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Review Article

# FRP strengthening of RC structures: Sustainable, environmental and structural evaluations

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## ABSTRACT

Strengthening and rehabilitation have been widely implemented for many years to extend the service life of reinforced concrete structures. The paper begins with a comprehensive review of the fiber-reinforced polymers (FRP) utilization on strengthening, particularly over the traditional materials formerly used in practice with respect to materials, manufacturing, operation, Construction, and maintenance phases as the engineering and environmental performance of such materials. Carbon and Glass FRP, the most frequently used strengthening materials, are particularly designated in the study and are employed to conduct an environmental performance evaluation using the previously published data in the literature. The paper then investigates the punching shear strength of flat slab-column connections strengthened with externally bonded FRP using a nominated database comprising 57 data points harvested from the recent literature. The database is used to evaluate the test data with TS 500 code equations and the recent modification of Chen and Li. The study enabled the key factors affecting the punching shear strength of such connections to be emphasized and highlighted that the TS 500 code equations fall conservative in predicting the punching shear strength of slab-column connections strengthened with FRP. The study is novel as it provides a comprehensive review of the FRP as a strengthening material regarding environmental sustainability. It also provides insight into the structural implications of this material by evaluating the current TS 500 code provisions and recent modifications.

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## 1. INTRODUCTION

Strengthening refers to converting a non-damaged structure or structural element to a higher level of performance than its existing condition [1]. Inadequate maintenance, overloading, changes in the standards of application, or exposure to severe environmental conditions often necessitates strengthening reinforced concrete structures [2].

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Steel plate bonding, external pretension addition, cross-sectional enhancement, and reinforced concrete coating are some of the strengthening techniques that have been developed in the past and have gained significant popularity over the last decades. Although the methods mentioned above can successfully increase the load-bearing capacity of such components, they are often prone to corrosion [3]. This feature causes the strengthening system to lose its function both in the medium and long term. Consequently, the traditional strengthening methods have mainly been replaced with new non-corrosion strengthening systems such as fiber-reinforced polymers (FRPs). Hence, the potential to extend reinforced concrete structures' service life has been considerably expanded with reduced maintenance costs [4].

Strengthening materials can be investigated in two categories as traditional and advanced strengthening materials [5]. Steel and concrete are the most utilized traditional strengthening materials [2, 6]. The traditional materials' strengthening methods comprise cross-sectional enlargement, external prestressing and steel plate bonding, and Ferro-cement coating methods. FRP composite materials, the so-called advanced material, are successfully used to construct new structures and repair and strengthen existing structures [7]. The most commonly used FRP reinforcement methods are external bonding and near-surface mounting [8, 9].

The cement industry is an essential source of greenhouse gas (GHG) emissions, particularly $CO_2$ emissions. The cement industry, for instance, accounts for about 7% of global $CO_2$ emissions [10]. This is mainly due to the calcination process of raw materials necessary for producing cement and fossil fuels burned to maintain the high temperatures needed during production. This process requires about 3.2–6.3 GJ of energy and 1.7 tons of raw materials (mainly limestone) per ton of clinker produced [11]. In addition, it is devastating, particularly from an environmental perspective, to note that approximately one kilogram of $CO_2$ is released while producing one kilogram of cement [12]. Steel production processes account for about 9% of total $CO_2$ emissions worldwide. Since the construction industry consumes about half of all steel produced worldwide, the impact of this material is critical in determining the carbon footprint of the construction industry [13]. The traditional primary steel manufacturing method is essential oxygen furnace steel production. This process is divided into two main parts: iron production in a blast furnace (BF) and steel production in a basic oxygen furnace. 70% of $CO_2$ emissions are produced during the BF processes [14]. Approximately 65% of the total steel produced in the world is produced using this method. $CO_2$ corresponds to 82% of all GHG emissions. Industries are responsible for 21% of all $CO_2$ emissions, which includes cement and steel production. 30% and 26% of all carbon emissions are released in steel and cement production processes, respectively, which means that more than half of the $CO_2$ emissions of all industrial activities are caused by steel and cement production [14]. High temperatures, 1,400 °C for glass; 1,200–2,400 °C for carbon, are required during producing (FRP) [15]. This indicates that a significant amount of energy is spent during their production. The epoxy resin, the most commonly used adhesive in FRP utilization, and FRP have the highest unit carbon dioxide emissions (~5 and 6 kg/kg, respectively). These emission rates are approximately 0.2 kg/kg for concrete and 1.8 kg/kg for reinforcing steel [16]. It must be emphasized, however, that the production of FRP causes much lower water and air pollution rates compared to that of structural steel, aluminum, and concrete, indicating its environmentally friendly features [17].

Due to their widespread availability, cost-effectiveness, and well-defined material properties, steel and concrete were widely used in reinforcement applications. However, the labor and cost-intensive phases of repair and maintenance, the low corrosion resistance of steel, and the limited lifespan of these traditional strengthening materials have encouraged exploring new strengthening materials. Considering the above-mentioned features, FRP have a longer service life and high corrosion resistance and stand out as an optimum alternative material. [7, 9, 18]. Moreover, FRPs are available in more considerable lengths than steel plates, usually limited to 6 m, which avoids the need for joints [19]. The frequency of maintenance required for FRP material is almost two times less than for traditional materials. Considering the main phases of Construction, maintenance, or demolition, it can be concluded that the carbon emissions of these processes can be substantially reduced using FRPs compared to traditional materials [20]. On the other hand, FRP composites have almost eight times higher environmental impact when used to strengthen reinforced concrete structures than conventional steel [21–24].

It is well documented in the literature that the reinforced concrete flat slabs suffer from brittle punching shear failure due to the shear stresses and the imbalanced moment conveyance between the slabs and columns [25–31]. When the existing flat slab-column connections become incapable of meeting the punching shear strength requirement primarily as a result of the structural deficiencies, either the structure will be demolished to rebuild, or the structure will be strengthened [32]. Rebuilding the structure not only results in an expensive solution but also is not consistent with the sustainable development goals of the United Nations Foundation [33]. The strengthening strategy thus is often executed utilizing FRPs, a composite material composed of a polymer matrix packed with fibers. The precedence of the FRP strengthening, previously aforementioned, comprises high tensile strength, lightweight, and simplicity of installation [6, 34–37]. Although the FRP strengthening techniques can widely range, it is worth noting that the externally bonded (E.B.) FRP is the most commonly implemented strengthening method for enhancing the strength and energy dissipation of inadequately detailed members.

Although the utilization of FRP on flat slab-column connections is widely recognized and implemented in practice frequently, especially over the last decade, a unified formula that systematically addresses the FRP utilization on such connections does not exist in the literature. Even though the literature comprises several studies concerning the FRP strengthening of flat slab-column connections, TS 500 [38] code provisions, for instance, do not constitute the influence of FRP strengthening on the punching shear strength of slab-column connections. It is widely documented in the literature that FRP strengthening significantly influences the punching shear capacity of flat slab-column connections [39–44]. Therefore, its impact on such structural performance cannot be neglected. Individual researchers such as Chen and Li [45] introduced modifications to reflect the influence of FRP strengthening on punching shear strength by modifying the adequate depth and reinforcement ratio parameters with the equivalent effective depth and equivalent reinforcement ratio. Although the influence of these modifications on punching shear strength, examined by Chen and Li [45], improved the expertise in this context, these studies mainly utilized their specific experiments. They hence failed to provide adequate preciseness into the diverse implementation of FRP strengthening on connections. This feature necessitated further investigations to achieve a comprehensive assessment of the aforementioned modifications, particularly concerning the preciseness of the TS 500 [38] code provisions.

The paper, therefore, aims to provide a comprehensive review of the FRP utilization on strengthening, particularly concerning the traditional materials formerly used in practice. The utilization of FRP and traditional strengthening materials and methods have been reviewed concerning the materials, manufacturing, operation, Construction, and maintenance phases, as well as the engineering and environmental performance of such materials. Carbon and Glass FRP, the most frequently used strengthening materials, are particularly designated in the study and are employed to conduct an environmental performance evaluation using the previously published data in the literature. The environmental performance evaluations comprised elastic modulus, energy input, average yield strength, the temperature needed for the production, and cost and cost efficiency of Carbon and Glass FRP. The second phase of the paper investigates the punching shear strength of flat slab-column connections strengthened with externally bonded FRP using a nominated database comprising 57 data points harvested from the recent literature. The database is used to evaluate the test data with TS 500 [38] code equations and the recent modification of Chen and Li [45]. The study's second phase enabled the key factors affecting the punching shear strength of such connections to be emphasized and highlighted that the TS 500 [38] code equations fall conservative in predicting the punching shear strength of slab-column connections strengthened with FRP.

## 2. DATABASE DEVELOPMENT

The database used in the study is on the punching shear strength of the flat slab-column connections. The analysis is focused on the externally bonded FRP use without shear reinforcement. The inner columns strengthened with FRP are considered only. The database is developed using specimens with concrete compressive strength higher than 10 MPa, slab depth of at least 50 mm, and a slenderness ratio higher than 5.0. The database principally encompasses the geometrical information of the concrete section, steel yield strength, reinforcement ratio of both internal steel reinforcement and the external FRP strengthening, and measured failure load. The selected articles used in the database development and the associated parameters are presented in Appendix A. The data summarised in the database are converted to the S.I. unit system. Data with incomplete information were omitted from the database. It is worth noting that initially, more than 100 data points were harvested from the literature; however, nearly one-third of this could not be included in the database due to the inconsistency attained with respect to the set criteria, such as determined for concrete compressive strength, slab depth, span to depth ratio and FRP strengthening technique.

## 3. THEORETICAL BACKGROUND

This section includes the theoretical basis of the TS 500 [38] code provisions and the modifications introduced by Chen and Li [45] on the use of FRP in flat slab-column connections. According to TS 500 [38], the punching shear capacity is calculated using the following equations:

$$V_{pr} = \Upsilon f_{ct} u_p d \quad \text{Eq. 1}$$

$$f_{ct} = 0.35\sqrt{f_{ck}} \quad \text{Eq. 2}$$

$\Upsilon$=1.0 (in the case of axial loading) Eq. 3

$V_{pr}$ is the punching shear strength, $f_{ct}$ is the concrete tensile strength (MPa), $u_p$ is the critical perimeter which is $\frac{d}{2}$ away from the column face, and the $d$ is the adequate depth. The unbalanced moment's effects are reflected by the coefficient $\Upsilon$, which is 1.0 for the axial loading case. The punching shear strength design equation provided in TS500 [38] is moderately similar to the code provisions of ACI 318 [46]. The main drawback of TS500 [38] is the disregard of the effect of the reinforcement ratio in predicting the punching shear strength of slab-column connections, even though it is one of the most influential parameters affecting the punching shear capacity of such connections [47–49]. Additionally, the size effect is not included in the code equations in relation to the punching shear strength despite its strong impact on the punching shear capacity of such connections [50]. Considering that the minimum reinforcement ratio is now defined, and the size effect parameter is included in the code equations about the punching shear strength of flat slab-column connections calculation in ACI 318 [46], the code equations provided in TS500 are practically similar to the code provisions provided in the former version of ACI 318 [51].

Consequently, further computations were performed using the Chen and Li [45] modification to reflect the effect of FRP strengthening in the punching shear calculations. The adequate depth and reinforcement ratio parameters were replaced with equivalent effective depth, $d_{eq,\,Chen}$, and equivalent reinforcement ratio, $\rho_{eq,\,Chen}$, respectively. Because TS500 [38] does not consider the reinforcement ratio, only the effective depth could be replaced with an equivalent effective depth herein. Modified equations by Chen and Li [45] are as follows:

$$\rho_{eq,Chen} = \frac{T_s+T_f}{b d_{eq,Chen} f_y} \quad \text{Eq. 4}$$

$$d_{eq,Chen} = \frac{M_{nf}}{T_s+T_f} + \frac{a}{2} \quad \text{Eq. 5}$$

where the $T_s$ is the tension force of the steel; $T_f$ is the tension force of the FRP; $b$ is the unit width of the slab section; $a$ is the depth of the rectangular stress block; and $M_{nf}$ is the flexural strength of strengthened R.C. slab, which is the moment taken about the tension steel reinforcement and is determined as:

$$M_{nf} = C_C\left(d - \frac{a}{2}\right) + T_f(h-d) \quad \text{Eq. 6}$$

in which, $C_C$ is the neutral axis depth and can be calculated iteratively from internal force equilibrium until the following equation is achieved:

$$C_C = T_s + T_f \quad \text{Eq. 7}$$

It is investigated in section 4.2 that the measured ultimate punching shear strength over TS 500 [38] and TS 500 with Chen and Li [45] modification predictions ratio versus key parameters such as tensile reinforcement ratio, concrete compressive strength, and FRP reinforcement ratio to evaluate the accuracy of these predictions depending on influencing parameters.

## 4. RESULTS AND DISCUSSIONS

### 4.1. The Overview of the FRP as a Strengthening Material

#### *4.1.1. Materials and Methods*

Fiber materials and the matrix from the two primary components of FRPs. The most commonly used fibers are carbon, glass, basalt, and aramid, whereas resins comprise the majority of matrix materials. These two materials, combined in an appropriate proportion prior to a multifarious procedure to constitute the innovative high-performance FRP material, are used in reinforced concrete structures in the form of laminates, rods, grids, and sheets. Externally bonded FRP sheets and strips (EBR) and near-surface mounting FRP strips (NSM) are the two most commonly used strengthening techniques [52, 53]. Due to the ease of application, externally bonded reinforcement (EBR) is the most widely used strengthening method. Externally bonded FRPs, divided into two main categories: "wet laying" (or "cured in place") systems and "prefabricated" (or "precured") systems [52], can be applied in different configurations such as orthogonal, skewed, radial, and whole-layer configurations. The number of FRPs used in each direction and the distance between the FRP and the column face have an important role in the effectiveness of the strengthening. For instance, the skewed FRP reinforcement with orthogonal internal steel reinforcement is more effective in preventing crack propagation since cracks caused by the punching shear force propagate in several different directions [54]. Moreover, since the FRPs in the critical punching shear area are evenly distributed in all directions, the radially located strengthening performs even better than the diagonal orientation [55].

The near-surface mounted (NSM) technique, developed to strengthen reinforced concrete structures, is an effective alternative to the external bonding of FRPs. Cutting a series of shallow grooves in the concrete surface is the first step in the process. The depth of the groove is suggested to be less than the concrete cover to prevent any damage to the existing reinforcement. Following this aspect, the carbon fiber composite rods or strips are then placed into grooves partially filled with epoxy resin. The rest of the groove is filled with epoxy resin, and the surface is leveled then [56]. The most imperative advantage of this implementation is the soundness of the reinforcement compared to that of the external bonding method, which often experiences premature debonding between the concrete surface and the FRP.

#### *4.1.2. Manufacturing Process of FRPs*

Pultrusion and wet laying (manual method) are the manufacturing procedures for FRPs used as construction materials. FRP reinforcement, FRP strips for external strengthening, and FRP profiles are produced by pultrusion. The wet laying method is used more frequently for FRP sheets to strengthen the existing buildings [57, 58]. Pultrusion is the most cost-effective method for producing FRP rods, profiles, and strips. The energy required for the pultrusion process is approximately 3.1 MJ / kilogram [58]. This method automatically produces FRP forms with a fixed cross-section. I-beam, channel, and multi-cellular profiles are all made by pultrusion. Pultrusion consists of a fiber and a matrix system. Pultrusion consists of six stages: (1) a series of spools piled on creels for fiber reinforcement handling; (2) performing guides; (3) resin impregnation bath; (4) forming and curing die; (5) a pulling system; and (6) cutting system [58].

Hand layup, a manual procedure of stacking fiber layers in a resin system, is commonly used to reinforce FRP sheets and textiles. After hardening, the solid FRP compo-

**Table 1.** Energy required for extraction and production of the main constituents of FRP composite [18]

| Materials | Energy input (M.J./kg) |
|---|---|
| Polyester | 63–78 |
| Epoxy | 76–80 |
| Glass | 13–32 |
| Carbon | 183–286 |
| Steel | 30–60 |

nent takes the shape of the mold. This method is known as laminating or wet layup. Hand layup can be done on-site or off-site; however, on-site manufacturing is essential for strengthening applications. In this case, an appropriate connection between FRP elements and the newly strengthened structural section is essential; hence, resins with strong adhesive capabilities are used in connection with carbon or glass fibers [58–60].

The first step of the manufacturing process is extracting the essential components of FRPs from their sources as raw materials. Glass, the most commonly used fiber type in FRP composites, has the lowest energy density when considering the production stages because of the ease of extraction and production. The carbon fibers in FRP composites, however, require the highest energy for the extraction and production of all fibers and hence are recognized as the least cost-effective options. This factor poses a severe obstacle to the widespread use of carbon FRPs, despite their superior mechanical properties compared to other fibers or traditional engineering materials [18].

Table 1 demonstrates the energy required for the extraction and production of the main constituents of FRP composite. The energy required to extract and produce glass is, on average, twelve times less than the energy required for carbon (13–32 M.J./kg for glass and 183–286 MJ/kg for carbon). Approximately the same amount of energy is required for the extraction and production of polyester and epoxy, the two most commonly used matrix components (63–78 M.J./kg for polyester, 76–80 M.J./kg for epoxy). The energy consumed on the matrix components corresponds to one-third of the energy consumed on carbon. In addition, the energy required to extract and produce steel as a raw material (30–60 M.J./kg) is about twice the energy required for glass (13–32 M.J./kg); however, the energy required for steel is lower than carbon, polyester, and epoxy.

Glass fibers (G.F.) have a minor diameter among all fibers, ranging from 1 to 4 microns. Glass fibers are formed by several oxides, mainly silicon oxide [59]. The components are combined and melted at temperatures above 1400 °C during the manufacture of glass fibers, and a large amount of non-renewable energy is used for this production [61]. The production of 1 kilogram of glass fiber consumes approximately 54.7 MJ of energy [12, 20].

Two leading processes often used in manufacturing carbon fibers are the petroleum-based pitch and the polyacrylonitrile (PAN) [57, 59]. The pitch technique removes graphite strands from hot liquid pitch using an injector. The PAN method involves heating and oxidation to remove a chain of carbon atoms from polyacrylonitrile (PAN). The polymer is stretched in a straight line parallel to the axis of the fiber. The polymer is then converted into a non-melting precursor fiber following the oxidation process between 200–300 °C in air. The precursor fiber is then heated in a nitrogen-rich atmosphere. The temperature continues to rise until the carbon fiber reaches a minimum 92% of carbon ratio. As the production process reaches temperatures ranging from 2500–3000 °C, carbon fibers have one of the highest environmental impacts compared to other types of fibers used for strengthening in composite applications considering that a significant amount of non-renewable energy is consumed to reach such temperatures required during this stage. It must be noted that the superior mechanical properties result in a considerable reduction of carbon fibers used for the strengthening and hence yields an overall reduced environmental impact [57, 61].

Polyester resins are widely used in strengthening applications due to their mechanical properties and low cost; however, the main drawback of this material is its negative impact on human health [12]. Peroxide and styrene substances are known to cause the sources of adverse effects of polyester resin. While these compounds can cause severe damage to the eyes and skin, they can also potentially negatively affect the brain [62]. It is widely noted in the literature that polyester resins have the highest environmental impact compared to epoxy and vinyl ester resins [18]. Epoxy resin is a popular choice for strengthening reinforced concrete structures with FRPs due to their superior mechanical qualities and easy adaptability [12]. The hardening process of epoxy mixtures also causes significant effects on human health [62]. However, it must be noted that epoxy resins are pretty challenging to recycle [12]. Vinyl ester resin is a composite material comprising mainly polyester and epoxy resins, and vinyl esters can be made using a mixture of epoxy and polyester resins. This attributes that the vinyl ester resin comprises all the harmful effects of the two inclusive resins observed in the mixture [12].

#### *4.1.3. The Operation, Construction, and Maintenance Phases of FRPs*

The production of FRP creates a higher unit quantity of carbon emissions compared to other traditional materials such as concrete or steel. Despite the high unit amount of carbon emissions during the manufacturing phase, several life-cycle evaluations have shown that carbon emissions may decrease when other factors like Construction, maintenance, and disposal are considered. Garg et al. [63] compared the $CO_2$ emissions and energy consumption of steel rebars with FRP rebars such as CFRP, GFRP, and BFRP. The results revealed that replacing FRP with steel rebars reduced $CO_2$ emissions and energy consumption by 39%, 43%, and 40% when CFRP, GFRP, and BFRP reinforcement were used, respectively, instead of steel. Furthermore, the energy consumption of FRP-reinforced beams was lower than that of steel-reinforced beams by 30%, 47%, and 50% for CFRP, GFRP, and BFRP, respectively. Inman et al. [64] conducted a similar study where the basalt FRP rebars were compared to steel rebars using crucial indicators such as $CO_2$ emissions, ozone depletion, and human toxicity. The results revealed that replacing steel rebars with BFRP reduced $CO_2$ emissions by 38%, human toxicity by 79%, and ozone depletion by 40% for the best scenario in each case. Although the life cycle assessment does not address the strengthening method's structural efficiency, it demonstrates the environmental and ecological advances of such material compared to that of steel, taking the operation, construction, and maintenance phases into account [65].

The resins used in the FRP components are known to create the highest ozone depletion, one of the environmental impacts of such implications. Maxineasa et al. [66] studied the strengthening of a structural element using carbon FRPs and epoxy resin by the external bonding method. It has been shown in the study that epoxy resin causes 98% of ozone depletion throughout the whole process of FRP strengthening. The study also stated that half of the human toxicity effect occurs at the stages of transportation, Construction, and maintenance.

#### *4.1.4. Engineering Performance of FRP Application*

The most commonly used FRP strengthening materials are carbon (CFRP) and glass (GFRP) based FRPs. Carbon fibers are often used for strengthening due to their high strength, high creep levels, chemical resistance, low conductivity, low density, and high elastic modulus. The disadvantages of carbon fibers are their high cost and anisotropic nature [67]. Glass fibers are the most widely used type of fiber. E-Glass, S-Glass, and C-Glass are the three common glass fiber varieties. The main characteristics of glass fibers are their high strength, low cost, and superior water and chemical resistance [68].

The method of external bonding under axial load is considered a successful approach. Ten square-section columns were strengthened using near-surface mounting (NSM), external bonding (E.B.), and hybrid strengthening methods by Challapandian et al. [69]. While the NSM system increased the axial capacity by 8%, the E.B. system increased the axial capacity by 42% in the same column. It was reported in the study that the most effective method of strengthening the columns is the combination of NSM strips and the E.B. system. It is known that strengthening a rectangular section with externally glued FRP usually results in a relatively low bending rigidity along its flat side and an uneven axial stress distribution under compression while significantly increasing the rigidity in circular sections [70].

As structural elements can be subjected to repeated bending movements, it is necessary to strengthen their bending strength. The type of strengthening method used, the qualities of FRP and adhesives, and the additional anchors used considerably affect the performance of the strengthened structural element. It is known that the externally utilized FRP strengthening applied along the stretched face of the structural elements significantly increases the bending performance. In order to enhance the performance to a maximum level, it is recommended to apply FRP along the surface of the structural element [71]. In addition, the near-surface mounting (NSM) method is a more effective method compared to the external bonding (E.B.) method due to its potential to increase the strength by 200% under bending. [69, 72]. Attari et al. [73] conducted experiments to strengthen reinforced concrete structures using carbon, glass, and carbon-glass fiber hybrid sheets. Experimental results have shown that the bending strength of a beam strengthened using a carbon-glass fiber sheet increased by 114%. Carbon-glass hybrid FRP strengthening was found to be more effective in bending compared to that of carbon FRP.

Externally bonded FRP shear strengthening can strengthen shear-weak R.C. beams in vertical, inclined, side-bonded, U-wrapped, or anchored designs. The performance of strengthened structures are affected by the fibers' quality and amount, the FRP's orientation and distribution, and the interaction between internal steel bars and FRPs [74]. The inclined wrapping system was shown to be the most effective strategy for increasing the shear capacity of all wrapping systems investigated. According to Singh et al. [75], wrapping a concrete beam with a 45° angled CFRP sheet, and bidirectional CFRP sheets increased the load capacity against shear force by 11.9% and 7.7%, respectively. In addition, in 2013, Hussein et al. [76] achieved a 57% improvement in the load-bearing capacity by strengthening a damaged beam with a U-wound CFRP system along with the external prestressed force in this study.

In addition, Chen and Li [45] conducted experiments on slab-column connections with relatively low and medium reinforcement ratios (0.31% and 0.62%, respectively) to investigate the effect of glass fiber reinforced strengthening on punching shear strength. The results showed that the FRP strengthening attachment to the slab's tension surface increases the bending strength of the slab-column connection considerably. However, after the shear strength was increased to the point where the bending shear strength of the plate was less than the ultimate shear strength, increasing the FRP strengthening area did not significantly improve the shear strength or stiffness of the plate. Haraji et al. [77] conducted experiments using sixteen samples with different plate depths and reinforcement ratios. The same carbon FRP configuration was tested using FRPs with different widths. The results showed that using CFRP significantly increased the sheets' bending stiffness and punching strength. It is also stated that the increase in the two-way shear force can be between 17–45%, depending on the area, the thickness of the applied CFRP sheets, and the reinforcement ratio of the slab. Esfahani et al. [48] experimented with eleven slab-column systems with two different reinforcement ratios (0.84% and 1.59%) with CFRP sheets with different widths (100–300 mm). The results showed that the punching shear strength of the floors was improved when using CFRP sheets in addition to steel reinforcement bars. It is stated that this application is more effective in slabs consisting of high-strength concrete with a low steel reinforcement ratio.

Farghaly et al. [78] conducted experiments using three flat slab-column connection specimens. Carbon FRP sheets of two different widths are bonded to the tension face of the slab in two perpendicular directions parallel to the internal reinforcement. In order to prevent FRP from debonding, CFRP sheets were applied in a single layer and extended from one end of the slab to the other. Experimental results have shown that the stiffness and punching shear strength of sheets are improved using FRP. In addition, the behavior of externally connected slab-column connections strengthened with different CFRP arrangements was investigated by Silva et al. [79].

In some cases, anchoring was used at the end of the FRP. The results showed that skewed placement of CFRP is more effective than orthogonal configurations. It has been shown that the appropriate strengthening arrangement makes it possible to increase the punching capacity for slab-column connections by 46%. In addition, FRP debonding without end anchors was also observed, while anchored samples did not have the same premature failure, indicating the failure can be prevented by end anchors.

Kim et al. [80] studied the effectiveness of prestressed and non-prestressed externally bonded FRP strengthening on the punching shear of slab-column connections. A total of four different samples were used in this study. While one Sample was left non-strengthened, the other was strengthened with non-prestressed externally bonded FRP, and the other two were strengthened by adding different prestresses. It was found that the prestressed FRP sheets did not significantly improve the system at the punching shear. Abdullah et al. [81] studied the effectiveness of prestressed externally bonded FRP strengthening on the punching shear in flat slab-interior column connections. This study was then re-evaluated by Abdullah and Bailey [82]. In the study, five slabs with dimensions of 1800×1800×150 mm and columns with dimensions of 250×250×150 mm were used. While one Sample was not strengthened, one other was left without prestress, and the remaining three were strengthened using prestress. The study suggests that prestressed externally applied FRP strengthening reduces crack openings, while its effect on the ultimate load was not as significant as in the case of the non-prestressed externally applied FRP strengthening.

#### *4.1.5. Environmental Performance of FRP Applications*

The life cycle assessment (LCA) technique, widely used and accepted, is also utilized to measure the environmental impact of the activities of the construction industry in general. Maxineasa et al. [66] used LCA to compare the environmental impact of strengthening an existing reinforced concrete beam with FRP with the environmental impact of building a new reinforced concrete beam. The research includes FRP strengthening techniques such as externally bonded (EB) FRP and near-surface mounted (NSM) techniques. This study considered global warming, human toxicity, and ozone depletion. The results showed that building a new beam has the highest adverse environmental impact. According to the results, the most environmentally friendly solution is the application of the CFRP strip, which is glued on a cross-section of 1.4×36 mm and a length of 2600 mm to the lower base of the beam.

The total $CO_2$ emissions of the strengthening process are 69% lower than those from the Construction of a new reinforced concrete beam. It has also been stated that the near-surface mounted technique increases the load capacity the most, which could go up to a 207% increase (from 60KN to 184KN). It has also been noted that strengthening the existing beam instead of building a new beam reduces human toxicity by 73% and the effect of ozone depletion by 48%. The parameters of ozone depletion and human toxicity are highly related to the production process of materials. The amount of cement and rebar production required to build a new beam is much more than the amount of FRP required to strengthen the existing beam. Therefore, when the existing beam is strengthened instead of building a new beam, the damage caused to the thinning of the ozone layer and human health is reduced. Palacios-Munoz et al. [83] research findings align with the study by Maxinease et al. [66]. Palacios-Munoz et al. [83] conducted a LCA on the environmental impacts of strengthening an existing beam with CFRP or steel plates and demolishing and rebuilding the existing beam. The results showed that the demolition and reconstruction of the existing beam caused two times higher $CO_2$ emissions than strengthening the existing beam with CFRP. In addition, it has been determined that demolishing the existing beam and building a new one will increase energy consumption by up to 60%.

Vitiello et al. [84] conducted a LCA on a building located in Naples. The building was constructed in the 70s using old standards and without considering the area's seismic conditions. In this case study, four different strengthening techniques were used. The first strengthening technique was EB FRPs to prevent brittle failure, the second technique was concrete coating to increase the bending and shear capacity, the third technique was adding two shear walls to enhance the building against seismic movements, and the fourth one was to integrate a horizontally flexible and dissipative interface on the building's first floor to minimize demand rather than increase structural capacity. The results showed that FRP sheets and concrete coating have almost the same effect on human health, while shear wall strengthening significantly affects human health.

Moreover, considering the effects on ecosystem quality and climate change, it has been observed that FRP sheets have a less negative impact than the shear wall and concrete coating techniques. Maxineasa et al. [12] evaluated strengthening methods by conducting experiments on six beams. While one beam remains as a control specimen, two beams strengthened with different sizes (1.4×36×2600 mm and 1.4×72×2600 mm) of EB CFRP; the other three beams strengthened with different sizes (1.4×18×2600, 1.4×12×2600 1.4×24×2600 mm) of CFRP using the near-surface mounting technique. The results showed that the near-surface mounting technique could increase the load capacity up to three times that of the control specimen and is the best strengthening method in this sense. In addition, it was concluded in the study that strengthening the existing beam in place of rebuilding could reduce the effect of ozone depletion by 87.5%.

Moreover, all other cases compared to building a new beam achieved approximately 74% reduction of $CO_2$ emission. Shi et al. [85] studied a supported reinforced concrete beam as a case study. The concrete beam represents the beam on a bridge spanning 20 meters. CFRP fabrics and CFRP plates were used as strengthening materials. The results showed that the environmental effects of the CFRP fabric strengthening technique are greater than those of CFRP plates. CFRP fabric strengthening materials have consumed more CFRP materials and epoxy resin adhesives, resulting in increased environmental effects. In addition, the environmental impact of CFRP plates is also considerably less, mainly when the maintenance during the service life is considered.

#### *4.1.6. The Environmental Evaluations of the FRP Utilization*

This section addresses the environmental evaluations of FRP utilization as a strengthening material. Carbon and glass FRPs, the most commonly used strengthening materials, are chosen for this evaluation. Structural performance is often plotted versus an environmental parameter to provide insight into implementing such materials in a more holistic approach.

Figure 1 demonstrates the elastic modulus and energy input of carbon and glass FRPs. The elastic modulus of glass FRP is between 35–51 GPa, while this value ranges from 120 to 500 GPa for carbon FRPs [21]. As the resistance of a material to elastic deformation, when subjected to stress, is governed by its elastic modulus, the carbon FRP offers a higher deformation capacity than the glass FRP and has superior structural properties over glass FRP. On the other hand, it must be emphasized that glass FRP consumes much lower energy than carbon FRP during the production stage, which comprises raw material extraction and manufacturing of FRP. The low energy consumption of glass FRP indicates these materials' sustainable and environmental advances over carbon FRP. The energy required to extract one kilogram of glass FRP as raw material along its complete production process is approximately 20 M.J., while the same process necessitates about 200 MJ for carbon FRP. The studies by Dong et al. [86] and Zhang et al. [87], published in the literature, agree greatly with the findings in Figure 1.

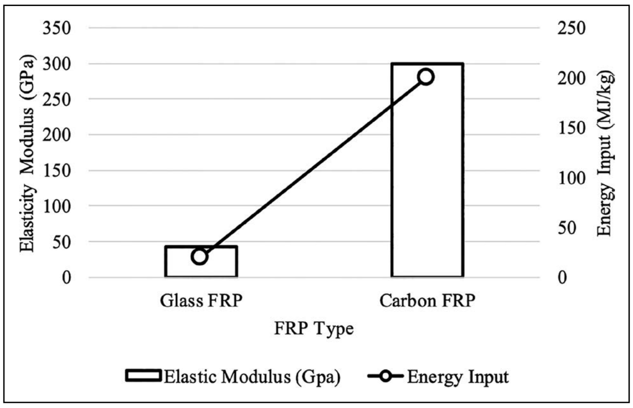


**Figure 1**. Average elastic modulus versus energy input of carbon and glass FRPs [18, 21].

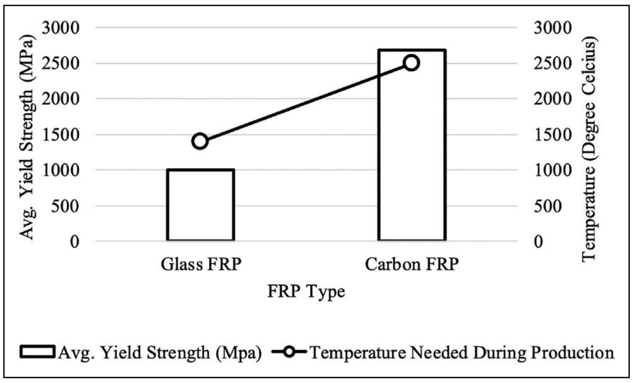


**Figure 2**. Average yield strength versus temperature needed during the production of carbon and glass FRPs [21, 57].

Figure 2 exhibits the average yield strength and temperature required while producing carbon and glass FRPs. The average yield strength of carbon FRP is around 2700 MPa, while the average yield strength of glass FRP is around 1000 MPa. Yield strength is an essential parameter in evaluating structural performance, as it is the stress point at which materials begin to deform permanently. The required temperature for production is closely associated with environmental sustainability, mainly due to fossil fuel consumption during this process [88]. The increase in the temperature required for the production also necessitates higher energy consumption that implicates higher fossil fuels consumptions for this phase. The maximum temperature required for producing glass FRPs is around 1400 °C, which is around 2500 °C for carbon FRPs [57]. The results

**Table 2.** Classification system for distribution of $V_{test}/V_{pred}$

| Vtest/Vpred | Classification |
|---|---|
| <0.5 | Extremely dangerous |
| 0.5–0.65 | Dangerous |
| 0.65–0.85 | Low safety |
| 0.85–1.30 | Appropriate safety |
| 1.30–2.00 | Conservative |
| >2.00 | Extremely conservative |

**Table 3.** Comparison of prediction by TS500 [38] and TS500 modified by Chen and Li [45] code equations

| Code | TS500 [38] | TS500 modified by Chen and Li [45] |
|---|---|---|
| Mean | 1.61 | 1.42 |
| SD | 0.377 | 0.346 |
| COV | 0.23 | 0.24 |

SD: Standard deviation; COV: Coefficient of variation.

shown in Figure 2 indicate that although carbon FRPs have structurally superior properties, glass FRPs have more outstanding environmental advances. The studies by Sen et al. [89], and Preinstorfer et al. [90], published in the literature, agree greatly with the findings in Figure 2.

Figure 3 demonstrates the cost efficiency and the cost of glass and carbon FRPs. In addition to structural and environmental factors, the cost of materials is also a decisive factor that is taken into account before implementation. The unit price of glass FRPs is approximately 5.5$, while the price of one kilogram of carbon FRPs is about 38$ [91]. Despite their structurally superior properties, carbon FRPs are about seven times more expensive than thass FRPs, which at first sight could restrict the frequency of use of carbon FRP. Cost efficiency incorporates the FRP implementation's cost and structural aspects. It, therefore, provides a more holistic approach to evaluating the authentic performance of such utilization cost efficiency, demonstrated in Figure 3, which is determined by dividing the average yield strength by the unit price of the material. The cost efficiency value of glass fiber reinforced polymers is 182MPa/kg, while the cost efficiency of carbon fiber reinforced polymers is around 70.5MPa/kg. These results indicate that the cost efficiency of glass FRPs is nearly two and a half times higher than the cost efficiency of carbon FRPs.

## 4.2. The Evaluation of the TS 500 Code Equation

This section evaluates the TS 500 code equation in predicting the punching shear strength of flat slab-column connections strengthened with FRP laminates. The selected database is used to conduct the Ratio of the measured ultimate punching shear strength, $V_{u,\ test}$, to the calculated value from TS 500 Code Equation, $V_{u,\ pred}$. This is then utilized to compare and nominate the safety factor, $\gamma$. The safety factor, $\gamma$, is provided in Eq. (8).

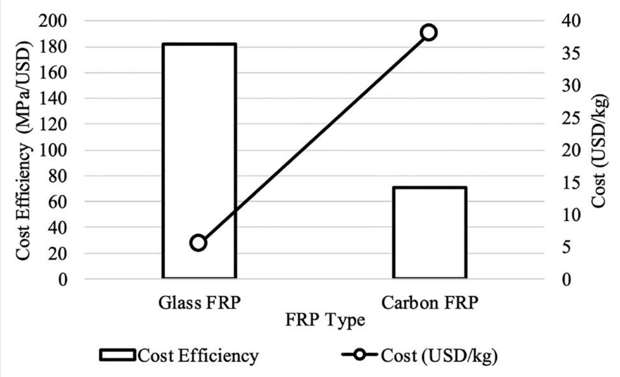


**Figure 3**. Cost efficiency versus the cost of carbon and glass FRPs [21, 91].

$$\gamma = \frac{V_{u,test}}{V_{u,pred}} \quad \text{Eq. 8}$$

A given test's predicted value is considered conservative when $\gamma>1$. The material properties introduced in the formula were the average values obtained from the test reports.

It should be noted that all strength reduction factors, and material strength reduction factors are equal to unity when assessing the performance of the code equations in predicting the experimental results. Mean, Standard Deviation (SD), and coefficient of variation (COV) of the strength ratio $V_{test}/V_{pred}$ are used to examine the performance of the code provisions. In addition, the classification system proposed by Collins [92] is used to assess the distribution of $V_{test}/V_{pred}$, summarised in Table 2.

### *4.2.1. Evaluation of the Performance of TS 500 Code and Modified TS 500 Code Provisions*

Table 3 shows the means, standard deviation (S.D.), and coefficient of variation (COV) for the Ratio $V_{test}=V_{pred}$ for the code provisions examined in this study.

TS 500 [38] performed more conservative predictions than the TS 500 modified by Chen and Li [45], as the modifications considered the effect of the FRP contribution on the strength of slab-column connections subjected to FRP strengthening. When the TS 500 [38] code provision is computed, it was determined that 72% of the data had $\gamma>1.4$, while with TS 500 [38] modified by Chen and Li [45], this is reduced to 54%. 15% of the predictions are categorized as highly conservative for TS 500, while this value is reduced to 6% with TS 500 modifications. It is well recognized that TS 500 [38] is not taking the reinforcement ratio and size effect into account, leading to conservative predictions resulting in a mean value of 1.61, a standard deviation of 0.377, and a covariance of 0.23. However, the modifications provided by Chen and Li [45] include the contribution of FRP that yields a substantial improvement on the aforementioned parameters and therefore results in considerably improved predictions.

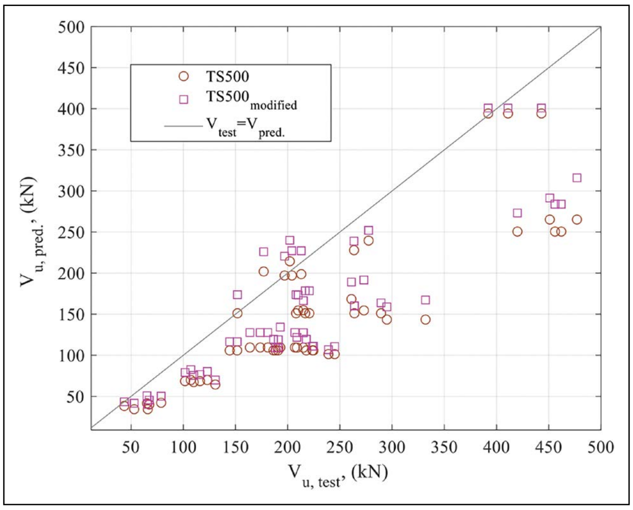


**Figure 4**. Comparison of predictions of TS 500 and TS 500 modified with the experimental test results .

#### *4.2.2 Comparisons with the TS 500 Design Equation*

Figure 4 demonstrates the predictions of punching shear strength of slab-column connections strengthened with FRP using TS 500 [38] and T.S. 500-modified with the experimental results harvested for the paper using the $V_u$, pred data plotted versus the $V_u$, test. It is eminently demonstrated in Figure 4 that the predictions show a large scatter for both models. Predictions by T.S. 500-modified lead to less conservative results, mainly as a result of the inclusion of the FRP in computing the strength of such connections.

The safety factor, $\gamma$, is plotted versus concrete compressive strength in Figure 5. It must be underlined that the concrete compressive strength is the only parameter considered in TS500 [38]. According to the distribution of the test data shown in Figure 5-a, the TS-500 [38] code equation appears conservative when the concrete compressive strength is less than 30 MPa. It is shown that when the concrete compressive strength is between 30 and 35 MPa, TS 500 [38] code equation provides approximately safe predictions. It was evident that the modified equation of TS 500 that adopted the equivalent adequate depth (proposed by Chen and Li [45]) in the code equation leads to less conservative predictions for all ranges of concrete compressive strength in this study.

The safety factor, $\gamma$, is plotted versus the flexural reinforcement ratio $\rho = As/bd$ in Figure 6. It must be noted that the flexural reinforcement ratio is not considered in TS500 [38]. Results shown in Figure 6 indicate that the safety factor is increasing with the increase in flexural reinforcement ratio. It can be seen in Figure 6 that the overall safety of TS-500 for slabs with $\rho_{flex}<0.8\%$ is 1.25, which is categorized as approximately safe, while for slabs with $\rho_{flex}>0.8\%$ is 1.69, which makes conservative predictions. The results in Figure 6 demonstrate that the safety factors increase gradually with the increase in reinforcement ratios, which validates the pronounced influence of the reinforcement ratio on the punching shear strength of slabs without shear reinforcement. Figure 6-b shows that the mean value of the safety factor for the modified version of TS 500 on predicting the punching shear strength of

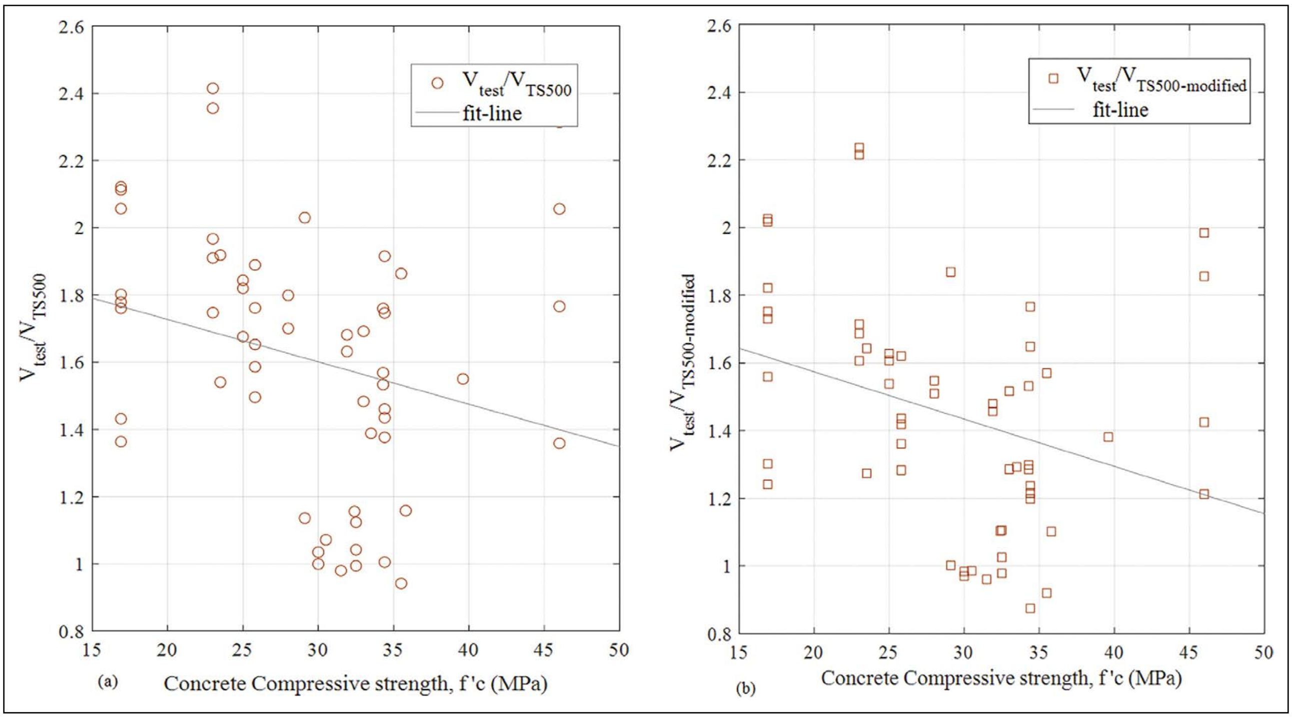


**Figure 5**. Safety factor $\gamma = V_{u, test}/V_{u, cal}$ for TS500 plotted versus concrete compressive strength.

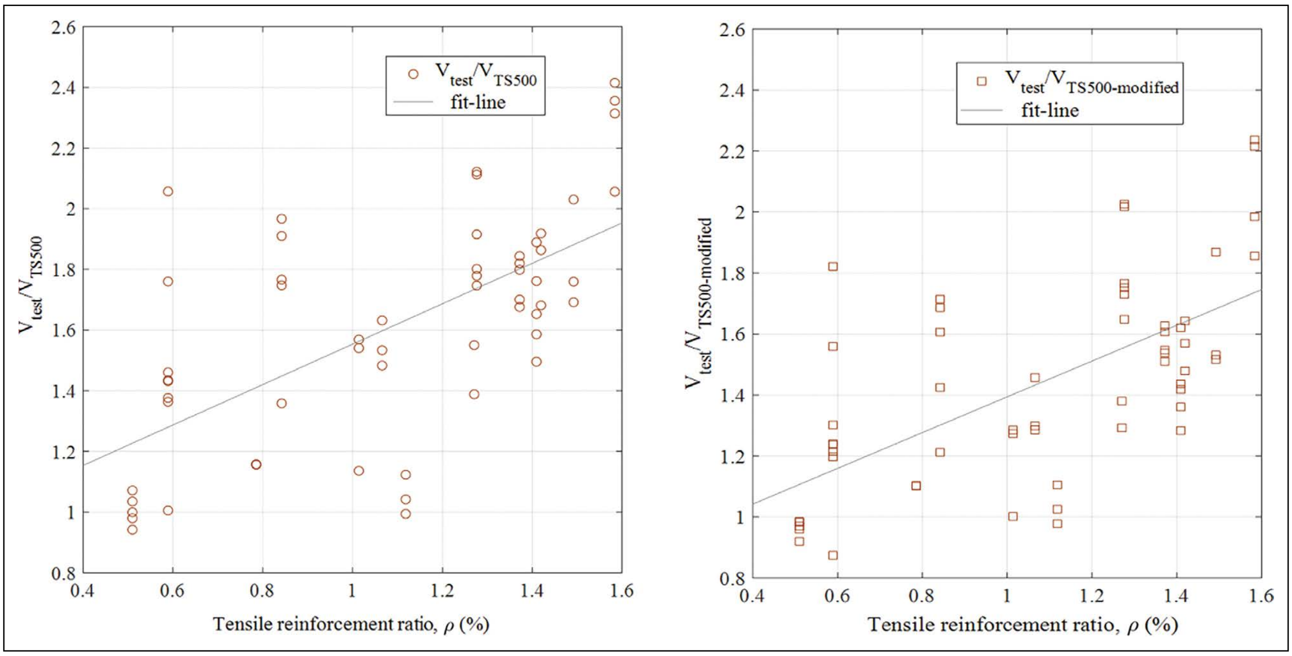


**Figure 6**. Safety factor $\gamma = V_{u,\ test}/V_{u,\ cal}$ for TS500 plotted versus Tensile Reinforcement ratio.

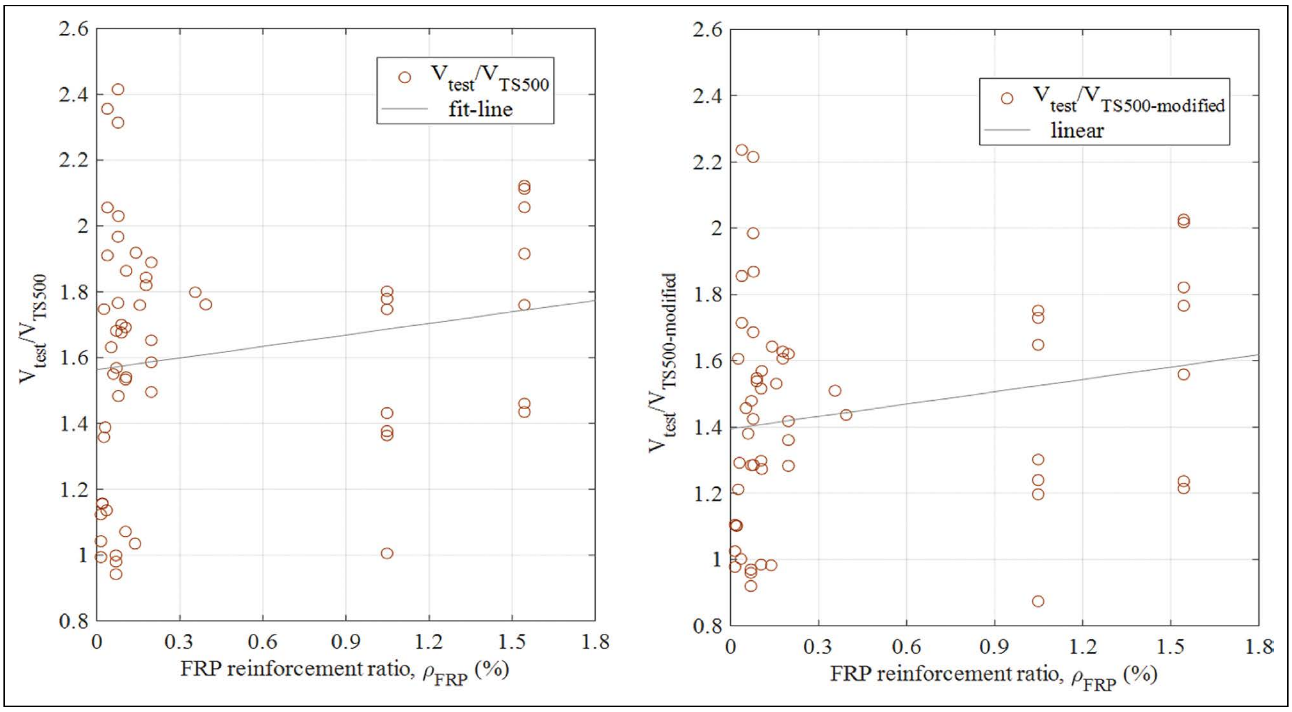


**Figure 7**. Safety factor $\gamma = V_{u,\ test}/V_{u,\ cal}$ for TS500 plotted versus concrete compressive strength.

such connections with $\rho f_{lex}$<0.8% is 1.12 and for slabs with $\rho_{flex}$>0.8% is 1.51. This implies that the modified TS500 equation leads to less conservative predictions.

The safety factor, γ, is plotted versus the FRP reinforcement ratio $\rho_{FRP} = A_{FRP}/bd$ in Figure 7. It must be noted that TS500 does not include the contribution of FRP laminates in increasing the punching shear strength of such connections. The flexural reinforcement ratio is not a parameter in TS500. Results shown in Figure 7 indicate that the safety factor is increasing with the increase in FRP reinforcement ratio. It can be seen in Figure 7 that the overall best-fit line safety of TS 500 for all types of slabs is categorized as conservative for both TS500 and T.S. 500-Modified.

## 5. CONCLUSION

The paper reports a comprehensive review of the FRPs utilization on strengthening, particularly over the traditional materials formerly used in practice with respect to materials, manufacturing, operation, Construction, and maintenance phases as the engineering and environmental performance of such materials. The results provided in the paper suggest that carbon FRP requires a higher temperature during manufacturing, resulting in a higher energy input than the glass FRP. Although its superior structural properties, such as higher elastic modulus and higher yield strength, carbon FRP has lower cost efficiency as a result of the higher cost of production. Glass FRP, on the other hand, has weaker structural properties, lower environmental impact, and cheaper production costs compared to that of the carbon FRP. The results are paramount as they offer a comprehensive review of the structural performance of such materials by considering the environmental and sustainable implications.

The paper also investigates the punching shear strength of flat slab-column connections strengthened with EB FRP using a nominated database comprising 57 data points harvested from the recent literature. The database is used to evaluate the test data with TS 500 code equations and the recent modification of Chen and Li. The results have shown that TS 500 code equation does not consider the contribution of flexural reinforcement and size effect in the calculation of punching shear strength of slab-column connections; moreover, the code does not include the contribution of FRP laminates in enhancing the strength of such connections. The results have also shown that TS 500 often provides conservative predictions for the cases examined in the paper. However, the modifications by Chen and Li that replace adequate depth with the equivalent effective depth improve the strength predictions of such connections and hence result in less conservative approximations.

The study is novel as it provides a comprehensive review of the FRP as a strengthening material regarding environmental sustainability and provides insight into the structural implications of this material by evaluating the current TS 500 code provisions and recent modifications. The authors encourage the researchers to conduct further studies in this context to suggest modifications to improve further the TS 500 code equation in predicting the punching shear strength of flat slab-column connections.

### ETHICS

There are no ethical issues with the publication of this manuscript.

### DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

### CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.


### FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.


### PEER-REVIEW

Externally peer-reviewed.

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**Appendix A.** Key properties of selected studies for database

| No | # of sample | Authors | h (mm) | Span/depth ratio | $f'_c$ (MPa) | ρ (%) | $\rho_{FRP}$ (%) | $V_{test}$ (K.N.) |
|---|---|---|---|---|---|---|---|---|
| 1 | 12 | Harajli et al. [77] | 55 and 75 | 5.18 and 7.70 | 23.5~34.3 | 1.01~1.49 | 0.035~0.155 | 43.5~130.7 |
| 2 | 14 | Chen and Li [45] | 100 | 5.1 | 16.9~34.4 | 0.59 and 1.28 | 1.048 and 1.544 | 144.4~289.4 |
| 3 | 5 | Sharaf et al. [40] | 150 | 7.89 | 25 and 28 | 1.37 | 0.089 and 0.178 | 420~477 |
| 4 | 9 | Esfahani et al. [48] | 100 | 5.82 and 6.16 | 23 and 46 | 0.84 and 1.58 | 0.025~0.076 | 191~332 |
| 5 | 2 | Farghaly et al. [78] | 120 | 7.73 | 33.5 and 39.6 | 1.27 | 0.030 and 0.060 | 215 and 261 |
| 6 | 3 | Kim et al. [80] | 150 | 8.12 | 32.5 | 1.12 | 0.015 | 392~443 |
| 7 | 5 | Soudki et al. [54] | 100 | 7.64 | 25.8 | 1.41 | 0.197 and 0.393 | 163.8~206.9 |
| 8 | 5 | Akhundzada et al. [93] | 120 | 6.62 | 30~31.5 | 0.51 | 0.069~0.138 | 177~213 |
| 9 | 2 | Abdel-Kareem [94] | 130 | 4.32 | 32.4 and 35.8 | 0.79 | 0.02 | 263.5 and 277.5 |