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RESEARCH ARTICLE

STRUCTURAL PERFORMANCE OF FRP STRENGTHENED CONCRETE BEAMS

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ABSTRACT

This paper reviews research works published on the structural performance of concrete beams strengthened using fibre reinforced polymer (FRP) sheets. Furthermore it discusses the effect of various FRP sheets on the structural performance of concrete beams subjected to static loading condition. A total of 35 research papers relating this study have been collected and reviewed. The properties and structural applications of different types of FRP have been presented. Also a gap analysis has been conducted to propose recommendations for future research in this field.

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INTRODUCTION

In the present era, an increasing number of reinforced concrete structures have reached the end of their service life, either due to deterioration of concrete or reinforcement caused by environmental factors and the widespread application of deicing salts or due to increase in applied loads. These deteriorated structures may be structurally deficient or functionally obsolete and most are in need of extensive rehabilitation or replacement.Strengthening these deficient structural members using fibre reinforced polymer (FRP) has emerged as a potential method to address strength deficiency problems. This approach has shown significant advantages compared to traditional methods, mainly due to the outstanding mechanical properties of the composites (Len Hollaway and Jin-Guang Teng, 2008). Several types of FRPs are available in the market. However, carbon fibre reinforced polymer (CFRP) and glass fibre reinforced polymer (GFRP) composite materials have been used for strengthening applications because of their inherent material properties. The existing methods for laminating FRP on concrete structures are externally bonded FRP (EB-FRP), Near-surface mounted FRP (NSM-FRP), Fibre anchored FRP (FB-FRP) and Hybrid bonded FRP system (HB-FRP) (ACI 440.2R-08, Guide for the design and construction of externally bonded FRP systems for strengthening concrete structures, 2008). The selection of strengthening material and method depends on the nature of strengthening. Many researchers have conducted studies on the behaviour of concrete beams strengthened with externally bonded CFRP sheets (Barros *et al.,* 2007; Nadeem AhsanSiddiqui, 2010; Ehsan Ahmed *et al.,* 2011; Habibur Rahman Sobuz, 2011; Jose Sena-Cruz *et al*., 2012; MagdaMousa *et al*., 2015; Rajeswari and Meikandaan, 2015; Renata Kotynia and Szymon Cholostiakow, 2015; Mohan Babu *et al*., 2007). Several authors haveconducted research on the performance of concrete beams strengthened with GFRP laminates (Sing-Ping Chiew and Qin Sun and Yi Yu, 2007; Jadhav and Shiyekar, 2011; Katarey Damodar and Satish, 2015; Ravichandran *et al*., 2012; Mariappan Mahalingam *et al*., 2013; Ayad Adi *et al*., 2014; Parthiban *et al*., 2014; Gopinathan *et al*., 2016; Gugulothu Rambabu *et al*., 2016). A hybrid FRP is formed from a combination of different types of fibres in a polymer. The hybridization of fibres provides improved specific characteristics that cannot be obtained by any original fibre acting alone. But the works on the behaviour of concrete beams strengthened with externally bonded hybrid FRP sheets are limited (Xiong *et al.,* 2004; Zhishen *et al.,* 2006; Attari *et al.,* 2008; He *et al.,* 2013; Khaled Galal and Amir Mofidi, 2009; Dong *et al.,* 2012; Hee Sun Kim and Yeong Soo Shin, 2011; Attari *et al.,* 2012; Eunsoo Choi *et al.,* 2013; Mohammed Rashwan *et al.,* 2015; Tara Sen and Jagannatha Reddy, 2013; Rami Hawileh *et al.,*2014; Thomas Kang *et al.,* 2014; Moshiur Rahman *et al.,* 2015; Nachimuthu *et al.,* 2015; Karthick *et al.,* 2017).

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Research status

Static response of FRP strengthened concrete beams

Barros *et al.* (2007) examined the efficiency of near surface mounted (NSM) and externally bonded reinforcement (EBR) techniques for flexural and shear strengthening of concrete beams using CFRP laminates. The author investigated the influence of reinforcement ratio and spacing of FRP strips on the efficiency of flexural strengthening technique. A total of 24 beams in two series were cast and tested under four-point bending for this study. The effectiveness of NSM and EBR techniques for flexural and shear strengthening of reinforced concrete beams was compared. Nadeem (2010) presented the results of an experimental study made on beams wrapped with CFRP. Ehsan Ahmed *et al*. (2011) studied the flexural strengthening of reinforced concrete beams with CFRP laminates attached to the soffit by epoxy adhesive.A total of six reinforced concrete beams having different degrees of strengthening scheme weretested under transverse bending over an effective span of 1900 mm. Habibur Rahman Sobuz *et al*. (2011) investigated theflexural behaviour of reinforced concrete beams strengthened with CFRP laminates. A total of five beams were cast for this study. One beam served as the control beam and the rest were strengthened by changing the level of CFRP laminates. All the beams were tested under four-point bending over a clear span of 1900 mm. Sena Cruz *et al*. (2012) investigated the effect of two different techniques in flexural strengthening of beams under monotonic and fatigue loading. One was externally bonded reinforcement (EBR) and the other was near surface mounted (NSM) FRP. Both the strengthening techniques were applied on the cover concrete, which was normally the weakest region of the element to be strengthened. Magda Musa (2015) evaluated thefactors affecting the bond strength between fibre reinforced polymer laminates and concrete surface.A total of 17 plain concrete beams were cast in three groups with concrete strengths 33.5, 40.7 and 67 MPa for this study. The beams were simply supported and had a length of 1110 mm with 120 × 250 mm cross-section. Carbon fibre reinforced polymer (CFRP) sheet of uni-directional type was bonded to the tension face of beams.

All the beams were tested under four-point bending. The factors affecting the bond between CFRP sheets and concrete were studied. Rajeswari and Meikandaan (2015) investigated the flexural behaviour of reinforced concrete beams strengthened with CFRP laminates. Three RC beams were cast and tested under two-point loading. One beam served as the control beam and two beams were strengthened with one and two layers of carbon fibre reinforced polymer sheets bonded with an inorganic epoxy resin. Renata Kotynia and Szymon Cholostiakow, (2015) evaluated the performance of a novel strengthening system involving T-shaped carbon fibre reinforced polymer (CFRP) profiles. The author reported that the proposed system successfully combines the advantages of two established strengthening techniques, namely the near surface mounted (NSM) and externally bonded (EB) methods. Seven flexurally-strengthened and two non-strengthened full-scale reinforced concrete (RC) beams were cast. Two T-shaped profiles having heights of 15 and 30 mm were applied. All the specimens were tested under a quasi-static six-point bending configuration. Concrete strength and composite ratio were considered to evaluate the efficiency of the proposed flexural strengthening system. Mohan Babu *et al*. (2007) investigated the flexural behaviour of reinforced concrete beams strengthened with CFRP sheets.Six reinforced concrete beams were cast and strengthened in flexure using carbon fibre reinforced polymer (CFRP) laminates. All the beams were tested under four-point bending with a span of 1000 mm. Sing-Ping Chiew *et al*. (2007) investigated the flexural behaviour of reinforced concrete beams strengthened with glass fibre reinforced polymer (GFRP) laminates. Ten strengthened beams and two unstrengthened beams were tested under four-point bending for this study. Number of GFRP layers and bond length of GFRP laminates in shear span were taken as test variables. Jadhav and Shiyekar (2011) investigated the effect of length, width and number of layers of glass fibre reinforced polymer (GFRP) strips in strengthening RC beams. Katarey Damodar and Satish (2015) conducted an experimental study on RC continuous beams strengthened with FRP sheet. An experimental analysis was carried out on the behavioural attributes of continuous RC beams subjected to static loading. These beams were reinforced with externally bonded glass fibre reinforced polymer (GFRP) sheets. Ravichandran *et al*. (2012) examined the effectiveness of glass fibre reinforced polymer (GFRP) laminates on the performance of high strength reinforced concrete beams. Ten beams were cast and tested under four-point bending. Test beams were strengthened with two types of GFRP laminates of varying thicknesses of 3 and 5 mm respectively. Mariappan *et al*. (2013) conducted an experimental study on steel fibre reinforced concrete beams with externally bonded glass fibre reinforced polymer laminates. A total of ten beams were cast and tested to failure. Three fibre reinforced concrete beams were used as reference beams and six fibre reinforced concrete beams were strengthened with externally bonded GFRP laminates. One concrete beam was left virgin without any fibre reinforcement and externally bonded laminates. The static responses of all the beams were evaluated in terms of strength, stiffness and ductility.

Ayad Adi *et al*. (2014) presented experimental results on Reinforced Concrete (RC) beams strengthened with GFRP wraps in the tension-zone of the beams.A total number of 12 reinforced concrete beams were cast for this study. The width and number of layers of GFRP strips were varied. The specimens were tested under four-point bending until failure. Parthiban *et al*. (2014) examined the effectiveness of GFRP laminates on the performance of hybrid fibre reinforced concrete beams.Four beams cast with a fibre volume fraction of 1% (80% of steel fibre and 20% of polyolefin fibre) and tested under four-point bending. The beams were strengthened with two types of GFRP laminates of varying thicknesses of 3 and 5 mm respectively. Gopinathan *et al*. (2016) examined the effectiveness of glass fibre reinforced polymer (GFRP) laminates on the performance of high strength concrete (HSC) beams under static and cyclic loading. A total of fourteen beams of size 150x250x3000 mm were cast and tested. Two beams were treated as control beams and twelve beams were strengthened with three different configurations of GFRP laminates. The thickness of GFRP laminate waskept at 3mm and 5mm. Gugulothu Rambabu *et al*. (2016) investigated the flexural and shear behaviour of RC beams strengthened with continuous glass fibre reinforced polymer sheets.Two sets of beams were cast for this study. In SET I, three beams weak in flexure were cast, out of which one is the control beam and the other two beams were strengthened using continuous glass fibre reinforced polymer (GFRP) sheets in flexure. In SET II, three beams weak in shear were cast, out of which one is the control beam and the other two beams were strengthened using continuous glass fibre reinforced polymer (GFRP) sheets in shear. All the beams were tested under four-point bending. Xiong *et al*. (2004) studied the behavior of reinforced concrete beams strengthened with externally bonded hybrid carbon-glass fibre sheets. One beam served as the control beam and six beams were strengthened with two different strengthening systems. One was hybrid carbon and glass fibre reinforced polymer system and the other was carbon fibre reinforced polymer system. The beams were tested under four-point bending. The parameters such as mid-span deflection, ductility and stiffness were considered in this study. Zhishen Wu *et al*. (2006) investigated the structural behaviour of reinforced concrete beams strengthened with hybrid FRP laminates. Six beams were cast and strengthened with hybrid FRP laminates. CFRP sheets were mounted on the soffit of the beam while GFRP sheets were also wrapped to carry the shear load. In strengthened beams, GFRP sheets provided confinement to concrete core and prevented premature debonding of CFRP sheets. All the beams were subjected to four-point bending test. Attari *et al*. (2008) investigated the strengthening of reinforced concrete beams using hybrid FRP laminates. The authors used a combination of one-way glass and carbon fibres as well as bi-directional hybrid fabric of glass and carbon fibres. A total of ten beams were strengthened by various hybrid configurations of reinforcement and tested until failure under four-point bending to determine the best combination of strengthening scheme. The effects on ultimate load capacity, stiffness, ductility and energy absorption capacity were examined. He *et al*. (2013) studied the crack arresting and strengthening mechanism of reinforced concrete beams using hybrid fibre reinforced polymer laminates. The main aim of the study was to retard the cracks propagation in reinforced concrete beams using hybrid FRP laminates. Two types of beams were cast. One was conventional reinforced concrete beam and the other was strengthened with hybrid glass and carbon FRP sheets. The beams were tested under four- point bending. Finite element modeling analysis was also conducted to substantiate the crack arresting and strengthening mechanism of RC beams using HFRP composite. Khaled Galal and Amir Mofidi (2009) investigated the flexural strengthening of RC beams using hybrid FRP laminates and a ductile anchor system. All the beams were tested under four-point bending. Three retrofitted beams were strengthened using one layer of carbon FRP sheet.

Comparison has been made between new hybrid FRP sheet/ductile anchor system and conventional FRP bonding method. Dong-Uk Choi *et al*. (2012) studied the flexural and bond behaviour of concrete beams strengthened with hybrid FRP sheets. Six reinforced concrete beams of size 160X240X2000 mm were cast and tested under two-point loads. Six bond tests were conducted to demonstrate that the ultimate bond-shear stress between the hybrid sheet and concrete is similar to the case of the carbon sheet. Hee Sun Kim and Yeong Soo Shin (2011) investigated the flexural behavior of reinforced concrete beams strengthened with hybrid fibre reinforced polymer laminates under sustained loading. The experiment consisted of casting and testing fourteen beams of size 150X250X2400 mm. One beam served as the control beam and thirteen beams were strengthened with hybrid FRP laminates. The load was increased in increments until failure. Attari *et al*. (2012) examined the flexural strengthening of concrete beams using CFRP, GFRP and Hybrid FRP sheets. The experiment consisted of casting and testing seven beams of size 100X160X1500 mm. One beam served as the control beam and six beams were strengthened by FRP sheets with different strengthening schemes. All the beams were tested under four-point bending. Eunsoo Choi *et al*. (2013) evaluated the debonding of hybrid FRP laminates in flexurally strengthened reinforced concrete beams. Eighteen RC beams with width, depth and length equal to 150, 150 and 550 mm, respectivelywere fabricated. After 28 days of curing, the centres of the beams were cut (width of 5 mm and depth of 75 mm) with an electronic saw. These saw-cuts were planned to induce debonding failure in beams because the highest tensile stress can be fully transferred to FRP. After cutting, the beams were flexurally strengthened withone or two sheets of CFRP or GFRP, the sizes of which were 130 mm in width and 300 mm in length. All the beams were tested under three-point loading with an effective span of 450 mm. Mohammed Rashwan *et al*. (2015) examined thesize effect of reinforced concrete beams strengthened with CFRP and GFRP sheets in flexure. Two types of FRP sheets were considered in this study; Carbon and Glass fibre reinforced polymer sheets (CFRP and GFRP). FRP sheets were bonded to the soffit of the beams using a two-part epoxy. Tara Sen and Jaganatha Reddy (2013) investigated the flexural and tensile behavior of reinforced concrete beams strengthened using natural textile jute fibre and it was compared with CFRP and GFRP strengthening systems. A total of fourteen beams were cast in three groups. Among these three groups, the first group comprised of control specimens and the other two groups were strengthened RC beams. Rami Hawileh *et al*. (2014) studied the behavior of reinforced concrete beams strengthened with externally bonded hybrid fibre reinforced polymer systems. The experiment consisted of casting and testing five beams of size 120X240X1840 mm. One beam served as the control beam and four beams were strengthened in flexure with GFRP, CFRP and Hybrid FRP sheets. The beams were tested under four-point bending. The results were presented in terms of observed failure modes, load versus mid-span deflection and load versus FRP strain relationship at mid-span. Thomas Kang *et al*. (2014) examined the hybrid effects of FRP laminates (carbon-glass FRP) in concrete beams. The author investigated the tensile behaviour of 94 hybrid carbon-glass fibre sheets and 47 carbon and glass fibre roving sheets. Comparisons have been made between the rule of mixtures and test data. Moshiur Rahman *et al*. (2015) conducted a study on an innovative hybrid bonding technique (combination of plate bonding and near surface mounting (NSM) techniques) for strengthening reinforced concrete beams in flexure. The study consisted of casting and testing seven beams. One beam served as the control beam and six beams were strengthened using composites. The plates were selected with two different thicknesses of 2 mm and 2.76 mm. Nachimuthu *et al*. (2015) investigated the behaviour of structurally damaged reinforced concrete beams strengthened with jute and GFRP laminates in flexure. The parameters such as stiffness, energy absorption and ductility were calculated in this study. Nine beams were cast in three series. Three beams were control beams and the rest were strengthened with hybrid FRP laminates made of jute and glass fibres. All the beams were tested under four-point bending. Karthick *et al*. (2017) investigated the structural upgradation of concrete beams using advanced fibre composites. A total of seven beams were cast and tested under four-point bending. One beam without FRP served as the control beam, two beams were strengthened using glass fibre reinforced polymer laminates (GFRP) and four beams were strengthened using hybrid FRP (carbon+ glass) laminates in flexure.

Gap Analysis

A review of past research work showed that many studies have been conducted on beams strengthened with CFRP, GFRP and AFRP laminates to improve their flexural capacity. But only few studies have been conducted on beams strengthened with hybrid FRP laminates under static and cyclic loading condition.

The review results clearly show that the beams strengthened using CFRP laminates improve the strength but reduce the ductility of beams. The beams strengthened using GFRP laminates improve its ductility but provide only marginal increase in the strength of beams. So the study has to be conducted to derive the advantages of both CFRP and GFRP sheets for structural strengthening under static and cyclic loading condition using hybrid FRP laminates.

RESULTS AND DISCUSSION

Static response of FRP strengthened beams

Load carrying Capacity

The review results clearly reveal that the beam strengthened using FRP laminates exhibited higher load carrying capacity than the conventional concrete beams (Barros *et al.,* 2007; Nadeem AhsanSiddiqui, 2010; Ehsan Ahmed *et al.,* 2011; Habibur Rahman Sobuz, 2011; Jose Sena-Cruz *et al*., 2012; MagdaMousa *et al*., 2015; Rajeswari and Meikandaan, 2015; Renata Kotynia and Szymon Cholostiakow, 2015; Mohan Babu *et al*., 2007; Sing-Ping Chiew and Qin Sun and Yi Yu, 2007; Jadhav and Shiyekar, 2011; Katarey Damodar and Satish, 2015; Ravichandran *et al*., 2012; Mariappan Mahalingam *et al*., 2013; Ayad Adi *et al*., 2014; Parthiban *et al*., 2014; Gopinathan *et al*., 2016; Gugulothu Rambabu *et al*., 2016; Xiong *et al.,* 2004; Zhishen *et al.,* 2006; Attari *et al.,* 2008; He *et al.,* 2013; Khaled Galal and Amir Mofidi, 2009; Dong *et al.,* 2012; Hee Sun Kim and Yeong Soo Shin, 2011; Attari *et al.,* 2012; Eunsoo Choi *et al.,* 2013; Mohammed Rashwan *et al.,* 2015; Tara Sen and Jagannatha Reddy, 2013; Rami Hawileh *et al.,* 2014; Thomas Kang *et al.,* 2014; Moshiur Rahman *et al.,* 2015; Nachimuthu *et al.,* 2015; Karthick *et al.,* 2017). However, the percentage increase in load carrying capacity depends on many factors such as reinforcement ratio, grade of concrete, spacing of stirrups, degree of strengthening, type of strengthening material and the type of strengthening method (Barros *et al*., 2007; Nadeem AhsanSiddiqui, 2010; Jose Sena-Cruz *et al*., 2012; MagdaMousa, 2015). The beams strengthened using CFRP laminates show an appreciable increase in load carrying capacity when compared to the conventional concrete beam and the beams strengthened using GFRP laminates (Mohammed Rashwan *et al*., 2015). Carbon fibres are usually of higher strength when compared to glass fibres. It is quite natural to expect that the degree of confinement and bridging effect caused by carbon fibres is more pronounced (Karthick *et al*., 2017). Hence, the increase in the load carrying capacity. The beam strengthened using GFRP laminates also exhibited increase in load carrying capacity (Ravichandran *et al*., 2012; Ayad Adi *et al*., 2014; Gopinathan *et al*., 2016). But it was comparatively less than that of CFRP strengthened beams. In case of hybrid FRP strengthened concrete beams, particularly the hybrid FRP made of carbon and glass fabric, the percentage increase in load carrying capacity depends on the number of carbon layers (Ehsan Ahmed *et al*., 2011; Attari *et al*., 2008; Thomas Kang *et al*., 2014). An increase in carbon layers improves the load carrying capacity (Attari *et al*., 2012; Rami Hawileh *et al*., 2014). On the other hand, debonding of CFRP laminates was observed in case of multi-layer strengthening system. An attachment of edge strip plates substantially influenced the performance of CFRP strengthened beams (Ehsan Ahmed *et al.,* 2011). Among the various strengthening techniques, externally bonded reinforcement is more suitable technique for strengthening the concrete members (Barros *et al*., 2007; Jose Sena-Cruz *et al*., 2012). Debonding of FRP laminates was observed in some cases. The debonding level of FRP plate was more influenced by the thickness of the strengthening material. The debonding of FRP laminates was also significantly influenced by resin type.Hence care should be taken on this aspect. The debonding of FRP laminates from the concrete surface can be avoided through providing proper anchorage (Jose Sena-Cruz *et al*., 2012; Zhishen Wu *et al*., 2006; Khaled Galal and Amir Mofidi, 2009). In the case of hybrid FRP strengthened beams, the debonding of FRP laminates was also influenced by the arrangement of the FRP layers and the debonding can be reduced when a layer of CFRP was attached to concreteprior to a GFRP layer (Eunsoo Choi *et al*., 2013).

Deformation

The review results clearly reveal that the beam strengthened using CFRP laminates exhibited an appreciable reduction in deformation than the conventional concrete beams and the beams strengthened with other type of FRP laminates. The addition of CFRP sheets to the tension face of beams exhibited significant reduction in deflection (Habibur Rahman Sobuz *et al*., 2011; Renata Kotynia and Szymon Cholostiakow, 2015). Also the width of CFRP sheet and roughness of concrete surface play a vital role in the reduction of deformation (Magda MousaI, 2015). The beams strengthened with GFRP laminates also show an appreciable reduction in deflection than the conventional concrete beams and the beam strengthened using CFRP laminates because of its ductile nature. In hybrid FRP strengthened beams, the carbon to glass fibre ratio governs the performance of the beams (Karthick *et al*., 2017). But a slight difference was observed between hybrid FRP strengthened beams and mono FRP strengthened beams (Karthick *et al*., 2017).

Ductility

In the majority of research, the beams strengthened using GFRP laminates exhibit better ductility when compared to the conventional concrete beams and beams strengthened with CFRP laminates (Ravichandran *et al*., 2012; Mariappan Mahalingam *et al*., 2013; Gopinathan *et al*., 2016; Gugulothu Rambabu *et al*., 2016). Because glass fabrics are more ductile than the carbon fabrics. This inherent basic material property imparts ductility to GFRP strengthened concrete beams. The beams strengthened using CFRP laminates exhibit better ductility when compared to the conventional concrete beams (Nadeem AhsanSiddiqui, 2010; Ehsan Ahmed *et al*., 2011; Rajeswari and Meikandaan, 2015; Renata Kotynia and Szymon Cholostiakow, 2015). But it was comparatively less than that of beams strengthened using GFRP laminates. Because carbon fabrics are brittle in nature. This basic material property reduces the ductility significantly. Also in the beams strengthened with CFRP laminates, ductility has been reduced because of debonding and peeling of CFRP laminates (Habibur Rahman Sobuz *et al*., 2011). In case of hybrid FRP strengthened concrete beams, particularly the hybrid FRP made of carbon and glass fabric, the increase in ductility depends on the number of glass layers (Thomas Kang *et al*., 2014). An increase in GFRP layers improves the ductility significantly (Xiong *et al*., 2004; Thomas Kang *et al*., 2014; Nachimuthu *et al*., 2015). The beam strengthened using hybrid FRP laminates shows an appreciable increase in ductility when compared to conventional concrete beams and the CFRP strengthened beams (Xiong *et al*., 2004). The hybrid glass/carbon FRP composite changed the linear elastic characteristics of CFRP which has good impact on the ductility of strengthened RC beams (He *et al*., 2013). However a reduction in ductility was observed when compared to the concrete beams strengthened with GFRP laminates alone. Also the order of attaching different types of FRP affects the ductility of RC beams retrofitted with hybrid fibre reinforced polymer laminates. It was also reported that the beams with glass fabric attached prior to carbon fabric exhibit improved strength and ductility (Hee Sun Kim and Yeong Soo Shin, 2011).

Failure Mode

In the majority of research, the conventional under-reinforced concrete beams exhibited yielding of internal reinforcement followed by the crushing of concrete that is the flexural mode of failure (Barros *et al.,* 2007; Nadeem AhsanSiddiqui, 2010; Ehsan Ahmed *et al.,* 2011; Habibur Rahman Sobuz, 2011; Jose Sena-Cruz *et al*., 2012; MagdaMousa *et al*., 2015; Rajeswari and Meikandaan, 2015; Renata Kotynia and Szymon Cholostiakow, 2015; Mohan Babu *et al*., 2007; Sing-Ping Chiew and Qin Sun and Yi Yu, 2007; Jadhav and Shiyekar, 2011; Katarey Damodar and Satish, 2015; Ravichandran *et al*., 2012; Mariappan Mahalingam *et al*., 2013; Ayad Adi *et al*., 2014; Parthiban *et al*., 2014; Gopinathan *et al*., 2016; Gugulothu Rambabu *et al*., 2016; Xiong *et al.,* 2004; Zhishen *et al.,* 2006; Attari *et al.,* 2008; He *et al.,* 2013; Khaled Galal and Amir Mofidi, 2009; Dong *et al.,* 2012; Hee Sun Kim and Yeong Soo Shin, 2011; Attari *et al.,* 2012; Eunsoo Choi *et al.,* 2013; Mohammed Rashwan *et al.,* 2015; Tara Sen and Jagannatha Reddy, 2013; Rami Hawileh *et al.,*2014; Thomas Kang *et al.,* 2014; Moshiur Rahman *et al.,* 2015; Nachimuthu *et al.,* 2015; Karthick *et al.,* 2017). The beams strengthened with CFRP laminates exhibited flexural mode of failure primarily. A secondary failure mode is by debonding of CFRP sheets from the concrete surface (Barros *et al*., 2007; Nadeem AhsanSiddiqui, 2010; Ehsan Ahmed *et al*., 2011; Habibur Rahman Sobuz *et al*., 2011; MagdaMousa, 2015; Rajeswari and Meikandaan, 2015; Renata Kotynia and Szymon Cholostiakow, 2015; Mohan Babu *et al*., 2007; Sing-Ping Chiew *et al*., 2007; Jadhav and Shiyekar, 2011; Katarey Damodar and Satish, 2015). A premature debonding of FRP sheets was observed by some researchers (Zhishen Wu *et al*., 2006). The beams strengthened with GFRP laminates exhibited flexural mode of failure primarily. A secondary failure mode is rupture of GFRP material (Jadhav and Shiyekar, 2011; Katarey Damodar and Satish, 2015; Ravichandran *et al*., 2012; Mariappan Mahalingam *et al*., 2013; Ayad Adi *et al*., 2014; Parthiban *et al*., 2014; Gopinathan *et al*., 2016; Gugulothu Rambabu *et al*., 2016). The beam strengthened with hybrid FRP laminates also exhibited same primary mode of failure. A secondary failure mode by rupture of hybrid FRP sheets was observed by some researchers (Xiong *et al*., 2004; Attari *et al*., 2008; Attari *et al*., 2012). In some cases, debonding of FRP sheets was observed (Jose Sena-Cruz *et al*., 2012; Rami Hawileh *et al*., 2014). In some cases partial delamination of FRP sheets along with ripping of cover concrete was observed (Hee Sun Kim and Yeong Soo Shin, 2011; Karthick *et al*., 2017). As far as the secondary failure mode of hybrid FRP strengthened RC beam is concerned, it primarily depends on the combination and number of layers of individual FRPs.

Conclusion

In this article, a review has been conducted on the topic of structural performance of concrete beams strengthened using FRP laminates under static loading condition. Based on the review, the following conclusions are drawn.

- The beams strengthened with CFRP laminates exhibit an appreciable increase in strength and stiffness and reduction in deformation than the other FRP strengthened beams. However the brittle nature of CFRP laminates reduced the ductility of the beams siginificantly. CFRP laminates are most suitable for structural strengthening where strength is in demand.
- The beams strengthened with GFRP laminates exhibit an appreciable increase in ductility. But the increase in strength is in margin level only. GFRP laminates are most suitable for structural strengthening where ductility is in demand.
- The beams strengthened with hybrid FRP laminates exhibited increase in both strength and ductility. Because the advantages of both CFRP and GFRP laminates are derived in hybrid FRP laminates.The performance of hybrid FRP strengthened beams mainly depends on the number of layers of individual FRP laminates.
- Yielding of steel followed by the crushing of concrete is the primary mode of failure for all the FRP strengthened beams.
- The use of anchors in externally bonded FRP strengthened concrete beams improved their overall performance significantly.

Recommendations for future research

Based on the review results and gap analysis, the following recommendations are suggested for further research

1. The impact of internal confinement coupled with externally bonded hybrid FRP laminates on the structural performance of concrete beams can be evaluated.
2. The effect of hybrid FRP laminates on the performance of concrete beams with micro-reinforcements can be examined.
3. The influence of externally hybrid FRP laminates on the structural behaviour of high strength concrete beams can be investigated.
4. The use of surface mounted hybrid FRP laminates for beams under reversed cyclic loading condition can be explored.

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