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NFRP strengthening of reinforced concrete beams

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Abstract. The construction industry is currently the second largest consumer of synthetic FRP products. Increasing environmental awareness and the push for sustainable development fuels the drive to develop high strength natural fibres and bioplastics that can replace the conventional synthetic FRP components. Lignocellulosic plant fibres have considerable high strength and they are currently being used for non-structural applications in various industries. With proper fibre selection, the right fibre orientation, optimal fibre aspect ratio and good interfacial adhesion property between fibre and matrix, natural fibre reinforced polymer (NFRP) composite can be developed for structural applications. This review discusses NFRP composite in terms of its constituents, the fibre-matrix interaction, its manufacture and its use for strengthening of reinforced concrete (RC) beams.

1. Introduction

Fibre reinforced polymer (FRP) plates or wraps for strengthening structural members was introduced as an alternative to the use of steel plates and has gained popularity over the last four decades for its high strength and stiffness to weight ratios, its corrosion resistance and its ease of handling and installation [1–4]. The use of steel plates bonded to structural members with adhesive resin was very effective in increasing the flexural strength of structural members but had some drawbacks; over time the steel plate corroded which compromised the bond between the plate and concrete. It was also accompanied with strenuous delivery of plates to site, difficulty in handling and installation leading to the need for heavy equipment, anchoring issues, long installation periods, and increase of structures dead load [3,5–7].

Conventional FRP composite is a combination of synthetic fibres and petroleum-based plastic. These synthetic polymer composites are often non-recyclable and this creates negative environmental implications as the production of synthetic fibres from petroleum adds to global warming issues [8]. The use of natural fibres as reinforcing material in fibre reinforced polymer composites is gaining considerable attention over synthetic fibres due of its relatively low cost, its high strength to weight ratio, it induces less damage to processing equipment, it is renewable and abundant, flexibility during processing, biodegradability and minimal health hazards accompanied with its use [9]. Another environmental advantage to the use of natural fibres is that they absorb more carbon dioxide than they produce, making them carbon positive [10]. Though there are advantages in favour of natural fibres over synthetic fibres but NFRP composites will only be commercially viable when they can be used in the same application as the existing materials for which they are intended to replace [11].

2. FRP composites

Similar to the internal structure of wood that is a composite of cellulose fibres in a matrix of natural lignin gel, fibre reinforced polymer or fibre reinforced plastic is a composite material comprising of a load transference medium which is the matrix material and the reinforcement material (Figure 1).

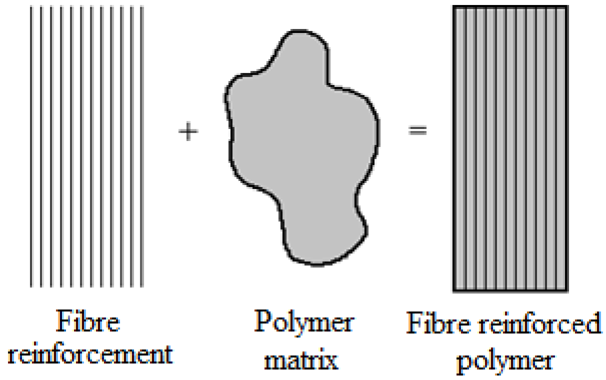

Figure 1. Formation of FRP composites

2.1. The matrix material

The matrix component of FRP composites receives and transfers loads imposed on the material, it binds the reinforcing fibres together providing the rigidity and shape of the composite, it provides a good surface finish, it protects the fibres from chemical attack and mechanical damage, it isolates the fibres so they can act individually, it slows down the propagation of cracks, it controls the ductility of the material, it protects the reinforcing fibres from impact and also absorb seismic induced vibrations on rigid structures [8,12,13]. Polymer matrices are classified into thermosets and thermoplastics. Thermosetting matrices are resins formed as a result of a chemical reaction between resin and hardener resulting in an irreversible hard resin while on the other hand, thermoplastic matrices are hard when cured but become soft when exposed to heat. Common examples of thermosets are polyester, vinyl ester and epoxy and common examples or thermoplastics are polypropylene (PP), low density polyethylene (LDPE), high density polyethylene (HDPE) and nylon.

2.2. The reinforcing material

The reinforcing material in FRP composites determines the strength and stiffness of the material carrying 70-90% of the load imposed on the composite [12] hence the mechanical properties of the reinforcement determines the mechanical properties of the composite [8,10]. Reinforcing material in FRPs is usually in the form of fibres with the most common fibres being carbon, glass and aramid. These materials have been widely used in various industries due to their high strength and modulus [14]. Due to the increasing awareness of the environmental implications of the use synthetic fibres, it has become crucial to explore the potential of natural fibres as a substitute to synthetic fibres [15]. The low cost of natural fibres in relation to synthetic fibres also increases its commercial and research potential [13].

3. NFRP composites

The performance of an NFRP composite plate is dependent fibre orientation, fibre strength, fibre aspect ratio and the interfacial adhesion property of fibre and matrix [9,16]. Similar to typical synthetic FRP composites, NFRP composites consist of a polymer matrix reinforced with natural fibres as shown in Figure 2.

Figure 2. Components of an NFRP plate; (a) hardened polymer [17] (b) natural fibre [18] (c) Fabricated NFRP plates with different natural fibres [18]

3.1. Natural fibres

Natural fibres can be gotten majorly from plant and animal sources making it a renewable resource. Animal based fibres mainly target biomedical applications while plant based fibres are commonly used to make polymer composites for domestic and structural applications [13]. Plant fibres are composed of cellulose, hemicellulose, lignin, pectin and waxy substances [19]. Fibres with cellulose, hemicellulose and lignin as its main components are classified as lignocellulosic. Generally, lignocellulosic plants have their structure similar to that of FRP composites made up of cellulose fibrils in a hemicellulose and lignin matrix. In this composite, cellulose is the main structural composite [19] and the strength of the fibre increases with the cellulose content but the amount of cellulose in a plant varies on the age and specie of the plant [20].

The mechanical properties of natural fibres are derivative of the fibres structure, defects, physical properties, chemical properties, microfibrillar angle and cell dimensions and these properties are a function of the plants origin, species, soil and weather conditions in which it was grown [9,15,21]. Table 1 outlines the mechanical properties of some natural fibres along with the synthetic fibre types.

Table 1. Properties of selected natural and manmade fibres [22–26]

Fibre	Fibre type	Density (g/cm^3)	Elongation at break (%)	Tensile strength (MPa)	Elastic Modulus (GPa)
Jute	Bast	1.3	1.5 – 1.8	393 – 773	26.5
Flax		1.5	2.7 – 3.2	500 – 1500	27.6
Hemp		1.47	2 – 4	690	70
Kenaf		1.45	2.7 – 6.9	295 – 930	53
Ramie		1.44	4 – 4	400 – 938	61.4 – 128
Sisal	Leaf	1.5	2.0 – 2.5	511 – 635	9.4 – 22
Pineapple		1.5	1 – 3	170 – 1627	34.5 – 82.5
Banana		1.35	3 – 10	529 – 914	8 – 32
Cotton	Seed	1.5 – 1.6	7.0 – 8.0	400	5.5 – 12.6
Coir	fruit	1.2	30.0	593	4.0 – 6.0
Wheat	Stalk	0.6 – 0.8	2.7	10 – 200	1 – 12
Rice		1.65	2.2	449	1.21 – 1.25
Bamboo	Cane	0.6 – 1.1	4.0 – 7.0	140 – 230	11 – 17
Spider silk	Silk		17 – 18	875 – 972	11 – 13
E-glass	Synthetic	2.5	0.5	2000 – 3150	70.0
S-glass		2.5	2.8	4570	86.0
Aramid		1.4	3.3 – 3.7	3000 – 3150	63.0 – 67.0
Carbon		1.4	1.4 – 1.8	4000	230 – 240

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Lignocellulosic fibres are light weight and have lower costs than synthetic fibres and can be substituted for glass fibre reinforced polymer (GFRP) composites in diverse applications [13,27] but glass fibre is still more preferred for engineering applications that need mechanical performance due to its higher strength. The market base of NFRP composites will increase when the mechanical properties are aligned towards structural application [28]. Natural fibres can become a viable substitute for synthetic fibres in certain applications when high strength fibres are used and when a good fibre-matrix bond is guaranteed.

3.2. Natural fibre – matrix bond

Polymer matrix and natural fibre in NFRP composites have different susceptibility to moisture; matrix materials have a hydrophobic nature and natural fibres are hydrophilic. This contrasting property of the two materials causes poor adhesion leading to an improper load transference from matrix to fibre [28,29]. Natural fibres consist of hydroxide functional groups that permit water absorption from the surrounding and this in turn weakens the binding between the fibre and matrix [9]. This poor fibre-matrix adhesion can be solved either by fibre surface modification by physical means or chemical means. Physical treatment includes stretching, thermo treatment and calendaring; these aim to change the structural and surface characteristics of the fibres, increasing the mechanical bonding with the polymer [21]. Chemical modification changes the fibre surface condition by introducing another material to interfere and enhance the interface resulting in reduction of the moisture absorption capacity of natural fibres and increased mechanical strength of composites [9,29]. The various types of chemical modifications includes alkali treatment or mercerization, acetylation, graft copolymerization, coupling agents, permanganate and nanocellulose treatment [30].

Alkaline treatment facilitates the removal of non-cellulosic substances from fibre surface which when broken down increases the fibres surface area; the treatment also roughens the fibre surfaces and these enhance the interaction between fibre and matrix [31]. Alkaline treatment is usually carried out by soaking fibres in sodium hydroxide (NaOH) after which they are dried, this process has been reported in various literature (Alam & Riyami, 2018; Asim, Jawaid, Abdan, & Ishak, 2016; Aziz & Ansell, 2004; Chin *et al*., 2018; Hossain *et al*., 2011; Mahjoub *et al*., 2014; Zakikhani, Zahari, Sultan, & Majid, 2014).

3.3. NFRP composite manufacture

The various methods of FRP composite manufacture includes compression moulding, resin transfer moulding, pultrusion, pressure bag moulding and hand lay-up method [36]. Irrespective of the method used, composite manufacture involves wetting (impregnation), lay-up, consolidation and solidification [37]. Impregnation is the mixing of fibre and matrix to form lamina; lay-up involves arranging the fibres at the desired angles and building up the layers to fibre and matrix to the desired composite thickness; consolidation is the process that ensures entrapped air is removed that intimate contact between successive layer is established and solidification depending on the cure kinetics of resin used is the final step where vacuum or pressure is maintained. Hand lay-up or wet lay-up process is commonly used and has been used extensively reported in literature [32,38,39] as it is a flexible process that does not require any sophisticated equipment and involves little capital investment [37]. In producing large quantities of NFRP composites, hand lay-up method becomes labour intensive and the quality of composite produced may be inconsistent from part to part [37].

4. Synthetic FRP flexural strengthening systems

Though FRP were developed in the 1960’s and used in the aerospace and defense industries it was not until 1978 an experimental program was developed in Germany considering FRP for strengthening of concrete structures then later applied for flexural strengthening of reinforced concrete bridges in Switzerland in 1987 [6]. The use of FRP laminates for flexural strengthening principally involves bonding the laminate to the tension face of structural elements with the fibres parallel to the principal stress direction [5]. Deflection is a function of load, beam length, section moment of inertia and the moment of elasticity of concrete; thus attaching carbon fabric results in reduced deflections due to the increase in beam stiffness [40].

Sobuz, Ahmed, Hasan, & Uddin (2011) [41] investigated the effect of carbon fibre reinforced polymer (CFRP) strengthened RC beams using various number of CFRP layers (1, 2 and 3) bonded to the tension face of the beams. The cracking load of the beam with 1, 2, and 3 layer of CFRP increased by 25%, 50% and 75% respectively and ultimate loads also increased by 54%, 73% and 85% respectively; these beams failed by laminate debonding. Toutanji et al. (2006) [42] externally reinforced concrete beams with CFRP sheets; various number of layers CFRP sheets (3 to 6 layers) where bonded to the tension face of the beam for flexural strengthening. It was observed that three, four, five and six layers of CFRP increased the ultimate load of the beam by 42.6%, 49.2%, 67.8% and 70.2% respectively compared to the strengthened beam. There was no significant gain observed with six layers as compared to five and the increase in FRP layers also facilitated the change of failure mode from FRP rupture to FRP delamination. This delamination occurred after the formation of flexural cracks causing bond deterioration between CFRP laminate and concrete surface.

Stallings et al. (2000) [2] used studied the strengthening effect of CFRP and GFRP plates on a 48year old bridge. The bridge needed to be strengthened to account for increasing loads due to increase in truck weight limits; the bridge was seriously deteriorating with visible cracks from the bottom of the bridge to the soffit of the deck slab. CFRP sheets were bonded to the tension beam face for flexural strengthening and GFRP sheets were bonded to the beam sides for shear strengthening. Results of the tests carried out showed that the FRP strengthening system reduced mid-span deflections and reduced rebar stresses up to 12%.

Concerning flexural strengthening of RC beams, high strengths and stiffness of synthetic FRP sheets have led to premature failure of the beams due to debonding of the sheets from the concrete surface. As a result of this, the capacities of synthetic FRP sheets are not utilized leading to waste of materials. Also, beams strengthened with synthetic FRP sheets have also been characterised with very brittle failure. The use of NFRP laminates for the strengthening RC beams in place of synthetic FRP has attempted to confront these issues.

5. Natural FRP strengthening systems

A number of researchers have developed high strength natural fibres polymer composites and have reported that they can be used for structural applications but the use of this for strengthening reinforced concrete structures is not often done [18].

Sen & Reddy (2013) [38] investigated the effectiveness of using jute fibre textile reinforced polymer (JFRP) composite for flexural strengthening of reinforced concrete beam and compared the results with CFRP and GFRP composites. The beams strengthened with JFRP had an increase in its load of 62.5% with failure occurring by rupture of the FRP composite while the beams bonded with CFRP and GFRP increased the load carrying capacity of the beams by 150% and 125% respectively. The ductility of the strengthened beams was measured using a deformation index determined as the ratio of the ultimate deflection to the deflection at first crack. Beams strengthened with JFRP had the highest deformity index and this higher deformity index indicated more plastic deformation leading to the conclusion that JFRP strengthened beams were more ductile than CFRP and GFRP strengthened beams.

Cervantes et al. (2014) [3] strengthened reinforced concrete beams using green natural fibre reinforced polymer (GNFRP) comprising of a bio-derived resin reinforced with hemp fibres and compared the results with a beam strengthened with one layer of CFRP. Experimental study was done and results were verified with numerical analysis and both results showed good correlations. The GNFRP plate, strengthened the beam by about 68% while the CFRP strengthened beam had a 120% increase in its load carrying capacity. The increase of the rigidity of the CFRP strengthened beam was at a cost to the ductility of the beam; failure mode of the beam changed from ductile to brittle.

Shear strengthening with FRP laminates involves bonding strips of the laminate to the sides of the beams in contrast to the soffit of the beams in the case of flexural strengthening. Alam et al. (2015) [43]

proposed a theoretical model for kenaf fibre reinforced polymer (KFRP) laminate shear strengthened beams. RC beam were strengthened with both CFRP and KFRP laminates; KFRP strengthened beams failed by rupture of KFRP laminate then shear while CFRP strengthened beams failed by flexural shear failure then by debonding of the laminate. Though the CFFR laminate had an elastic modulus which was 1310% more than the KFRP laminate they had similar strengthening effects on the beams. Shear failure started occurring at the same loads in the two cases recording a 100% increase in the shear crack load compared to the control beam. Also, KFRP increased the ultimate load capacity by 32.85% to the control beam while CFRP caused a 34.31% increase. KFRP laminates reached their full capacities while CFRP laminates debonded before reaching its ultimate strength.

6. Conclusion

High strength natural fibres can be used as a substitute to synthetic fibre as reinforcement in polymer composites. The hydrophilic nature of natural fibres is a drawback to its use but can be addressed with chemical treatment.

RC beams strengthened with NFRP laminates are more ductile than beams strengthened with synthetic FRP laminates and have been proven to increase the load carrying capacity of reinforced concrete beams but more than 50%. The use of NFRP laminates in place of CFRP and GFRP is a promising development concerning the strengthening of RC beams but there is a need to further understand the failure modes of RC beams strengthened with NFRP.

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