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RETROFITTING OF STRUCTURAL ELEMENTS: A REVIEW

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ABSTRACT

The awareness of the strengthening of structures came into being in the minds of engineers and scientists during the 1960s. The strengthening technique was essentially originated and developed keeping the bridge structures in mind. This technique was particularly a dire need for bridges because alternate solutions may affect the traffic conditions very seriously for a prolonged or unacceptable span of time. Different methods of structural strengthening/retrofitting techniques have been developed over the years such as external bonding of steel plates, glass fibre-reinforced plastic (GFRP), fibre-reinforced polymer (FRP) sheets, external prestressing, carbon fibre wrapping, external bar reinforcement, and very recently improved external (bars) reinforcement techniques. The objective of this paper is to critically review the strengthening techniques developed so far with reference to the effect of each technique and their salient features in enhancing the strength of RC beam elements. However, it is hoped that the review on the use of different techniques for retrofitting of RC beams presented in this paper will widen the horizon to retrofitting technology as a cost-effective and easy-to-execute method.

Keywords: Retrofitting, Rehabilitation, Repair, Flexural Strength, FRP, Composite Materials, Steel, Shear Strength, Plate Bonding, Prestressing.

INTRODUCTION

The awareness of strengthening of structures came into being in the minds of engineers and scientists during the 1960The strengthening technique essentially originated and developed keeping the bridge structures in mind. This technique was particularly a dire need for bridges because alternate solutions may affect the traffic conditions very seriously for a prolonged or unacceptable span of time. Different methods of structural strengthening/retrofitting techniques have been developed over the years such as external bonding of steel plates, fibre-reinforced plastic (GFRP), fibre-reinforced polymer (FRP) sheets, external prestressing, carbon fibre wrapping, external bar reinforcement, and very recently improved external (bars) reinforcement techniques. The objective of this paper is to critically review the strengthening techniques developed so far with reference to the effect of each technique and their salient features in enhancing the strength of RC beam elements. However, it is hoped that the review on the use of different techniques for retrofitting RC beams presented in this paper will widen the horizon to retrofitting technology cost-effective and easy-to-execute method.

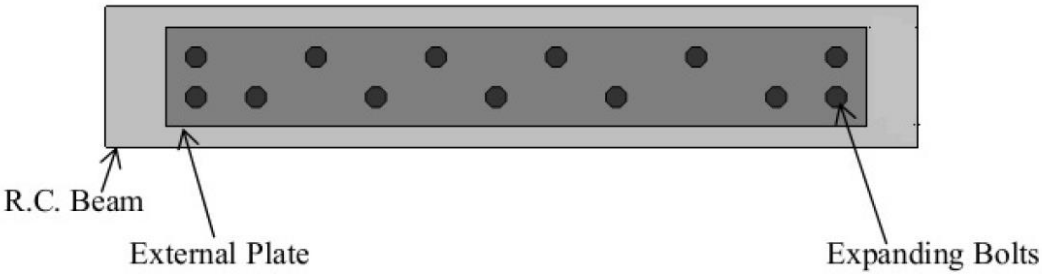
STRENGTHENING BY STEEL PLATE BONDING

Regarding the technique and materials for strengthening structural elements, engineers and scientists had initially tried attaching steel plates to the tension zone of the elements. L'Hermite and Bresson (1967) reported a pioneering work of epoxy-bonded steel plates for strengthening RC elements. Swamy et al (1982) studied the behaviour of distressed RC beams by bonding steel plates. They concluded that epoxy resin adhesives ensured full composite action between the distressed RC beams and steel plates. The stiffness and strength of the plated distressed RC beams were higher than that of the original beams. Davis and Powell (1984) reported that the strengthening of the Rotherham bridge was carried out by bonding steel plates. The load-carrying capacity of the bridge was enhanced from 100t to an extraordinary level of 465t. The main problem encountered with this technique was the debonding of steel plates. Debonding of steel plates will lead to brittle failure indicating high interfacial shear or normal stresses caused by the transfer of the tensile stresses from bonded steel plate to the RC beam (Arslan et al, 2006). Much early research (Jones et al, 1988; Oehlers, 1992; Hussain et al, 1995) findings have already encountered this problem. The corrosion at the adhesive steel interfaces which affects the bond strength was found to be another disadvantage of this technique. In order to determine the interfacial shear stress, several closed-form analytical solutions were proposed by many authors (Raoof et al, 2000; Adhikary et al, 2000, Ye, 2001; Smith et al, 2001; Teng et al, 2002).

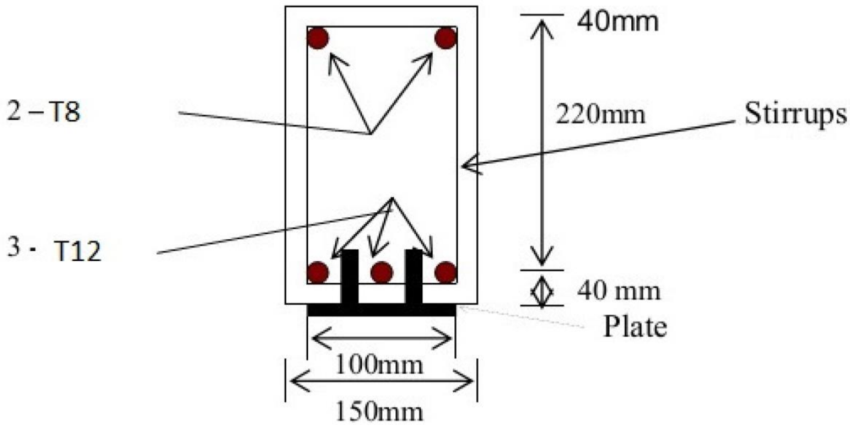
In order to overcome the debonding problem researchers had tried with bolting the plate with beams. This includes bolted anchorage systems, bonded angle section to improve the anchorage of reinforcing plate to the sides of beam and trapping the plate under the beam supports. Hussain et al (1995) studied the effect of end anchorage on tested reinforced concrete beams. They used bolts at the ends of the bonded plates to provide additional anchorage and reported an improvement in the performance. Adhikary and Mutsuyoshi (2002) examined the effect of end anchoring bolt on steel plated beams. It was found that the provision of anchors at the plate ends did not change the failure modes of the beams, but it delayed the failure in debonding mode significantly. The studies carried out to investigate the flexural and shear behaviour of coupling beams (Su and Zhu, 2005) and the behaviour of connecting bolt groups (Su and Siu, 2007; Siu and Su, 2009) witnessed that these anchoring techniques could enhance the flexural strength and maintain sufficient ductility. Jumaat and Alam (2008) reported that the use of L shaped and intermediate anchorages at the end of the strengthened beams prevented premature failure. Su et al (2010) used two structural performance criteria such as post-elastic strength enhancement and displacement ductility. They reported that these two criteria have greatly influenced by the strength of the bolts and plates used. They also emphasized that the `Strong bolt weak plate' arrangement lead to a design in which sufficient strength enhancement and ductility could be achieved. Goldar et al (2012) studied the effect of steel plates attached to the bottom and side faces of RC beam using bolts. Fig. 1 shows the bolting arrangement for the bottom plate. The diagram furnished by them did not reveal the presence of side plates. They reported that flexural strength had been enhanced considerably.

Shear strengthening

When the load-carrying capacity of a beam element is enhanced by suitable flexure retrofitting technique



(a) Bottom plan showing plate anchor



(b) Section showing plate anchor

Fig. 1: Bolting arrangement for the bottom plate (Source: Goldar et al, 2012)

then the beam may face a shear deficiency problem. Obviously, the flexural retrofitting technique must be supplemented with shear-enhancing methods to safely and effectively handle the retrofitting problems. Many early studies appeared in the late 1990s (Sharif et al, 1995; Swamy et al, 1996; Subedi and Baglin, 1998) reported that the use of steel plates to increase the shear strength of an RC beam was found to be effective. Barnes et al (2001) investigated the shear strengthening of RC beams by attaching steel plates adopting two methods namely adhesive bonding and bolting. They found that a large increase in the shear capacity was experienced while plates were fixed to the sides of a beam. Adhikary and Mutsuyoshi (2006) focused on an experimental investigation on strengthening of an RC rigid frame against possible shear failure using different techniques such as steel brackets, steel plates, vertical strips and externally anchored stirrups. All these techniques were found to be effective in enhancing the shear strength of beams. However, the externally anchored stirrups were found to be the most effective in which the beam strengthening failed at a load almost 117% higher than that of the control beam.

STRENGTHENING BY PLATE BONDING USING FRP

Strengthening of RC beams using steel plates leads to the danger of corrosion at the epoxy-steel interface, which adversely affects the bond strength, this is one of the major shortcomings of this method besides difficulty in handling plates, deterioration of bond at the steel-concrete interface, and the need for massive scaffolding or heavy lifting equipment during installation. To eliminate these problems, the use of corrosion-free composite materials was tried by engineers and researchers. The term composite refers to any combination of two or more separate materials. FRP sheets made of carbon (CFRP), glass (GFRP) or aramid (AFRP) fibres bonded with a polymer matrix such as epoxy, polyester, or vinylester are widely used as a substitute for steel. FRP comes in a variety of forms such as plates, sheets, shells and tapes. Out of them, Plates are the most common form of FRP composite used in structural applications due to their superior material properties viz. corrosion and weather resistance, high mechanical strength and low weight, ease of handling, good fatigue resistance, and versatility of size, shape or quality (Bakis et al 2002; Quattlebaum et al, 2003; and Ede, 2008). Fig. 2 illustrates the stress-strain relationship between different FRP composites and steel.

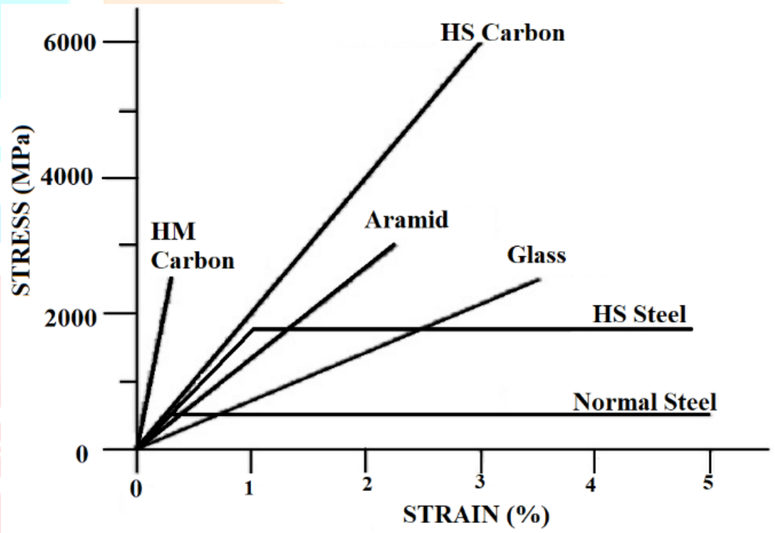


Fig. 2: Stress-Strain in different FRP composites and steel (Source: Nanni, 1996)

Many years ago, Fibre reinforced polymer (FRP) composites were introduced in the fields of aerospace and automotive industries in Germany and Switzerland. The use of FRP composites in the field of civil engineering structures took place during the late 80s. The first pioneering work for a bridge repair using FRP was reported by Meier (1987). Since then many researchers had explored in detail the use of advanced composites to strengthen RC structures. Research efforts made by Ritchie (1988), Saadatmanesh and Ehsani (1990), Saadatmanesh and Ehsani (1990a), An et al (1991), Meier and Kaiser (1991), Ritchie et al (1991), Triantafillou and Deskovic (1991), Rostasy et al (1992), Karam (1992), Triantafillou (1992), and Ross et al., (1994) revealed promising applications of composite materials. A variety of civil engineering structures including the bonding of FRP composite plates to reinforced concrete and prestressed concrete beams to improve flexural stiffness and strength have been reported. However, the predominant problem encountered in this technique was the delamination of the FRP.

Ritchie (1988) upgraded RC beams using glass and carbon FRP composites and found that increase in stiffness ranged from 18^{th} to 116 per cent while the increase in the ultimate flexural capacity ranged from 47 to 97 per cent. The authors emphasized that the failure did not occur by flexure in the maximum moment region on many beams but rather by debonding at the plate ends. Saadatmanesh and Ehsani (1990) reported the results of strengthening of RC beams with GFRP plates using different epoxies which had a wide range of strength and ductility. The authors indicated that the most ductile epoxy did not enhance the ultimate capacity of the beam as it was too flexible to allow any shear transfer between the concrete and GFRP plate. However, the increase in ultimate flexural capacity of the beam by 30 and 11per cent was experienced. Meier and Kaiser (1991) attempted to strengthen the beams with a 1.0 mm thick CFRP laminate. It was noticed that the increase in ultimate flexural capacity was only 22 per cent and a sudden laminate peel-off was due to the development of shear cracks in the concrete. Ghaleb (1992) tried to increase the flexural strength of damaged RC beams with externally bonded fibreglass plates. He reported that the ultimate flexural capacity of the increased by 60 per cent. The results of a few more studies appeared in 1992 (Meier et al.; Raghavachary; Rostasy et al; and Triantafillou & Plevris) proved that the use of FRP significantly increased the strength of the beams as well as the quantity of the material used was very less in compassion with steel (e.g. 6.2 kg CFRP used in lieu of a 175 kg steel plate).

Chajes et al (1994) tested a series of reinforced concrete beams in four-point bending to determine the ability of externally bonded composite fabrics to improve the beams' flexural capacity. The fabrics used were made of aramid, E-glass and graphite fibres and were bonded to the beams using a two-part epoxy. The result showed that the external composite fabric reinforcement led to 36 to 57% increase in flexural capacity and 45 to 53% increase in flexural stiffness of RC beam elements. For the beams reinforced with E-glass and graphite fibre fabrics, failures were by fabric tensile failure in the maximum moment region. The beams reinforced with aramid fabric failed due to the crushing of the compression concrete. Moreover, the bond between the fabric and concrete, combined with the additional end anchorage ensured monolithic action between concrete and fiber. Varastehpour and Hamelin (1997) revealed that the use of FRP plates for retrofitting of concrete structures was attractive as an increase in rigidity and strength due to easy fixing and quick polymerization process *in situ*. Duthinh and Starnes (2001) found that the application of carbon FRP laminates was very effective for the flexural strengthening of reinforced concrete beams, provided proper anchorage of the laminate is ensured. It is reported that in one case, the strengthened beam was 3.33 times stronger than the unrepaired beam. As the amount of steel reinforcement increased, the additional strength provided by the carbon FRP external reinforcement decreased. When the percentage of steel was 11% of that required for a balanced section the strength was increased to twice the moment carrying capacity while this has been reduced by 15% when the steel area increased to 46%.

Sheikh (2002) indicated that the flexural strength of the damaged slabs, shear resistance of the damaged beams and seismic resistance of the columns could be improved. Both carbon and glass composites provided significant enhancement (approximately 150%) in flexural strength. Dave and Trambadia (2004) studied the behavior of prestressed concrete beams using GFRP wrapping. It was found that the experimentally observed failure loads were higher than the capacity of the beam evaluated theoretically. The percentages of failure load in the case of all the wrapped PSC beams increased in failure load for PSCWFC and PSCW beams were 17.24%, 16.67%, 15.78% and 25%, and 20.68%, 30%, 39.47% and 40.91% respectively compared to unwrapped PSC beams for different span loadings. It was apparently shown that the load-carrying capacity of the beam increased as the loading span increased.

Esfahani et al (2007) investigated the flexural behaviour of reinforced concrete beams strengthened using Carbon Fibre Reinforced Polymer (CFRP) sheets. The result showed that the flexural strength and stiffness of the strengthened beams increased compared to the control specimens. Kim *et al*. (2008) investigated the flexural behavior of fiber-reinforced cementitious composites (FRCC) with four different types of fibers and two volume fraction contents (0.4% and 1.2%) within identical mortar matrix (56 MPa compressive strength). The four fibers are high-strength steel twisted (T-), high-strength steel hooked (H-), high molecular weight polyethylene spectra (SP-), and PVA fibers. It was observed that all test series showed deflection-hardening behavior except specimens with 0.4% PVA-fibers, and very different performance levels were noted in terms of load carrying capacity, energy absorption, and cracking behavior, as a function of fiber type and volume content. It was also found that deflection-hardening FRCC behavior can be obtained for low volume fractions (0.4%) of T-, SP-, and H-fibers; and T-fiber specimens showed the highest load carrying capacity or MOR at 1.2% fiber volume contents, that is, 13.08 MPa.

Mukherjee and Rai (2009) reported that the ultimate load increased by more than 100%. The cracking was distributed all over the beam resulting in considerable post-yield deformation of the beam. An oft-found argument against FRC repairs was the apprehension of loss of ductility. Yang et al (2009) reported a study on the flexural performance of reinforced concrete members strengthened using CFRP plates, employing different FRP bonding and prestressing methods. The flexural test results showed the ultimate load of the beams strengthened with CFRP was reasonably constant. The ductility of the beams strengthened with CFRP plates having the anchorage system was considered high if the ductility index was above 3.

Lamanna et al (2012) tried to strengthen reinforced concrete T beams by attaching FRP strips with mechanical fasteners. The fastening procedure required no surface preparation. They found that the beam strengthened with one strip showed an increase of 8% in yield moment and 14.4 % at the moment at a mid-span deflection of 63.5 mm. whereas the beam strengthened with two strips showed an increase of 11.7 % in yield moment and an increase of 27.2 % in the ultimate moment respectively.

PRESTRESSING WITH FRP

Saadatmanesh and Ehsani (1991) felt that FRP can also be used to prestress RCC girders as FRP materials had high tensile strength and fatigue strength. They suggested that the tensioning of FRP may be achieved by casting the RCC elements with pre-cambering provided using jacks. Then FRP laminates are glued on both the positive and negative moment regions. Upon curing the temporary jacks will be released, the member allowed to straighten and prestressing takes place. Garden *et al.* (1998) conducted a study on the strengthening and deformation behaviour of reinforced concrete beams upgraded using prestressed composite plates. They found that the load ductilities of the prestressed beams fell with increasing plate prestress.

Shear Strengthening

Many studies on the shear strengthening of RC beams by bonding FRP composites appeared during the early 1990s (Uji 1992; Al-Sulaimani et al. 1994; Arduini et al. 1994; Chajes et al. 1995; Alexander 1996; Sato et al. 1996, 1997a; Araki et al. 1997; Funakawa et al. 1997; Triantafillou 1997, 1998a,b; Chaallal et al. 1998; Malek and Saadatmanesh 1998; Mitsui et al. 1998; Fanning and Kelly 1999; Hutchinson and Rizkalla 1999; Kachlakev and Barnes 1999; Khalifa et al. 1999; Mutsuyoshi et al. 1999; Khalifa and Nanni 2000) established clearly that such strengthened beams fail in shear mainly in one of the two modes: tensile rupture of the FRP and debonding of the FRP. Chen and Teng (2003) reported that the composites are generally capable of increasing the ductility and ultimate load resistance but are prone to peeling and delamination under shear stresses, and debonding under cyclic loading. The study is the realization of the fact that the stress distribution in the FRP along the shear crack is non-uniform at shear rupture failure, as a result of the non-uniform strain distribution in the FRP and the linear elastic brittle behavior of FRP, and the explicit account taken of this stress non-uniformity in the new strength model. This non-uniform stress distribution contrasts with the uniform stress distribution generally assumed for internal steel reinforcement which is a ductile material capable of stress redistribution after yielding, and provides a satisfactory explanation of the well-established phenomenon that the FRP contribution to the shear capacity is less than its full strength. The results of the study carried out by Diagana (2003) indicate that the strengthening technique with external bonded CFF strips could be used to significantly increase the shear capacity of the RC beams with shear deficiencies.

Sundarraja and Rajamohan (2009) reported that the use of GFRP strips is more effective in the case of strengthening structures in shear. The ultimate strength of beams could be increased by the use of GFRP inclined strips. The ultimate loads of beams retrofitted with U-wrapping were greater than the beams retrofitted by bonding the GFRP strips on the sides alone. Restoring or upgrading the shear strength of beams using FRP inclined strips could result in increased shear strength and stiffness with a substantial reduction in the shear cracking.

STRENGTHENING BY EXTERNAL REINFORCEMENT

Distressed RC beams with exposed reinforcement prompted the researchers to repair or retrofit RC elements with external reinforcement (Cairns and Zhao, 1993). Cairns and Watson (1993) argued that exposure of reinforcement may even increase strength of a beam deficient in shear. Unbonded reinforcement has got many advantages such as, the speed and simplicity of installation, simple operation, and minimal disruption during installation. (Cairns and Rafeeqi, 2002; Cairns and Rafeeqi, 2003).

Cairns and Rafeeqi (1997) introduced a new technique of external reinforcement to strengthen RC beams. They introduced two rods one at each side face of the beam kept at the level of embedded rods. The rods were secured at the ends using 'end- yokes'. Further, they introduced deviators/deflectors at the intermediate level so that the external rods could deflect along with the beam. They have conducted extensive studies both on the experimental and theoretical behavior of RC beams with external rods. Their essential conclusions include that up to 65% of the ultimate load both the reference and retrofitted beams behaved identically. However, at the ultimate load level, the deflections were reduced by 10 – 20% and the flexural strength was increased by 85%.

Shin *et al*. (2007) studied the flexural behavior of RC beams strengthened with external unbonded high-strength tension bars connected using anchoring pins or anchoring plates at the end of the beam. Deviators were used to make the external bars to follow the curvature of the tested beam. The strengthening system consisted of rods of diameters 18, 22 and 28 mm with two types of arrangements: a V-shape consisting of two bars with one deviator, and a U-shape consisting of three bars and two deviators type. Anchoring of high-tension bars was done by two methods: the penetrated pin type like a yoke, in which the pin penetrates in to a hole of concrete beam located 400 mm from the end of the specimen and 130 mm from the compressive fibre then high-tension bars are inserted into the holes of the pin and then fixed with nuts; and a penetrated rod type in which a steel plate is fixed at the anchoring spot with four anchors and is connected with bars. The result showed that the use of high-tension bars contributed less to increasing the stiffness before cracking but was very much effective in increasing the strength, that is yield strength increased by 37-81% and maximum strength increased by 42-112%, in comparison with an unstrengthened beam. Specimens with V-shaped high-tension bars showed remarkable increases in stiffness and strength compared to un-strengthened specimens. The V shape was not, however, as effective as the U shape. V-shaped bars showed 0.97-1.47 times increase in stiffness compared to 1.07-1.20 times increase in strength for U-shaped bars.

Khalil et al. (2008) studied the effect of variation in number of deflectors and external bar to internal bar ratio. It was observed that when the area of the external bar was increased from 100% to 178%. The gain in ultimate strength increased but with a smaller rate from 28% to 47%. Increasing the number of deflectors from one to three enhanced the ultimate strength of the beam by 9% and 24%. Minelli *et. al*. (2009) studied the effect of different percentages of external reinforcement on the collapse mechanism. The result showed that the external unbonded reinforcement alters the pattern of strain in a beam, and changes structural action from purely flexural to that of a flexure/tied arch hybrid. The compressive stresses related to the arch action enhanced the shear strength of the existing beam.

Kothandaraman and Vasudevan (2010) devised a new technique to retrofit RC beams with non-prestressed external reinforcing bars anchored at the soffit. This method is different from the earlier methods in eliminating the shortcomings of placing the external reinforcement bars by the sides of the beams such as the need for deflectors, mechanical anchoring devices and strengthening of the yoke/end zones. The results indicated that the retrofitted beams with 0.90% embedded and 0.60% external reinforcement exhibited a failure moment, which was 80% more than that of the reference beams. The moment carrying capacity in the case of under-reinforced sections could be enhanced as high as 70%. This is the major advantage and improvement made over the technique.

SUMMARY

This review has explored various methods and techniques developed for retrofitting of RC beam elements. Strengthening technique was originally developed for bridge structures. Engineers and scientists had initially tried by bonding steel plates at the tension zone of the RC beams. The use of epoxy resin adhesives ensured full composite action between the distressed RC beams and steel plates. The stiffness and strength of the plated RC beams could be enhanced through this technique. However, the problem encountered with this technique was the debonding of steel plates that lead to brittle failure of beams. Secondly, corrosion at the adhesive steel interfaces affected the bond strength. In order to control debonding problem the researchers had tried with bolting the plate with beams. This included bolted anchorage systems, bonded angle sections to improve the anchorage of reinforcing plate to the sides of the beam and trapping the plate under the beam supports. It was found that by anchoring the plates by bolting could enhance the flexural strength and maintain sufficient ductility. By this technique, the moment carrying capacity could be enhanced up to about 165% (Table 1). However, the steel corrosion problem could not be brought to control.

To alleviate the corrosion problem, corrosion-free composite material, that is FRP was tried by the engineers and researchers. There are varieties of fibres with different mechanical properties. For example, the tensile strength of glass fibre is around 4750 MPa, whereas carbon fibre has around 6750 MPa. Depending upon the financial and strength requirement, materials and methods could be prudently selected. Over and above, the use of FRP has another technique to strengthen structural elements. Wrapping is the technique through which the ductility of RC elements could be enhanced considerably apart from strength point of view. FRP could be used in the form of sheets, plates, and bars. Further, FRP could be used for prestressing applications. Externally prestressed carbon fiber reinforced composite, such as CFRP plates, strips, sheets, and laminates showed that both the design and ultimate loads could be doubled. The use of FRP could increase the moment carrying capacity of the retrofitted beams on the tension face up to 225% while the wrapping technique enhanced the moment carrying capacity by up to 150%. Fibers have gained a significant advantage in the field of structural retrofitting. However, cost factors and delamination of fibre or both may be kept in mind. Another technique, which is recently been developed in this area is external reinforcement. Cairns (1997) proposed the technique of providing reinforcing rods externally on both sides of beams at the level of embedded rods. The rods could be held in position with the help of end yokes. Deflectors could be used so that the external rods could bend along the beam. The major limitation of this technique is that it can hardly be extended to field applications.

Subsequently, the use of pre-tensioned high-strength steel was introduced for strengthening of RC beams by Shin et al (2007). This technique is possible for field application and moment capacity could be enhanced up to about 112%. However, this technique could be extended to discontinuous members only. Kothandaraman and Vasudevan (2013) brought an improvement to the external reinforcement concept. The external bars are anchored at the soffit of the beam. No end yokes or intermediate deflectors were employed to secure the external rods. The bent ends of the rods were inserted into the predrilled holes and anchored using chemical adhesive. This technique did not require specialized devices or skills to fix the reinforcements. More importantly, the placement of rods at the soffit of the beam helped to control the crack width and enhance the cracking moment and the ultimate moment. By this simple technique, the moment carrying capacity could be enhanced up to 140%. The ductility of the beam was much higher compared to the reference beams. Another important advantage of this technique is that it could be extended to field problems and even continuous beams could be retrofitted.

Table 1: Comparison of Flexural Strength of Various Techniques

S. No.	Author(s)	Year	Technique adopted	Increase in Strength (%)
1.	Swamy et al	1989	Steel plate bonding	50 to 70
2.	Adhikary	2000	Steel plate bonding	84
3.	Barnes et al	2001	Steel plate bonding	64 to162
4.	Arsalan et al	2006	Steel plate bonding	165
5.	Adhikary	2006	Steel plate bonding	132
6.	Jumaat et al	2008	Steel plate bonding	80 to158
7.	Su et al	2010	Steel plate bonding	32 to 60
8.	Goldar et al	2012	Steel plate bonding	50 to87
9.	Saadat et al	1990	FRP	65
10.	Triantafillou	1992	FRP	14 to 40
11.	Chajes et al	1994	FRP	36 to 57
12.	Varatephour et al	1997	FRP	56
13.	Garden	1998	FRP	25 to 50
14.	Duthinh and Starnes	2001	FRP	100
15.	Sheikh	2002	FRP	150
16.	Diagana et al	2003	FRP	94
17.	Dave and Trambadia	2004	FRP	17 to 40
18.	Hang et al	2005	FRP	225

19.	Esfahani etal	2006	FRP	100
20.	Yang et al	2008	FRP	35 to 150
21.	Sundarraja and Rajamohan	2008	FRP	50
22.	Cairns	1997	Steel reinforcement	80
23.	Cairns et al	2003	Steel reinforcement	65
24.	Shin et al	2007	Steel reinforcement	42 to 112
25.	Khalil et al	2008	Steel reinforcement	28 to 47
26.	Kothandaraman and Vasudevan	2013	Steel reinforcement	140

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