Among the FRPs, CFRP is very effective for flexural strengthening of beams with the provision of additionally required anchorage of the laminates to ensure perfect bonding. It was observed that there is a significant improvement in performance for CFRP strengthened beams which are about 3.33 times stronger than the un-strengthened RC beams (Duthinh and Starnes 2001, Esfahani *et al*. 2007, Varastehpour and Hamelin 1997, Razavi *et al*. 2015). It was also found that both the CFRP and GFRP composites enhanced the flexural strength of about 150% for the strengthened RC beams (Sheikh 2002). The application of FRP laminates/plates or sheets for the strengthening and rehabilitation of reinforced concrete element are well specified in the design guidelines of ACI 440-02 and European fib bulletin (ACI 2008, fib 2001).

Wrapping of FRP sheets enhances the flexural strength significantly in both the normal and prestressed concrete (PSC) beams (Dave and Trambadia 2004, El-Ghandour 2011). The failure load of the GFRP wrapped PSC beams increased from 25 to 41% with respect to the unwrapped PSC beams (Dave and Trambadia 2004). The promising anchorage techniques are to be developed to overcome the debonding failure through complete utilization of fibre strength over the small joint surface. This could profound

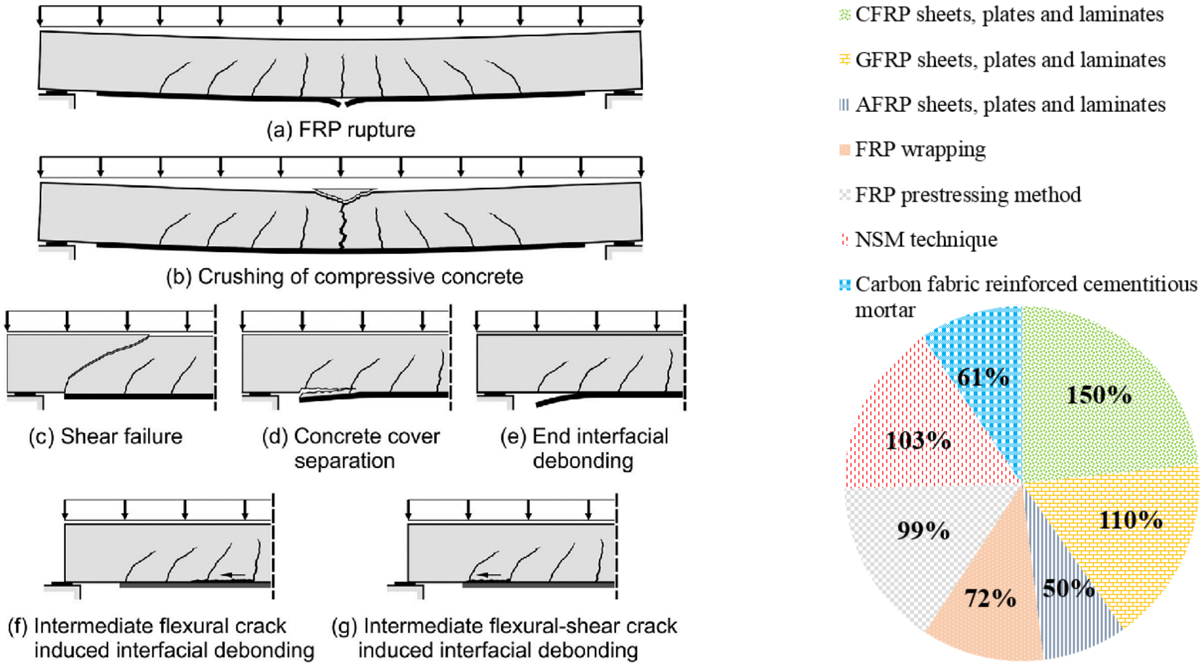

Fig. 9 Failure modes of FRP strengthened RC beams and its strength development over various schemes (Chen and Teng 2001)

the application of FRPs in the practical 3D joint strengthening (Engindeniz 2008). The flexural behaviour of RC structural component strengthened with CFRP plates was studied by equipping various FRP bonding and prestressing methods (Garden *et al*. 1998, Yang *et al*. 2009). It was observed that the ultimate strength of prestress-CFRP strengthened RC beams was nearly the same for both bonded and unbonded conditions. The ductility of the prestress-CFRP strengthened beams with an anchorage system is considerably high with the ductility index of above 3. Hence prestressed FRP exhibits superior structural properties such as enhanced flexural strength, reduced displacement, higher strength to weight ratio, enhanced ductility, resistance to corrosion and increased fatigue life makes it as a better choice of beam strengthening (Aslam *et al*. 2015).

Bonding of FRP strips for strengthening RC T-beam of 8.84 m long has investigated along with the mechanical fasteners which do not require any surface preparation. The flexural strength enhancement of about 15% with a maximum displacement of 63.5 mm at the mid-section for the strengthened beams bonded with one FRP strip was observed (Lamanna *et al*. 2012). On the other hand, the flexural enhancement is pronounced to 27% with respect to the beams strengthened with two FRP strips. The application of U-wrap CFRP laminates delays the delamination of concrete cover. However, the occurrence of premature debonding of CFRP laminates was observed at the mid-span of RC beams which could be due to the reduction in ductility of the laminates (Tahsiri *et al*. 2015). The externally bonded corrugated GFRP laminates are used for strengthening of RC beams which enhances the load carrying capacity to the greater extent than the plain GFRP sheets (Aravind *et al*. 2017).

Recently, FRP laminates or strips with near surface mounted (NSM) technique provides a practical solution to increase cracking resistance, yielding and maximum loads of beams failed in bending. Hence, CFRP laminates with NSM technique is an effective technique for the flexural strengthening of RC beams (Khalifa 2016, Dias *et al*. 2018). The flexural strength of RC beams is enhanced by the load range of 42 to 103% than the control beams. It is observed that a 34% increase in the yield load with respect to the control beams. However, there is a decrease in ductility is observed in using the NSM technique with respect to increasing in CFRP percentage. Recently, the studies were reported on the effectiveness of basalt FRP (BFRP) in the strengthening of RC beams (Chen *et al*. 2018, Gulsan *et al*. 2018). The experimental results showed that the external bonded BFRP is also an effective method to enhance the flexural strength of RC beams. The failure pattern varies with the anchorage, wrapping methods and adhesive used. The U-wrap of BFRP in the strengthening of RC beams attributed to the failure of RC beam by rupture of BFRP instead of debonding. Fig. 9 shows the different failure modes observed in the FRP strengthened RC beams and its strength development over various schemes.

In addition to strengthening and rehabilitation of the flexural deficiency of RC beams, it is also essential to restore its shear deficiency using FRP composites. Many studies were reported on the enhancement of shear strength of RC beams bonded with FRP composites (Uji 1992, Alexander 1996, Chaallal *et al*. 1998, Khalifa and Nanni 2000, El-shafie 2014). The shear failure predominantly occurs in two ways, (i) FRP rupture at tensile zone and (ii) debonding of FRP from concrete. The FRP composites are known for enhancing the flexural capacity and ductility of the RC beams; however, it is deficient in shear which could lead to peeling off and debonding of the composite. From the experimental data of the above investigations, the strengthening technique by FRP like wrapping, U-jacketing, and side bonded plate is failed due to initial debonding followed by FRP rupture. The beam failed when the FRP is peeled off from the beam surface which reduces the ductility of the member. The debonding mode of failure is mainly due to the non-uniformity of the shear crack formed in the FRP intersection (Chen and Teng 2003).

The strengthening of RC beams was carried out with externally bonded carbon fibre fabrics (CFF) strips with different orientations (45° and 90°) which significantly reduces the shear deficiencies (Diagana *et al*. 2003). The application of GFRP inclined strips enhanced the shear strength of beams significantly. It is evident that the behaviour of U-wrapped RC beams is superior to the beam bonded by GFRP strips on the sides alone. Shear strengthening and rehabilitation of the RC beams using FRP inclined strips enhanced the strength and stiffness by reducing the shear cracks. Hence, it is a vital requirement for the strengthening of RC beams to increase both the flexural and shear capacity of the members. The various schemes of externally bonded GFRP and CFRP sheets are used to improve the flexural-shear capacity of the RC beams (Dong *et al*. 2013). The sheets bonded at the bottom, and lateral sides of the RC beams enhanced the flexural strength and shear strength by 125% and 74% respectively.

The end anchorage of externally bonded CFRP wraps can restore the designed strength of RC beams (Frederick *et al*. 2015). The enhanced behaviour of external bonded CFRP with end anchorage could be mainly attributed to the additional end anchorage and its increased resistance to the premature debonding. The cement-based composites are used instead of an epoxy based system to bond the FRP on the RC beams for strengthening (Azam *et al*. 2017). The cement-based composites consist of CFRP grid embedded in mortar and called it as carbon fabric reinforced cementitious mortar (CFRCM). The performance of these cement-based composites is better than the conventional epoxy bonded system by possessing enhanced shear strength for the strengthened RC beams. The CFRP grid embedded in mortar shows excellent bonding behaviour with the concrete surface leads to promising shear strengthening system.

Also, numerous studies were reported in the literature on the flexural fatigue behaviour of beams strengthened by repair materials using laminates and plates of CFRP, GFRP and so on. The behaviour of CFRP strengthened RC beam was studied under static and fatigue loading (Shahawy and Beitelman 1999). The improvement in the fatigue behaviour, stiffness, and capacity directs the significantly extended fatigue life of RC beams with the strengthening of CFRP laminates. The fatigue performance of the concrete beams strengthened with CFRP laminates was investigated. It was observed that internal steel reinforcement play a key role in governing failure of CFRP strengthened RC beams due to the occurrence of fatigue facture of steel reinforcements. Therefore, the criterion required for fatigue strengthening using CFRP plates was suggested that the stress range of rebar should be limited than the permitted range in an un-strengthened beam (Barnes and Mays 1999).

The similar works with CFRP were carried out and observed that the fatigue life of the RC beams had been

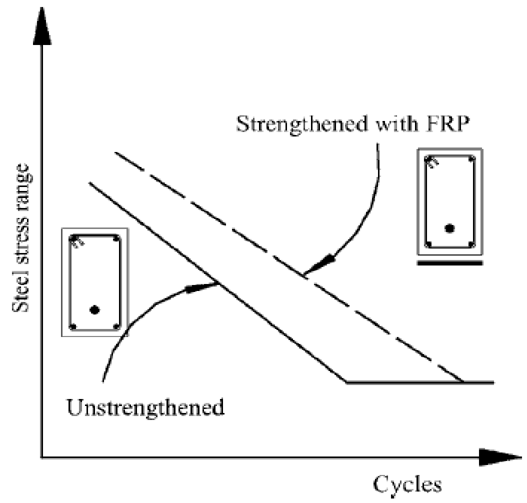

Fig. 10 Typical steel stress range versus no. of cycle's curves for strengthened and un-strengthened RC beams (Kim and Heffernan 2008)

enhanced with the usage of FRP plates and laminates which significantly reducing the stresses taken by the internal steel reinforcement (Aidoo *et al*. 2004). It was also observed that the quality of the bond between the parent and strengthening materials limits the fatigue life. Similar experiments on CFRP strengthened RC beams were performed by various researchers (Papakonstantinou *et al*. 2001, Quattlebaum *et al*. 2005, Gheorghiu *et al*. 2006, Wang *et al*. 2007, Kim and Heffernan 2008, Ferrier *et al*. 2011, Oudah and El-Hacha 2012). The common observation in all of them is that the fatigue life of the strengthened RC beams with externally bonded FRP, exhibit enhanced fatigue life and residual strength with respect to the un-strengthened beams. Perhaps, the failure mode of strengthened RC beams remains unchanged. The enhancement in the fatigue life could be due to the decreased stress concentration acting on the internal reinforced steel. Fig. 10 shows the typical S-N curves of strengthened and un-strengthened reinforced concrete structures.

Fayyadh and Razak investigated the flexural stiffness change and the effectiveness of the CFRP strengthened RC beams under different damage levels on static and fatigue loading (Fayyadh and Razak 2012). The principal study was to examine the flexural stiffness change after the strengthening on each incremental load steps. The datum stiffness taken as extreme stiffness comprised by the strengthened RC beams and the reduction of the stiffness was observed with the further loading. However, the common mode of fatigue failure observed in the RC beams is rupture of tensile reinforcement followed by FRP failure. The fatigue behaviour of pre-damaged RC beams after strengthening results in the reduction of fatigue life. Strengthening of RC beams with NSM bar effectively tolerates the applied fatigue load even after the rupture of reinforcing steel bars (Mahal *et al*. 2016). The behaviour of pre-cracked RC beams is taken care effectively by NSM CFRP strengthening technique compared to beam without pre-crack. However, strengthening by bonded FRP plate was found to be a more efficient technique in improving the fatigue life of pre-cracked beams. Strengthening by prestressed CFRP improves the fatigue behaviour of RC beams due to the reduction in the strain of the reinforcing steel and decreased displacement compared to non-prestressed CFRP strengthened beam (Peng *et al*. 2016). The RC beams strengthened with non-prestressed CFRP were failed by debonding of CFRP from the concrete. There is no debonding in prestressed CFRP.

3.4 External reinforcement/prestressing

External prestressing was one of the most powerful techniques for strengthening and rehabilitation of damaged or distressed RC beams of bridges. The strengthening technique by external prestressing tendons has become popular due to (i) economic strengthening application; (ii) layout of tendons is easier and precise, and (iii) faster construction. The strengthening of RC beams with a moderate amount of external prestressing tendons enhanced the flexural capacity of about 146% without affecting the ductility and ultimate flexural deformation (Harajli 1993). The external prestressing tendons are effectively taking care of crack behaviour and serviceability of flexural members at severe load conditions. Hence, strengthening by external prestressing tendons reduces the width of cracks or closing the cracks and significantly reduces the deformation at service loading conditions. The external prestressing technique substantially reduces the deformations of RC beams due to the service load because of its stiffer load-deformation behaviour. The deviated profile of external reinforcement increased the flexural resistance compared to the straight horizontal profile. Additionally, the external prestressing technique enhanced the fatigue life of the RC beam subjected to repeated loading conditions. There is a considerable reduction in stress level in the internal steel reinforcement of RC beams with no indication of shear distresses.

Strengthening and rehabilitation by the use of external unbounded reinforcement is a widely used technique for the RC beams introduced by Cairns and Co-investigators (Cairns and Zhao 1993, Cairns and Watson 1993, Cairns and Rafeeqi 1997, Cairns and Rafeeqi 2002, Cairns and Rafeeqi 2003). This concept has originated from the observation of the structural behaviour of RC beams with exposed bars during repair. Eventually, the RC beams with exposed reinforcement could enhance the strength of the shear deficient beam. The external reinforcement technique is popular due to its simplicity in the connection process, speedy application, and less disturbance during strengthening at service conditions. The factors influencing the behaviour of strengthened RC beams with externally unbonded reinforcement include (i) loading setup, (ii) depth of external unbounded reinforcement, and (iii) bonded reinforcement proportions.

By considering the above-said factors, it can be possible to obtain twice the ultimate strength of the RC beams with the application of external unbonded steel reinforcement. Typically, the enhancement in flexural strength is about 85% with the incorporation of external steel reinforcement strengthening technique for RC beams (Cairns and Rafeeqi 1997). However, it was observed that there is a significant reduction in ductility of RC beams. Fig. 11 shows the schematic representation of RC beams strengthened with external unbonded reinforcement. The strength of lightly reinforced RC beams has more advantage in enhancing the performance than that of the heavily reinforced RC beams (Cairns and Rafeeqi 2002). Hence, the percentage of bonded reinforcement is a critical parameter which decides the effectiveness of strengthened RC beams with external unbonded reinforcement.

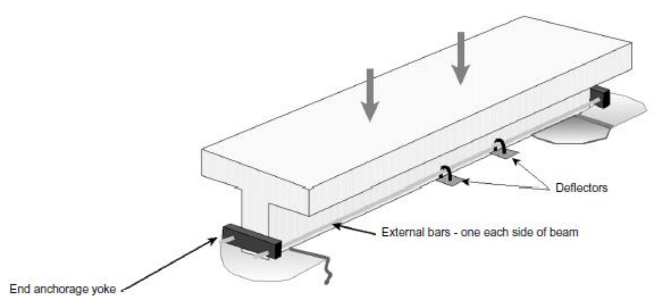

Fig. 11 Typical strengthening technique of RC beams with external reinforcement (Khalil *et al*. 2008)

A high strength tension bar with anchor pins and a saddle are used for strengthening the RC beams (Shin *et al*. 2007). The performance of strengthened RC beams is assessed by varying the bar arrangements, (i) V-shape (2 Bars, 1 deviator) and (ii) U shape (3 Bars, 2 deviators). This method is effective in enhancing the stiffness once the cracking starts and also there is a little enhancement in stiffness before the first crack. Strengthening of RC beams with externally unbonded high strength bars with deviator enhanced the flexural strength in the range of 42-112%. The effect of increasing the geometric ratio of externally unbonded reinforcement than the bonded reinforcement has been studied (Khalil *et al*. 2008). The increase in the geometric ratio of unbonded reinforcement varies from 100 to 178% of the bonded reinforcement; the ultimate strength is enhanced from 28 to 47%. The efficiency of this method is ensured by avoiding the local concrete failure against the end anchorage yoke.

The limitations of anchorage of external unbonded bars are (i) difficulty in obeying deflection behaviour of beam, (ii) requirement of deviator at higher span to depth ratio to elude the effective depth reduction, and (iii) stronger yoke requirement to withstand a huge concentrated load. These drawbacks were addressed by incorporating the external bars at the tension face of the RC beams to exclude the anchorage and deviators (Vasudevan and Kothandaraman 2014). The external reinforcement is attached to the tension face by oval-shaped grooves filled with chemical adhesives and the bars are lapped by continuous welding to reflect the lapping at real-time application. The ultimate moment capacity of the strengthened RC beams with external reinforcement is enhanced to 140% without reducing the ductility. The strength enhancement is mainly attributed to the increased effective depth of external bars. Fig. 12 shows strength development over various schemes of external reinforcement / prestressing technique. Embedded external reinforcement at the soffit of the RC beams was found to be

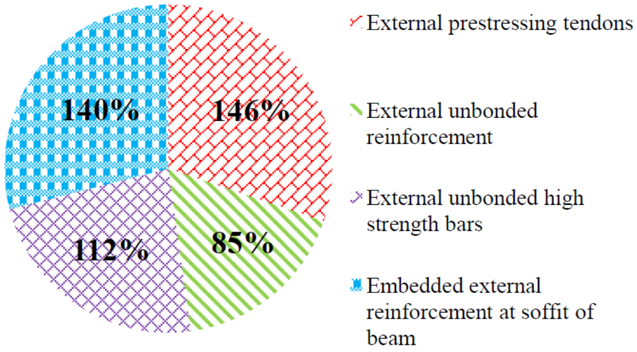

Fig. 12 Strength developments over various schemes of external reinforcement / prestressing technique

a promising scheme with the strength enhancement of about 140% compared to control beams.

3.5 Ultra high performance concrete overlay or strip

In the recent two decades, significant investigations were carried out to develop new cementitious materials with the incorporation of micro fibers which pave a way for the origin of UHPC. In the construction sector, it is becoming a promising novel material which exhibits excellent mechanical and durability properties. Also, UHPC exhibits better rheological properties at the fresh state which makes the concrete more workable even with the application of nominal construction tools. Subsequently, UHPC has enhanced control over the aggressive environmental conditions and can sustain severe mechanical loading, which makes them an ideal cementitious material for developing infrastructure (Oesterlee *et al*. 2007). The most important aspect of UHPC is rapid strength gain which is essential for the quick construction process. Even strength range of 80 to 100 MPa has been able to obtain by the UHPC cementitious material at standard curing conditions (Voo *et al*. 2011). Recently, the development of precast elements is mainly produced with the use of UHPC material under heat curing conditions which enhances the targeted mechanical properties in less than 5 days. Therefore, it was concluded that the cementitious material exhibits extremely low porosity and permeability along with significant resistance to mechanical loading. These properties make it a suitable material for the strengthening of concrete structures.

The extensive experimental work was carried out on reactive powder concrete (RPC) which used to develop the UHPC mix as a repair and retrofit material (Richard and Cheyrezy 1994, Richard and Cheyrezy 1995). It was observed that UHPC is a promising candidate for strengthening due to its distinct features like high dynamic modulus, better bond strength and significant durability compared to conventional concrete (Lee *et al*. 2006, Lee *et al*. 2007). Firstly, the essential requirements to choose a new strengthening material which have to be applied as the strengthening layer are material properties. Thus, the properties of strengthening material have to be close enough to the parent material. Perhaps, UHPC has exhibited a modulus of elasticity around 55000 MPa which is 60% higher than the conventional concrete whose elastic modulus ranges from 35000 to 40000 MPa. However, for strengthening purpose this difference in elastic modulus is efficiently taken care by the enhanced tensile property of UHPC (SAMARIS 2005). Recently, UHPC mixes are developed with the modulus of elasticity around 45000 MPa which considerably matches with the material behaviour of normal concrete. Secondly, the strain hardening capability of UHPC is an important criterion which is higher than the conventional concrete and it is significant compared to the ultimate elastic deformation of UHPC. Therefore, strain hardening of UHPC turns out to be an excellent property in addition to mechanical and durability properties, ideally a potential candidate to behave monolithically with conventional distressed parent concrete.

A thin layer of high performance fibre reinforced cementitious composite (HPFRCC) overlay around 10 to 50 mm thick layer was used to strengthen distressed bridge deck and pavements (Krstulov and Toutanj 1996). The thin layer of HPFRCC with high tensile strain-hardening capacity enhances the structure's energy dissipation and deformation capacity. Also, HPFRCC overlay was efficiently bridging the existing cracks in the distressed concrete bridge deck. A pilot-scale test was carried out to obtain the performance of beams made with conventional reinforcing bars and UHPC as a tensile reinforcing component (Bruhwiler and Denarie 2008). The beam composed with UHPC by replacing the conventional reinforcing steel results in enhanced load carrying capacity comparatively along with improved stiffness up to the maximum tensile force. After that, a distinct tensile softening behaviour is observed in the concrete flexural member with UHPC.

A strip or overlay made of a new cementitious composite material reinforced with micro fibers was developed (CARDIFRC) which was bonded over the tension zone of RC beams to improve the load carrying capacity (Alaee and Karihaloo 2003a, b). From the experimental study, it was observed that the parent and retrofit CARDIFRC strips performed together monolithically till fracture. It was also observed that the ultimate force of retrofitted beam was almost greater than that of the control RC beams. However, retrofitted beam exhibited additional strain softening behaviour after the ultimate load of the beam. Also, various strengthening schemes were used as shown in Fig. 13 to enhance the flexural and shear strength of distressed RC beams. Therefore, it was concluded that the CARDIFRC strip could effectively strengthen the RC beams by means of retrofitting and rehabilitation (Alaee and Karihaloo 2003a, b, Farhat *et al*. 2007).

Researchers reported that 30 mm thick UHPC overlay was used for the strengthening of short span road bridge. It was verified that the protection of UHPC overlay over the parent material by the air permeability test. The test results confirm that UHPC layer was nearly 30 times permeable than the parent concrete (Bruhwiler and Denarie 2008). But the cost-benefit analysis of rehabilitation with UHPC showed that on the average process is 12% more expensive than the normal but its traits of quicker installation, minor maintenance, more extended durability and lesser traffic

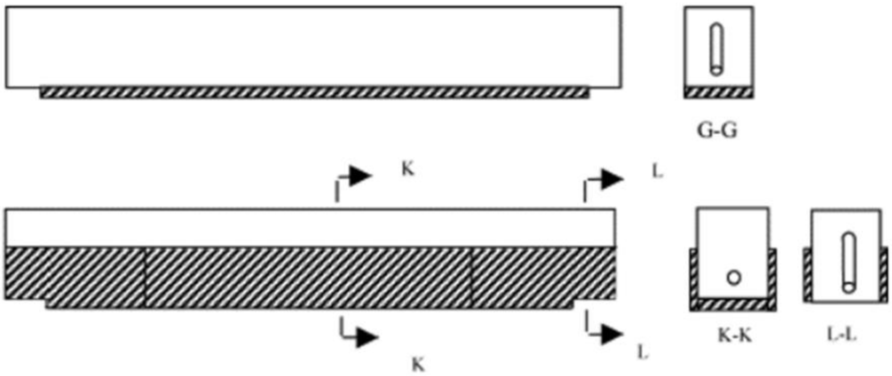

Fig. 13 Strengthening scheme of UHPC strip (Farhat *et al*. 2007)

disruption during installation somehow makes it up for the slight increase in the initial costs. Recently, a novel thin overlay or strips of UHPC is applied to RC beams to improve the behaviour in terms of ultimate strength, stiffness, and ductility (Xu *et al*. 2012, Prem *et al*. 2014, Benyahia and Ghrici 2018). It was observed that the retrofitted beams exhibited good bond behaviour between the parent and repair concrete. The attachment of thin overlay enhanced the flexural strength of damaged RC beams by about 30%. Similarly, strengthening studies were carried on RC beams by varying the UHPC overlay thickness of 10, 15 and 20 mm to predict the flexural behaviour of strengthened RC beams (Prem and Murthy 2016). The original flexural capacity of the RC beams is restored with the application of 10 mm UHPC strip. The flexural capacity is enhanced by about 24 and 35% for the UHPC overlay thickness 15 and 20 mm, respectively.

The pre-damaged RC beams were strengthened with ultra-high strength cementitious composite (UHSCC) overlay (Upreti *et al*. 2016). It was observed that there is a little reduction in deflection ductility of the strengthened beam. Moreover, it was observed that the enhancement in the ultimate capacity of strengthen beam with respect to the externally bonded UHSCC. The damage level of RC beams is taken as a parameter to study the strengthening behaviour with a thin UHPC strip (Murthy *et al*. 2018a). The composite behaviour of damaged RC beams and the strengthening material ensured that there is no debonding or delamination failure. The UHPC overlay of 10 mm thickness is found to be sufficient for rehabilitation to restore its original strength before preloading and strengthening. It was observed from the load-displacement results for all strengthened RC beams which show enhanced stiffness than the control RC beams.

Also, UHPC possessing similar principle for applying the repair material in the form of overlays or strips to be implemented in this work for better performance of RC beams under fatigue loading. The fatigue damaged RC beams can be effectively strengthened with the application of thin precast ultra-high performance fibre reinforced concrete (UHPFRC) overlay at the tension face of damaged RC beams (Murthy *et al*. 2018b, c). It was observed from the fatigue studies that the number of cycles to failure of the retrofitted RC beams was significantly more than that of the control beams. It was concluded that the UHPFRC is a promising candidate for strengthening of RC flexural elements that are damaged by fatigue. It was concluded that the concept of strengthening RC beams using UHPC can deliver durable solution which avoid multiple strengthening practices thorough out the life span of the structure. Therefore, strengthening and rehabilitation by UHPFRC are useful, especially for the members such as bridge girders, airport pavements, and machine foundations, which are subjected to repeated loads during their service lifetime.

4. Relative comparison over the existing strengthening techniques

The various techniques or methods developed for strengthening and rehabilitation of RC beams have been studied intensively. The strengthening RC beams were initially carried out by attaching steel plates at the tension phase of the beam with chemical epoxy adhesives. The application of chemical epoxy could enhance the composite behaviour between damaged RC beams and bonded steel plate. The external steel plate bonding technique enhanced the strength and stiffness of the rehabilitated RC beams significantly. But, the application of an external steel plate leads to abrupt brittle failure of concrete specifically due to the debonding of steel plate. Also, the corrosion of externally bonded steel affects the adhesive steel interface which reduces the bonding strength. To overcome the debonding failure, bolted anchorage systems, use of angle sections bonded with RC beams were developed. However, some of the drawbacks associated with the bolt anchorage systems on steel plate bonding are a temporary weakening of the beam due to the drilling of the bolt holes and the position of bolts within the main bars. Also, other drawbacks associated with the bolt anchorage systems are corrosion of the external plate on the bolt-plate interface, time, and labour costs associated with drilling the numerous bolt holes and aesthetic appearance of bolts and plates.

Even though there is an enormous enhancement of performance of strengthened RC beams using the concrete jacketing or section enlargement technique, weight to strength ratio is relatively low and degraded serviceability condition due to its larger dimension. To eradicate the corrosion problem associated with the bonded steel plate technique, an alternate corrosion free material which is

Table 1 Brief highlights of studies with respect to various strengthening schemes

S. No.	Author(s)	Technique Adopted	Mode of Failure	Increase in Strength (%)	Materials and Technical Parameters	Remarks and Highlights
1.1	Jones *et al*. (1982)	Steel plate bonding (Mild steel plate)	Plate separation	44 - 100 (Flexure)	→Parent concrete f_{ck} =63 MPa →Strengthening material thickness: 1.5, 3, 5, and 10 mm.	→Steel plate and concrete is monolithically behaved till yielding.
1.2	Subedi *et al*. (1998)	External steel plate with bolts and sockets	Crushing of concrete, plate buckles near the edge of loading	85 - 162 (Flexure) & 81 - 200 (Shear)	→Parent concrete f_{ck} = 60 MPa →Plate thickness: 2,4, and 6 mm →Beam with plate and bolt of 16 mm dia. (at selected location)	→Strengthened concrete beams showed better performance in terms of flexure as well as shear
1.3	Adhikary *et al*. (2000)	Bonding steel plate on web of the beam with epoxy adhesive	Plate debonding prior to concrete failure	25 - 150 (Shear)	→Parent concrete f_{ck} = 27.2 - 31.7 MPa →Plate thickness: 2.3 mm →Plate depth: 50 - 150 mm →Epoxy thickness: 2 mm	→Ultimate shear strength of a beam increased with respect to plate depth and thickness across the beam section
2.1	Diab *et al*. (1998)	Section enlargement by sprayed concrete	Flexural mode of failure	145 - 281 (Flexure)	→Parent concrete f_{ck} = 40 MPa →Scheme of concrete jacketing: Concrete cast, concrete cast with fibrous layer, additional bars + sprayed concrete, additional bars + sprayed fibrous concrete	→The strengthening with additional bars and sprayed fibrous concrete found to be an efficient technique
2.2	Altun (2004)	Concrete Jacketing	Concrete crushing at compression	742 - 966 (Flexure)	→Parent concrete f_{ck} = 20 MPa →Roughening of concrete: 4 - 6 mm	→The load displacement behavior of jacketed RC beams is similar to normal RC beams but with enhanced flexural capacity
2.3	Chalioris *et al*. (2014)	Thin Self-Compacting Concrete (SCC) Jacketing	Flexural and Shear mode of Failure	77 - 198 (Flexure)	→Parent concrete f_{ck} = 23.4 - 28.2 MPa →New SCC layer f_{ck} = 39.8 - 43.9 MPa →SCC layer thickness of 25 mm with main rod (5 mm) of various configuration tied with U-formed stirrup rod of 5mm and dowel bars	→Thin reinforced SCC jacket with reinforcement showed better performance than the conventional heavy concrete jacketing system
3.1	Saadatmanesh *et al*. (1990)	GFRP plate using rubber-toughened epoxy adhesive	Separation of plate, and delamination of concrete layer	110 (Flexure)	→Parent concrete f_{ck} = 36.4 MPa →Plate thickness: 6 mm →Four types of two component epoxy thickness: 1.8 mm	→Selection of suitable epoxy is very important →Flexural strength and stiffness has been improved significantly with the use of GFRP
3.2	Chajes *et al*. (1994)	Aramid, E-glass and Graphite fabrics	Tensile failure of fabrics and Compression concrete crushing	36 - 57 (Flexure)	→Parent concrete f_{ck} = 37.8 MPa →Layer of FRP fabrics: •Aramid: 1 layer •E-glass: 3 layer •Graphite: 2 layer	→Beam strengthened with aramid fabric exhibits better ultimate strain capacity
3.3	Sheikh (2002)	CFRP and GFRP fabrics	Rupture of fabrics	150 (Flexure)	→Parent concrete f_{ck} = 44.7 and 45.7 MPa →CFRP fabric thickness: 1.25 mm →GFRP fabric thickness = 1.00 mm	→Wrapping of RC beams with CFRP alters the brittle shear failure into ductile flexural failure
3.4	Yang *et al*. (2009)	Prestressed CFRP plate	CFRP debonding and rupture	45 - 153 (Flexure)	→Parent concrete f_{ck} = 18 MPa →Three-layer component with a bi-irectional CFRP sandwiched between vo unidirectional CFRP plates is used ›CFRP prestress levels: 0, 20, 40 and 0% of the ultimate tensile strength of CFRP plates	→After debonding, the behaviour of the bonded CFRP-plated beams changed to that of unbonded CFRP-plated beams due to the effect of the anchorage system which again took part in strengthening the beams.
3.5	Khalifa (2016)	NSM CFRP strips	Peeling off and debonding of CFRP strip	54 - 125 (Flexure)	→Parent concrete f_{ck} = 35 MPa →CFRP strip thickness = 1.2 mm →Strengthening scheme NSM CFRP strips: •2 NSM CFRP strip in 1 groove •1 NSM CFRP strip in 2 grooves •2 NSM CFRP strip in 2 grooves •Externally bonded CFRP strips	→The strengthened RC beams with NSM CFRP strips exhibited better flexural resistance than the conventional externally bonded CFRP strips for the same amount of CFRP materials ranged from 12% to 18%
4.1	Harajli (1993)	External prestressing tendons	Flexural mode of failure especially at constant moment region	146 (Flexure)	→Parent concrete f_{ck} = 26 - 39 MPa ›Seven wire strand dia.: 9.5, 8, 7, and 5 mm →Profile of prestressing: Straight horizontal tendon profile and single-point draped tendon profile with a deviator (saddle) at midspan.	→Deviated profile of external prestress increased the flexural resistance compared to the straight horizontal profile →Significant increase in flex ural strength without signific ant reduction in ductility or deformation of the member.

Table 1 Continued

S. No.	Author(s)	Technique Adopted	Mode of Failure	Increase in Strength (%)	Materials and Technical Parameters	Remarks and Highlights
4.2	Shin *et al.* (2007)	External unbonded high strength bars	Compression concrete crushing and strip failure of bars	42 - 112 (Flexure)	→Parent concrete f_{ck} = 31.2 MPa →Diameter of bars: 18, 22, and 28 mm →Bar arrangement: V shape (2 bars/1 deviator) and U shape (3 bars/2 deviators)	→U shape is more effective in enhancing strength comparatively
4.3	Vasudevan and Kothandaraman (2014)	Embedded external reinforcement at soffit of beam	Anchorage failure	140 (Flexure)	→Parent concrete fck = 33.4 - 49.2 MPa →Diameter of bars: 18, 22, and 28 mm →External bars are embedded in the holes of diameter equal to the bar plus 2 mm and a depth of 150 mm at the soffit of the RC beam	→Strength enhancement of embedded external reinforcement technique could be due to Increased effective depth of the RC beam Hybrid of flexure and tied-arch action Frictional grip between the external bars and the soffit.
5.1	Alaee and Karihaloo (2003a, 2003b)	High-performance fiber-reinforced concrete (CARDIFRC)	Flexural failure	9 - 102 (Flexure)	→Parent concrete f_{ck} = 45 and 47 MPa →Parent concrete f_{ct} = 4 and 3.5 MPa New concrete f_{ck} = 207 and 185 MPa →New concrete f_{ct} = 24 and 25 MPa →Strengthening scheme: (Strip thickness:16 and 20 mm) •Strip on tension side •Strip on tension side + 2 side strips •Strip on tension side + 4 rectangular side strips •Strip on tension side + 4 trapezoidal side strips Adhesive thickness: 3 mm	→CARDIFRC strip bonding method was significantly improved the flexural and shear capacity of RC beams and also maintaining the serviceability conditions of damaged RC beams.
5.2	Prem *et al.* (2014, 2016)	UHPC overlay	Flexural failure and concrete crushing at compression zone	10 - 35 (Flexure)	→Parent concrete f_{ck} = 30 MPa →New concrete f_{ck} = 196 MPa →New concrete f_{ck} = 170.29 MPa →New concrete f_{ct} = 22.6 MPa →Strengthening by 20mm thick overlay on the tension face of the RC beams →Curing methods of UHPC: Water, steam and hot air oven curing →Preloading: 80 and 90% of ultimate load	→Composite retrofitted beams acted monolithically under bending. →Integrity was observed between the UHPC and the retrofitted RC beams →10 mm thin overlay found to be sufficient to restore the damage developed in preloading.

globally used in the practice for the past two decades is fiber reinforced polymer. Fiber reinforced polymer (FRP) with huge varieties exhibit the various range of mechanical properties. FRP technique has been accessed with various forms in the structural element as bonding plates/sheets/ or laminates, FRP wrapping, Prestressed FRP, near surface mounted FRP strips, etc. Overall, FRP is a potential candidate for enhancing flexural capacity and ductility of strengthened RC beams. The most advantage of FRP strengthening technique is that the higher strength to weight ratio of the FRP. However, the FRP strengthened beams exhibit predominantly debonding or delamination mode of failure due to the mismatch in the properties such as the tensile strength of the substrate and repair material. Other techniques like external reinforcement and external prestressing tendons with deviators and end yokes are effectively used for strengthening of RC beams. However, a drawback associated with the provided external reinforcements is irrespective deflection behaviours of the strengthened RC beams. Strengthening by means of using UHPC strips or overlay is a relatively suitable material for strengthening RC beams unlike bonded steel plates and FRP, which was compatible and durable with respect to the parent RC beams. UHPC exhibits tensile strength, stiffness and thermal expansion coefficient which were comparable with respect to the parent structural element. However, some of the drawbacks associated with the UHPC technique are higher cement content which could cause shrinkage issues, required complex curing procedures and huge cement content indirectly generating larger CO_2 at the cement production process. Table 1 presents the brief highlights of existing studies with respect to various strengthening schemes.

5. Conclusions

The structural behaviour and extensive performance of strengthening by externally bonded steel plates, concrete jacketing, fibre reinforced plastic laminates or sheets, external prestressing/external bar reinforcement technique and UHPC overlay or strip have been extensively reviewed. It’s a cumbersome process to choose the best strengthening technique which is effectively suitable for the distressed RC beams. The necessities of construction sector over the different strengthening techniques relied on various factors such as locally available materials, overall cost, skilled manpower, ensure adequate load carrying capacity and serviceability after strengthening, and failure behaviours of strengthening techniques. Ensuring the above requirements, a relative comparison and detailed review have been carried out from the intensive experimental investigation and practical applications over the past four decades. Some of the limitations of the existing strengthening techniques of RC beams which are listed above suffer from either one or more limitations given below:

- Steel plate bonding and concrete jacketing are possessing low strength to weight ratio
- FRP is significantly mismatching in the properties such as tensile strength of the substrate and repair material and also the overall cost for strengthening using FRP is relatively high
- Steel plate bonding, external reinforcement and concrete jacking are prone to corrosion and other environmental hazards.
- Debonding of the repair material is a primary problem in steel plate bonding and FRP sheets/laminates which could lead to an undesirable brittle mode of failure.
- The drawback associated with the UHPC is higher cement content which could cause shrinkage and larger CO_2 emission at the cement production process, which leads to more greenhouse gas generation.

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