APPLICATION OF FRP COMPOSITES IN STRENGTHENING REINFORCED CONCRETE STRUCTURES - AN INTRODUCTION

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Abstract: *This paper reviews the use of fibre reinforced polymer materials in strengthening and retrofitting reinforced concrete structures. There is an increasing need around the world to strengthen concrete structures which are caused by many reasons in the service loads, deterioration of structures with time, fatigue of structures due to repeated loads, especially for bridge structures. FRP composites have been used as a promising solution in replacement of traditional strengthening methods to repair, strengthen and retrofit concrete structures for the last three decades thanks to its advanced properties. Methods of using externally bonded FRP laminates in strengthening concrete structures are presented herein.*

Keywords: *CFRP, composite materials, strengthening, concrete structures.*

1. Introduction

1.1. FRP materials

The use of fibre reinforced polymer (FRP) materials for strengthening existing reinforced concrete (RC) members has been widely recognized as a highly promising technique with many evident advantages including high strength-to-weight ratio, high corrosion and heat resistance, ease and speed of application, and practically unlimited availability in FRP sizes, geometries and dimensions [1, 2]. The types of FRP available for strengthening are carbon, glass and aramid in the shapes of plates, sheets, strips, rebars and rods. The most commonly used FRP strengthening methods are: the use of externally bonded FRP plates, sheets or strips on the surface of a concrete member or the use of near surface mounted FRP bars, which are embedded in concrete block via grooves, and the use of FRP rods as prestressing tendons. The application of FRPs to existing RC structures can be grouped into axial, shear, and flexural strengthening. External wrapping with FRP sheets for flexural, shear and axial strengthening of RC members is of the interest of this paper.

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1.2. Needs to strengthening

There are many reasons that a structure need to be strengthened including the increase in the service loads, deterioration of structures with time, or fatigue of structures when subjected to repeated loads, especially for bridge structures or errors during construction. In fact, deficiencies related to aging bridges or increase in the loading standards, have become a major concern in many countries in the last three decades.

In the United States, more than 70% of the bridges were built before 1935 [3], and a large proportion of the United Kingdom's current bridge stock was built between the late 1950s and early 1970s [4]. Due to various types of deterioration and partly because loading standards have increased over the years, many of these bridges are now defined as deficient bridges.

American Society of Civil Engineers [5]reported that in 2012, one in nine, or just below 11%, of the nation's bridges were classified as structurally deficient, in which 22 states have a higher percentage of structurally deficient bridges than the national average, while five states have more than 20% of their bridges defined as structurally deficient. 24.9% of the nation's bridges were defined in either deficiency category. In the United Kingdom, it was estimated that 20% of the 155,000 road bridges had some sort of strength deficiency [6].

In New South Wales, Australia, around 70% of bridges were built before 1985, with a significant percentage in the mid 1930's, and the peak in the 70's [7]. Australia's infrastructure condition was assessed to be in urgent need of rehabilitation especially for the highway bridges [8].

In Vietnam, most of bridges were built before 1954, in which 1,672 bridges were classified as structurally deficient bridges reported by Directorate for Roads of Vietnam (DRVN). In 2012, it was stated that there are 566 deficient bridges which need to be strengthened, wherein 148 bridges have been projected to repair, 111 bridges are in urgent need of repair and retrofitting using investment construction capital, while 45 bridges and 262 bridges call for retrofitting and upgrading in the periods of 2012-2015 and 2015-2020, respectively.

Strengthening RC structures using FRPs composites has been done and applied in many countries including Japan, United States, Canada, and United Kingdom since 1990s. It, however, is still a new material to Vietnam. As the author is aware, there was only a group of researchers at University of Transportation and Communication, Hanoi are involving in this field of research and application. This paper aims at giving a general view on the application of FRPs on strengthening RC structures.

2. Mechanical properties of FRPs

Three types of FRP laminates namely Glass fibre reinforced polymer (GFRP) laminates, Carbon fibre reinforced polymer (CFRP) laminates, and Aramid fibre reinforced polymer (AFRP) laminates have been used for strengthening RC structures both in practical and research. The details of mechanical properties of FRPs and their forming process can be found elsewhere [2, 9].

Figure 1 shows an example of a roll of CFRP laminate.

It is worthy to note that despite steel material, which show an elasto-plastic behavior after yielding, all three types of FRP laminates behave linearly elastically up to failure, which is brittle rupture in nature when subjected to tension (Fig.2)

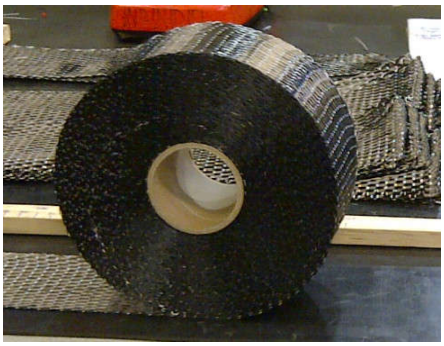

Figure 1. *A roll of CFRP laminates*

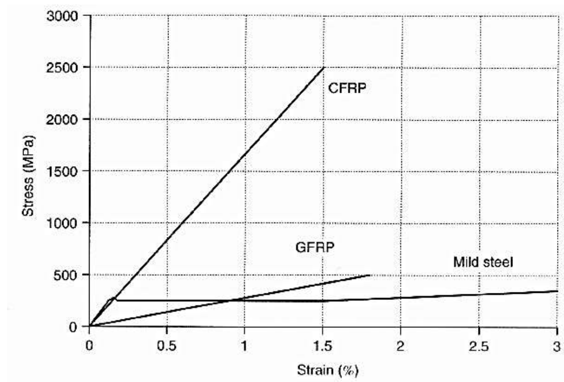

Figure 2. *Typical FRP and mild steel stress-strain curves*

3. Externally bonded FRP laminates

Externally bonded FRP systems can be used for flexural, shear strengthening, and axial strengthening of members subjected to axial forces or combined axial and bending forces. There are a number of guidelines and standards on the design and construction of externally bonded-FRP systems for strengthening RC structures [2, 10-12].

3.1. Flexural strengthening

Bonding FRP laminates to the tension face of a concrete flexural member with fibres oriented along the length of the member shows an increase in both flexural strength and ductility of RC beams (Fig. 3). The increase in the ultimate streng this found to be ranging from 28% to 97% of that of unstrengthened beams depending on different types of laminates used [13-15]. Faza and GangaRao [16] reported an increase of 200% in strength when CFRPC laminates are wrapped around beams.

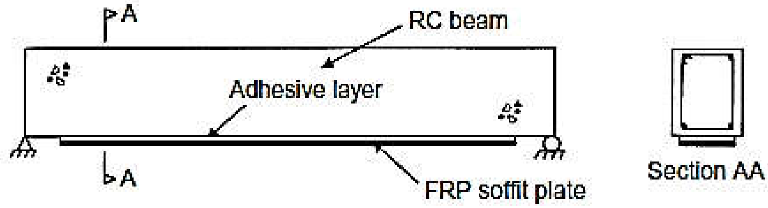

Figure 3. *Bonding FRPs to the soffit of a beam*

A key issue in the design of an effective retrofitting solution using externally bonded plates is the end anchorage strength [17]. The end anchorage strength greatly affects the failure modes of the strengthened system, which in turn affects the ultimate strength capacity of the strengthened beams and the selection of calculation models. If the ends of the plate are properly anchored, then failure occurs when the ultimate flexural capacity of the beam is reached, by either tensile rupture of the FRP plate or crushing of concrete in the compression fibre depend on the amount of strengthening (Fig. 4a, b).

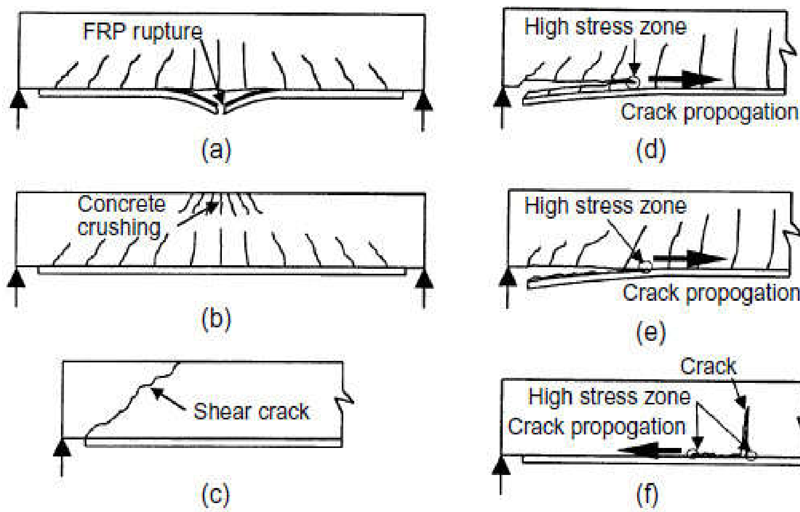

***Figure 4.** Failure modes of strengthened beams*

Whereas, incorrect anchorage system or beams without anchors at the plate ends may resulted in premature debonding failures characterized by plate end debonding and concrete cover separation due to the high interfacial shear and normal stresses at the laminate end (Fig. 4d, e, f). These interfacial shear and normal stresses can be reduced by extending the bonded length of the FRPs. There, however, exists a certain bonded length, over which no increases in the end anchorage strength are shown [17, 18]. As such, other methods in order to increase the end anchorage strength are developed. A review of anchorage systems for externally bonded FRP laminate systems was conducted by [19]. Examples of common anchorage systems are shown in Figures 5-8.

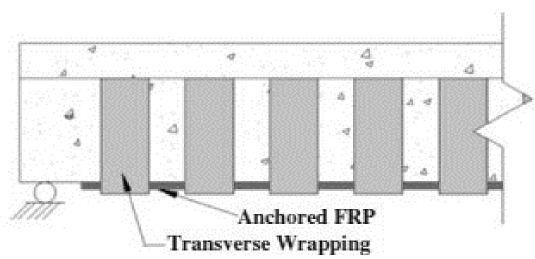

***Figure 5.** Transverse wrapping anchorage on T-beam*

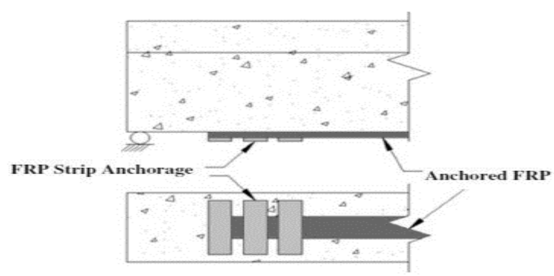

***Figure 6.** FRP strip anchorage*

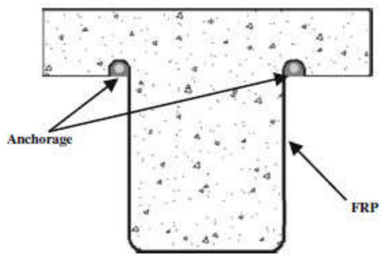

Figure 7. *Schematic of typical U-Anchor*

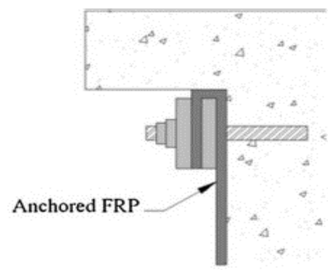

Figure 8. *Plated anchorage types*

3.2. Shear strengthening

Three types of wrapping schemes are often used to strengthen RC beams in shear, including side bonding, U-jacket and completely wrapping FRP around the section of the beams. FRP can be aligned vertically, horizontally or diagonally at an angle to the beam's longitudinal axis. An angle of 45° is normally used in the case of diagonally wrapping the FRP at an angle (Fig. 9).

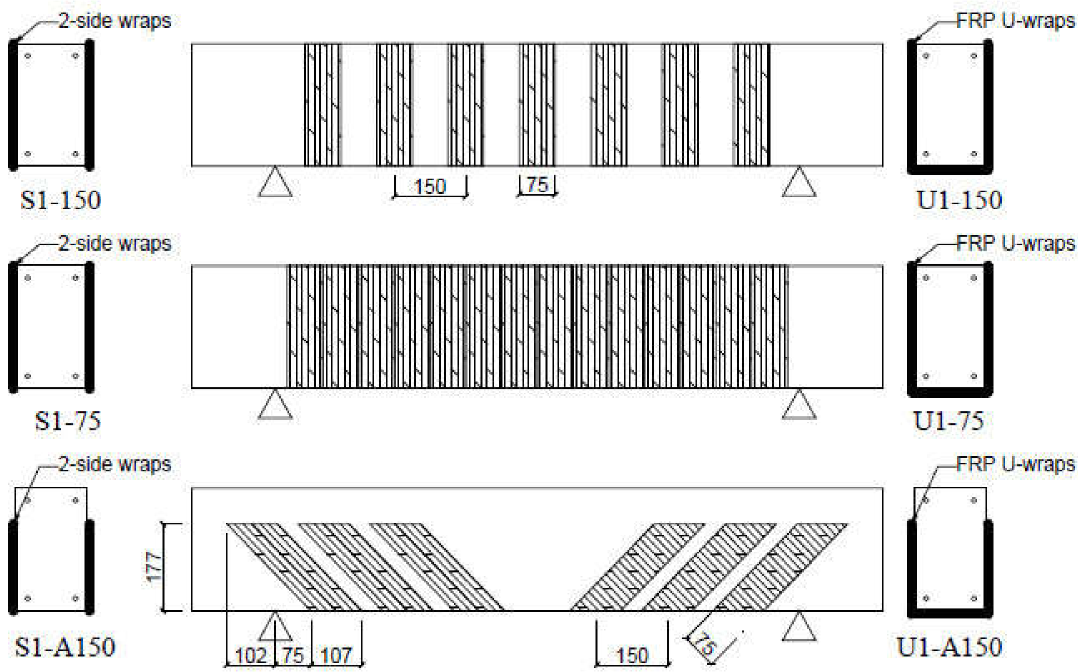

Figure 9. *Strengthening beams in shear*

Literature reveals that the fibre orientation of the FRP strongly affects the effectiveness of the FRP system in terms of shear enhancement and the propagation of inclined cracks of a FRP-strengthened beam in shear.

Vertical and diagonal FRP wraps were used by several researchers [20, 21]. The test results showed both vertical and diagonal strips contributed to the increase of the ultimate force of the beam, in which the diagonal strips outperformed the vertical strips.

Horizontal, vertical CFRP sheets and their combinations were used in the study of Adhikary and Mutsuyoshi [22] to strengthen RC beams in shear. The tests revealed that the specimen strengthened with vertical FRP sheets displayed a greater ultimate strength as compared to the specimen strengthened with horizontal FRP sheets. The beam with both horizontally and vertically aligned FRP sheets showed slightly higher diagonal crack strength than the beam with only horizontally aligned FRP sheets.

3.2. Axial strengthening

FRP systems can be used to increase the axial compressive strength of a concrete column by providing confinement with a FRP jacket [2]. By orienting the FRP layers transverse to the longitudinal axis of a member, the transverse or hoop fibres are similar to conventional spiral or tie reinforcing steel (Figs. 10-11). Due to its high modulus of tensile elasticity in the fibre direction, FRP layers can provide a considerable confinement pressure to the concrete core of the member under axial compressive loads. This confinement action delays the crushing of concrete, thereby increasing the compressive strength and deformation capacity of the column.

Figure 10. *Strengthening rectangular columns with hoop FRP sheets*

(a) (b)

Figure 11. *Strengthening circular columns with (a) hoop FRP sheets, (b) steel strips*

The improvement of the axial behavior of FRP confined concrete has been verified by a number of studies [23, 24]. Most of these studies were carried out on plain concrete cylinders, having typical dimensions of 150 mm in diameter and 300 mm in height. The specimens were wrapped with FRP layers in the hoop direction. All these studies have indicated that FRP jackets enhance the compressive strength and ductility of confined concrete. These increases substantially depend on: the properties of FRP jackets such as strain capacity and stiffness; thickness of FRP jackets such as the number of FRP plies; and types of FRP jackets such as CFRP, GFRP, and AFRP.

The effectiveness of FRP is also strongly influenced by the cross-section geometry. FRP jackets are most effective in confining members with circular cross-sections in terms of both strength and ductility. For noncircular cross-sections i.e. square and rectangular sections, the increase in the maximum axial compressive strength is marginal [25, 26]. This is due to the stress concentration at the corners of the section resulting in non-uniform distributed stress surrounding the member's cross-section.

These enhancements, however, are achieved only when a column is tested concentrically or when the eccentricity of the load is small. In fact, Bank [9] has shown that the strength enhancement is only of significance for members in which compression failure is the controlling mode. When the eccentricity is large, the effectiveness of hoop FRP layers is significantly reduced because both axial action and bending action are induced. This reduction due to the effect of eccentricity is true for both circular and non-circular cross-section columns [27, 28].

In the case, when the eccentricity of the load is large, the use of vertical and inclined oriented FRP layers significantly contributes to the gain in the strength and ductility of the strengthened columns [29, 30]. In their study, Hadi and Widiarsa [29] used square, reinforced concrete columns confined with CFRP. The influence of the presence of vertical FRP straps was investigated. The specimens were tested under eccentricities of 0, 25, 50 mm and pure bending loading. The results of the study showed that the application of the vertical CFRP straps significantly improved the performance of the columns with large eccentricity. In the case of concentric loading, the specimens with vertical FRP straps showed an 8.4% increase in the maximum strength relative to the unwrapped specimen. Meanwhile, increases of 17.8% and 14.8% were achieved when testing specimens under eccentricities of 25 and 50 mm.

4. Conclusion and recommendation

The use of externally bonded FRP laminates for flexural, shear and axial strengthening of concrete structures has been reviewed in this paper. Several conclusions can be made as follows:

FRPs can effectively be used as an alternative solution replacing traditional strengthening methods such as constructing an additional reinforced concrete cage or installing grout-injected steel jackets. Literature review shows that FRPs can ensure both structural, aesthetical and economical aspects in strengthening and retrofitting concrete structures.

Externally bonded FRPs can greatly enhance the strength and ductility of the concrete structures. FRPs can be used for strengthening concrete structures in flexure, shear and axial loads. The enhancement in the behavior of a FRP-strengthened beam is influenced by many factors including,1) FRP system,i.e. FRP properties, FRP thickness, wrapping schemes, fibre orientations; 2) Conditions of existing structures such as beam's geometry, concrete strength, steel reinforcement ratios (transverse and longitudinal steel reinforcement); 3) Loading schemes and loading types such as concentric or eccentric loads, static, or dynamic loads.

FRPs have been used for strengthening concrete structures since 1990s, however, it is still a new material to Vietnam both practical and research community. Therefore, it is highly recommended to study the application of this material in reply to the current need of repair, retrofit and strengthening structures in Vietnam. In which, factors affecting the actual working conditions of the structures such as traffic loading conditions, climate conditions on the long-term behavior of FRP system are focused on.

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