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Review Paper

Flexural strengthening of RC continuous T beam using CFRP laminate: A review

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Although a great deal of research has been carried out on simply supported reinforced concrete (RC) beams strengthened with Fibre-Reinforced Polymer composites (FRP), a few works has been focused on continuous beams. Particularly, experiments on strengthening the negative moment regions of continuous T beams are rare to find. This paper reviews 40 articles on CFRP strengthened RC beams and 6 articles on CFRP strengthened RC slabs. Existing 10 articles on CFRP strengthened RC continuous beams are critically reviewed. Finally, this paper attempts to address an important practical issue that is encountered in strengthening the negative moment region of RC continuous T beam. The negative moment region of continuous RC T beam is a critical region due to the concurrence of maximum moment and shear as well as installation restraint due to the presence of column .This paper also proposes a simple method of applying CFRP for strengthening the negative moment region of continuous T beam.

Key words: strengthening, CFRP, continuous beam, negative moment.

INTRODUCTION

The last decade has witnessed an increasing demand for strengthening or rehabilitation of existing reinforced concrete (RC) bridges and buildings. This is mainly due to: aging of structures, deterioration, increase in loads, corrosion of steel reinforcement and advancement in the design codes and knowledge. Several researchers pointed out that previous design provisions did not have a comprehensive understanding of the behaviour of the structures (Higgins et al., 2007). As a result, pre -1970s designs might be deficient in strength according to current codes. They overestimated the capacity of concrete and the permissible concrete stress was taken in the early 1960s to be $1.1\sqrt{f_c'}$ which is currently $0.95\sqrt{f_c'}$ in SI units (Higgins et al., 2007).Such deficient beams would fail in a non –ductile manner once their capacity is reached. In addition, construction materials are changing substantially. The AASHO bridge design provisions did not require modern deformed reinforcing bars until 1949 and explicit bond specifications for deformed bars were not announced until 1953. Awareness of proper anchorage and development of flexural reinforcement was unclear. Therefore, many existing structures designed before 1960s would have smaller cross-sectional sizes, smaller dimensions for stirrups and wider spaced reinforcement and decreased requirements for flexural bond stresses.

Concrete structures can become deficient during their service life and require strengthening and repair. This need may arise as a result of design or construction errors, functional changes, design code updates, damage accumulated over time or caused by accidental overloading, fires, or earthquakes. Since replacement of deficient structures requires huge investments, strengthening has become the suitable way for improving their load carrying capacity and prolonging their service life. While complete replacement of a deficient/deteriorated structure is a desirable option, strengthening/repair is often the more economical one.

There are many methods for flexural strengthening, such as: section enlargement, steel plate bonding, external post tensioning method, externally bonded (EB)

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Abbreviations: FRP, Fibre reinforced polymer; **CFRP,** Carbon fibre reinforced polymer; **RC,** reinforced concrete.

system and near-surface mounted (NSM) system. While many methods of strengthening structures are available, strengthening structures via external bonding of advanced fibre-reinforced polymer composite (FRP) has become very popular worldwide. During the past decade, their application in this field has been rising due to the well-known advantages of FRP composites over other materials. Consequently, a great quantity of research, both experimental and theoretical, has been conducted on the behaviour of FRP-strengthened reinforced concrete (RC) structures, including beams, slabs, and columns. In this regard, the evolving technology of using carbon-bonded fibre-reinforced polymers (CFRP) for strengthening simply supported RC beams has attracted much attention in recent years.

Fibre reinforced polymer (FRP) composites are formed by embedding continuous fibers in a resin matrix that binds the fibres together. Depending on the fibres used, FRP composites are classified into three types: Glass FRP composites (GFRP), Carbon FRP composites (CFRP) and Aramid FRP composites (AFRP). Although FRP composites are expensive and more susceptible to physical damage than steel, they have become an attractive substitute for steel in strengthening systems for concrete structures due to their many advantages: high strength to weight ratio, corrosion resistance, high fatigue resistance, easy and reliable surface preparation, reduced mechanical fixing, durability of strengthening system and reduced construction period.

Possible failure modes of FRP strengthened beams are classified into two types. The first type of failure includes the common failure modes such as concrete crushing and FRP rupture based on complete composite action. The second type of failure is a premature failure without reaching full composite action at failure. This type of failure includes: end cover separation, end interfacial delamination, flexural crack induced debonding and shear crack induced debonding. Different failure mechanisms in experimental tests were reported by Aram et al. (2008), Pham and Al-Mahaidi (2004) and Teng et al. (2003).

Premature failures can significantly limit the enhancement property and the ultimate flexural capacity of the retrofitted beams. Several studies were conducted to identify methods of preventing premature failure with the aim of improving the load capacity and ductility of RC beams. Researchers studied the use of end anchorage techniques, such as U-straps, L-shape jackets, and steel clamps for preventing premature failure of RC beams strengthened with CFRP (Ceroni, 2010; Jumaat and Alam, 2010; Wang and Hsu, 2009; Alam and Jumaat, 2008; Aram et al., 2008; Ceroni et al., 2008; Xiong et al., 2007; Pham and Al-Mahaidi, 2006; Teng et al., 2003). In particular, their practical implementations for flexural strengthening are numerous (Costa and Barros, 2010; Kothandaraman and Vasudevan, 2010; Ombres, 2010; Rasheed et al., 2010; Badawi and Soudki, 2009; Baghiee et al., 2009; Capozucca, 2009; Mohamed et al., 2009; Mukherjee and Rai, 2009; Tan et al., 2009; Wang and Hsu, 2009; Benachour et al., 2008; Chalioris, 2008; Sandeep et al., 2008; Bank and Arora, 2007; Barros et al., 2007; Benjeddou et al., 2007).

It is seen that most of the conducted experiments to validate the design methodology for FRP flexural strengthening, consisted of rectangular or T-beams on which the strengthening was applied to the positive moment region of the member.Generally, the researches were conducted on RC rectangular sections which are not representative because most RC beams would have a T- Section due to the presence of a top slab.

PREVIOUS RESEARCH WORKS ON CONTINUOUS BEAMS

Although several research studies have been conducted on the strengthening and repair of simply supported reinforced concrete beams using external plates, there is little reported work on the behaviour of strengthened continuous beams. In addition, most design guidelines have been developed for simply supported beams with external FRP laminates. An exhaustive literature review revealed that a minimum amount of research work had been done for addressing the possibility of strengthening the negative moment region of continuous beam using FRP materials.

On the field of strengthened structures, (Grace et al., 1999) tested five continuous beams. Four different strengthening systems were examined. Two beams were strengthened with two different types of carbon fibre reinforced polymer sheets. The first beam was strengthened only for flexure, while the second beam was strengthened for both flexure and shear. The third beam was strengthened with glass fibre reinforced polymer (GFRP) sheets, while CFRP plates were used in strengthening the fourth beam. The fifth beam was fabricated as reference. Each beam was loaded and unloaded for at least one loading cycle before failure. They found that the use of FRP laminates to strengthen continuous beams is effective for reducing deflections and for increasing their load carrying capacity. They also concluded that beams strengthened with FRP laminates exhibit smaller and better distributed cracks.

Later, (Grace et al., 2001) also investigated the experimental performance of CFRP strips used for flexural strengthening in the negative moment region of a full-scale reinforced concrete beam. The flexural strengthening of two categories of beams (I and II) was considered. Category I beams were designed to fail in shear, due to lack of proper shear reinforcement; while Category II beams were designed to fail in flexure. They tested five full scale concrete beams of each category.

They found that Category I beams failed by diagonal cracking with local debonding at the top of the beams,

Table 1. Reinforced concrete (RC) two-span beams strengthened in flexure with external bonded CFRP sheets (research by El-Refaie et al., 2003a).

Beam no.	Number of layers		Sheet length (m)		Base of selecting the size of sheet	Mode of failure
	Hogging zone	Sagging zone	Hogging zone	Sagging zone		
H1	None	None	None	None	-	Flexural failure
H2	2	None	2.0	None	Arbitrary	Rupture of sheet.
H3	6	None	2.0	None	Arbitrary	Peeling failure
H4	10	None	2.0	None	Arbitrary	Peeling failure
H5	6	None	1.0	None	Arbitrary	Peeling failure
H6	2	2	3.0	1.0	Arbitrary	Rupture of sheet
S1	None	None	None	None	-	Flexural failure
S2	None	2	None	2.0	Arbitrary	sheet separation
S3	None	6	None	2.0	Arbitrary	Peeling failure
S4	None	6	None	3.5	Arbitrary	Peeling failure
S5	None	10	None	3.5	Arbitrary	sheet separation

meanwhile Category II beams failed by delamination at the interface of the CFRP strips and the concrete surface, both with and without concrete-cover failure by means shear/tension delamination. It was also noted that CFRP strips were not stressed to their maximum capacity when the beams failed, which led to ductile failures in all the beams. The maximum stress experienced by the CFRP strips was 28.5% of their ultimate strength in the case of Category I, and 52% for Category II. The maximum increase of load-carrying capacity due to strengthening was observed to be 29% for Category I beams, and 40% for Category II beams with respect to corresponding control beams.

More recently, Grace et al. (2005) also worked on another research where three continuous beams were tested. One of those beams had no external strengthening and conventional ductile flexural failure occurred. The other two beams were strengthened along their negative and positive moment regions around the top and bottom face on both sides as a U-wrap. F-CT beam was strengthened using one layer of the triaxial ductile fabric. It was observed that reinforced beam failed by tensile rupture of the fabric over the central support, followed by rupture of the fabric at midspan. On the other part, F-CTC beam was strengthened using two layers of the carbon fibre sheet. That type of beam failed suddenly by shear-tension failure at one end of the negative moment region, followed by debonding of the CFRP at the positive moment region. F-CTC beam had a moment redistribution ratio of 6.5%, which was significantly less than the one of F-CT beam (13.4%). They concluded that the strengthened beams with the triaxial fabric showed greater ductility than those strengthened with CFRP sheets.

On the other hand, (El-Refaie et al., 2003a) examined 11 reinforced concrete (RC) two-span beams strengthened in flexure with external bonded CFRP sheets. The beams were classified into two groups according to the arrangement of the internal steel reinforcement. Each group included one non-strengthened control beam. All strengthened beams exhibited less ductility compared with the non-strengthened control beams. They found an optimum number of CFRP layers beyond which there was no further enhancement in the beam capacity. They also investigated that extending the CFRP sheet length to cover the entire hogging or sagging zones did not prevent peeling failure of the CFRP sheets, which was the dominant failure mode of tested beams. The summary of their research is shown in Table 1.

In another research, El-Refaie et al. (2003b) tested five reinforced concrete continuous beams strengthened in flexure with external CFRP laminates. All beams had the same geometrical dimensions and internal steel reinforcement. The main parameters studied were the position and form of the CFRP laminates. Three of the beams were strengthened using different lay-up arrangements of CFRP reinforcement, and one was strengthened using CFRP sheets. The performance of the CFRP strengthened beams was compared with a non-strengthened reference beam. Peeling failure was the principal failure mode for all the strengthened tested beams. It was found that the longitudinal elastic shear stresses at the adhesive/concrete interface calculated at beam failure were close to the limiting value recommended in (Concrete Society Technical Report 55, 2000). They also found that, strengthened beams at both sagging and hogging zone produced the highest load capacity. The summary of their research is shown in Table 2. Ashour et al. (2004) tested 16 reinforced concrete (RC) continuous beams with different arrangements of internal steel bars and external CFRP laminates. All test specimens had the same geometrical dimensions and were classified into three groups according to the amount of internal steel reinforcement. Each group included one non-strengthened control beam designed to fail in flexure. They observed three failure modes, namely

Table 2. Reinforced concrete continuous beams strengthened in flexure with external CFRP laminates (research by El-Refaie et al., 2003b).

Beam no.	Thickness of CFRP (mm)		Length of CFRP (m)		Base of selecting the size of CFRP sheet	Mode of failure
	Hogging zone	Sagging zone	Hogging zone	Sagging zone		
E1 (plate)	None	None	None	None	-	Flexural failure
E2 (plate)	1.2	None	2.5	None	Arbitrary	Peeling failure
E3(plate)	-	1.2	-	3.5	Arbitrary	Peeling failure
E4 plate)	1.2	1.2	2.5	3.5	Arbitrary	Peeling failure
E5 (sheet)	4.2	None	-	None	Arbitrary	Peeling failure

Table 3. Reinforced concrete (RC) continuous beams with different arrangements of internal steel bars and external CFRP laminates (research by Ashour et al., 2004).

Beam no.	Type of CFRP laminate	End anchorage	Length of CFRP laminate (m)		Base of selecting the size of CFRP laminate	Mode of failure
			Hogging zone	Sagging zone		
H1	-	-	-	--	--	Flexural failure
H2	sheet	None	2.0	-	Arbitrary	Rupture of sheet.
H3	sheet	None	2.0	--	Arbitrary	Peeling failure
H4	sheet	None	2.0	--	Arbitrary	Peeling failure
H5	sheet	None	1.0	-	Arbitrary	Peeling failure
H6	sheet	None	3.0	1.0	Arbitrary	Rupture of sheet
S1	-	-	-	-	-	Flexural failure
S2	sheet	None	-	2.0	Arbitrary	sheet separation
S3	sheet	None	-	2.0	Arbitrary	Peeling failure
S4	sheet	None	-	3.5	Arbitrary	Peeling failure
S5	sheet	None	-	3.5	Arbitrary	sheet separation
E1	-	-	-	-	- --	Flexural failure
E2	plate	None	2.5	-	Arbitrary	Peeling failure
E3	plate	None	-	3.5	Arbitrary	Peeling failure
E4	plate	None	2.5	3.5	Arbitrary	Peeling failure
E5	sheet	None	2.5	--	Arbitrary	Peeling failure

laminate rupture, laminate separation and peeling failure of the concrete cover attached to the composite laminate. The ductility of all strengthened beams was reduced in comparison with their respective reference beam. Additionally, they presented simplified methods for estimating the flexural load capacity and the interface shear stresses between the adhesive and the concrete material. As in previous studies, they observed that increasing the CFRP sheet length in order to cover the entire negative or positive moment zones did not prevent peeling failure of the CFRP laminates. The summary of their research is shown in Table 3.

A recent contribution by Aiello et al. (2007) compared the behaviour between continuous RC beams strengthened with of CFRP sheets at negative or positive moment regions and RC beams strengthened at both negative and positive moment regions. In general, all the beams were strengthened with one CFRP sheet layer and with the remark that the beams were not loaded at the middle of span. However, the control beams underwent a typical flexural. The failure of the strengthened beams occurred by debonding of the CFRP sheets, together with concrete crushing. They found out that when the strengthening was applied to both hogging and sagging regions, the ultimate load capacity of the beams was the highest and about 20% of moment redistribution could be achieved by CFRP sheets externally glued in the sagging region.

Recently, Maghsoudi et al. (2009) examined the flexural behaviour and moment redistribution of reinforced high strength concrete (RHSC) continuous beams strengthened with CFRP. Test results showed that by increasing the number of CFRP layers, the ultimate strength increases, meanwhile ductility, moment redistribution, and ultimate strain of CFRP sheet decrease. They also observed that by increasing the number of CFRP sheet layers, there was a change in the failure mode from tensile rupture to IC debonding. End U-straps were effective in limiting end debonding, but not intermediate span debonding. The summary of their

Table 4. Reinforced high strength concrete (RHSC) continuous beams strengthened with CFRP (research by Maghsoudi and Bengar, 2009).

Beam no.	End anchorage	CFRP sheet layers		Length of CFRP sheet (m)		Base of selecting the size of CFRP sheet	Mode of failure
		Hogging zone	Sagging zone	Hogging zone	Sagging zone		
CB	None	0	0	None	None	-	Flexural failure
SC1	None	1	1	1.8	2.2	Arbitrary	Rupture of sheet
SC2	Yes	2	2	1.8	2.2	Arbitrary	IC debonding
SC3N	None	3	3	1.8	2.2	Arbitrary	IC debonding
SC3	Yes	3	3	1.8	2.2	Arbitrary	IC debonding

research is shown in Table 4.

Finally, Akbarzadeh et al. (2010) conducted an experimental program to study the flexural behaviour and moment redistribution of reinforced high strength concrete (RHSC) continuous beams strengthened with CFRP and GFRP sheets. As the previous work, test results showed that by increasing the number of CFRP sheet layers, the ultimate strength increases, while ductility, moment redistribution, and ultimate strain of CFRP sheet decrease. However, by using the GFRP sheets in strengthening the continuous beams, it is possible to reduce the loss in ductility and moment redistribution but a significant increase in the ultimate strength cannot be achieved. The moment enhancement ratio of the strengthened continuous beams was significantly higher than the ultimate load enhancement ratio for the same beam. They also developed an analytical model for moment–curvature and load capacity which they used for the tested continuous beams in this current study and in other similar researches.

COMMENTS ON THE ACTUAL STATE OF ART

In all the above cases (Tables 1, 2, 3, 4), it is seen that the sizes of CFRP laminates were chosen arbitrarily. There is no design guideline for optimizing the length or thickness of CFRP sheet/laminate for strengthening continuous RC beams. Most of the researches were conducted on RC rectangular sections which are not representative of the fact that most RC beams would have a T- Section due to the presence of a top slab. In all the above cases, the restraint caused by the columns in the application of the strengthening system was not considered. Literature review on strengthening RC beams in the presence of RC slabs also reveals that the strengthening system is applied in the positive moment region and the restraint caused by the column in the application of the strengthening system is not considered (Elgabbas et al., 2010; Polies et al., 2010; Smith and Kim, 2009; Anil, 2008; Bonaldo, 2008; Brickner, 2008; Maaddawy and Soudki, 2008; Waleed et al., 2005).

PROBLEMS OF STRENGTHENING THE NEGATIVE MOMENT REGION OF CONTINUOUS T BEAM

The negative moment region, namely the support region, of continuous reinforced concrete (RC) beams is a critical zone due to the simultaneous occurrence of maximum moment and shear. In addition, the presence of columns and other components such as electric and plumbing lines or HVAC ducts make difficult to strengthen this region using conventional techniques, like steel plate bonding, section enlargement, external stirrups etc. In the negative moment region, the strengthening is not as simple as in the case of the positive moment region because the columns prevent the application of FRP system over the web portion of the beam. Another important point is that, the use of thick steel plates bonded to the floor surface will raise the floor level, which might be undesirable.

PROPOSED METHOD OF STRENGTHENING THE NEGATIVE MOMENT REGION OF T BEAM

To overcome the problems stated above, the proposed new method for strengthening is illustrated in Figure 1.

With the present method, the restraint caused by the column is considered, which is representative of the real field situation. CFRP is applied on the four sides of the column according to the Figure 1. CFRP1 is applied just above the web portion of the continuous T beam. CFRP2 is applied in the transverse direction of the beam, meanwhile CFRP3 is applied on the flange portion of the continuous T beam, parallel to CFRP1. The method for applying CFRP will be easy to implement in real structures. In this context, due to its high strength ratio and ease of installation, composite materials such as carbon fibre reinforced polymers (CFRP) can be used to provide an economical and versatile solution for extending the service life of concrete structures. At the end, this proposal brings new challenges for professionals who are working in the field of structural repair and strengthening of reinforced concrete structures.

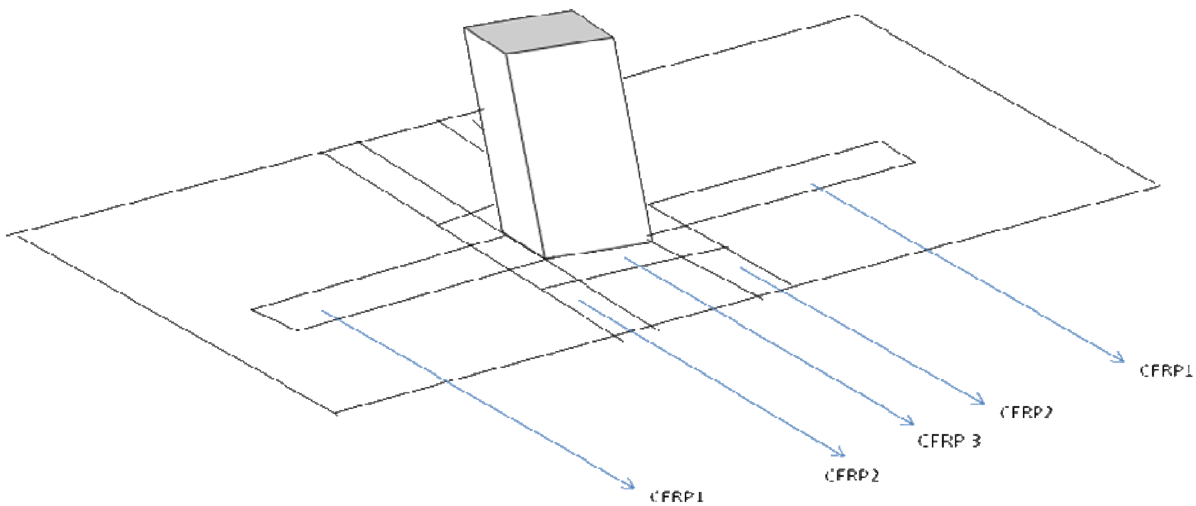

Figure 1. Method for applying CFRP in the negative moment region of continuous T beam.

FUTURE NEEDS

A review on existing research works shows that strengthening RC continuous beams, especially continuous T beams is still very young. The parameters like effective length, width, thickness and appropriate anchorage system of CFRP for strengthening RC continuous beams are in the need of extensive research. In other words, to prepare a complete design guideline for strengthening RC continuous T beam with CFRP, further research is necessary.

CONCLUSION

This paper reviewed the existing research works on continuous RC beams strengthening by CFRP. It is addressed an important practical issue which points into strengthening the negative moment region of RC continuous T beam.

The importance to study the strengthening of the negative moment region is due to its simultaneous occurrence of maximum moment and shear.

A simple method of applying CFRP for strengthening the negative moment region of RC continuous T beam is proposed in this paper and its development is visualized in further works.

Future research is needed for a complete design guideline for strengthening RC continuous beams with CFRP, with the aim to contribute in the concrete structures repair tasks.

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