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Investigation of the use of textile carbon yarns as sustainable shear reinforcement in concrete beams

Suhad M. Abd [a], Isam S. Mhaimeed [a], Bassam A. Tayeh [b], Hadee Mohammed Najm [a], Shaker Qaidi [c,d,*]

[a] University of Diyala, College of Engineering, Baqubah, Diyala, Iraq
[b] Civil Engineering Department, Faculty of Engineering, Islamic University of Gaza, Gaza Strip, Palestine
[c] Department of Civil Engineering, College of Engineering, University of Duhok, 42001 Duhok, Iraq
[d] Department of Civil Engineering, College of Engineering, Nawroz University, 42001 Duhok, Iraq

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ABSTRACT

In recent years, textile reinforcement has been widely researched and used in reinforced concrete beams, slabs, and thin plates. However, the design for bending is completely different from that of the shear case. The use of textile carbon yarns in place of or in addition to traditional steel stirrups to reinforce the shear has been investigated. Eight beams with dimensions of 200 mm × 300 mm × 1500 mm were used in this investigation. These beams were tested in shear under four load points. Two specimens were used with and without steel stirrups as reference specimens, while the other six beams used textile carbon yarns instead of steel stirrups. The variables of this study were the length of overlap, which was 30%, 60%, and 100%, the spacing was 90 mm and 130 mm, while inclination was 45° and 90°, and bonding with or without steel fibers. The results showed that using 100% overlap length, 90 mm spacing, a 45° angle, and adding steel fibers increased the shear capacity, increased the deflection, and made the cracking behavior better.

1. Introduction

Concrete is considered the most used construction material, which is due to its satisfactory mechanical properties and acceptable cost [1–5]. Yet, concrete is weak at withstanding 'tensile' forces in spite of combating high pressure. In such cases, concrete needs reinforcement, traditionally, steel bars. Reinforced concrete started to appear in structural building applications in the middle of the 19th century [6–9], and its development remains ongoing to this day. As a result, steel bar reinforcement is frequently combined with plain concrete to increase its tensile strength [10,11].

On the other hand, fiber reinforcement has been used to reinforce concrete members for decades. It has combined well with concrete to help control cracking and increase the toughness and other properties such as corrosion resistance[12–14]. "The use of traditional fiber reinforcement has led to the development of a new material called textile reinforcement (multifilament continuous fiber), which can also be used as the main reinforcement instead of steel reinforcement" [15–18].

Abbreviations: S.P, Superplasticizer; GFRP, glass fiber reinforced polymer; 12 k, 12000 filaments in each yarn; TRC, textile reinforced concrete; P_u, Ultimate Load kN; f_u, Textile Reinforcement Tensile Strength MPa; FRP, Fiber Reinforced Polymer Bars; $f'c$, Cylinder compressive strength of concrete, MPa; WMS, With mortar and steel fiber.

* Corresponding author at: Department of Civil Engineering, College of Engineering, University of Duhok, 42001 Duhok, Iraq.
E-mail address: shaker.abdal@uod.ac (S. Qaidi).

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Discontinuous fibers “have been used inside the concrete, mainly as a form of secondary reinforcement, in order to control cracking. This is not a method for replacing the main steel reinforcement [19–23]. Fiber materials such as alkali-resistant glass and carbon fiber have been used for decades to strengthen and rehabilitate reinforced concrete (RC) structural members. These materials do not corrode in the normal sense, which could lead to several structural benefits, i.e., reduced cover dimensions and hence structural element thickness [24–27]. While the purpose of short fibers is to improve the mechanical and non-mechanical properties of concrete, long continuous fibers are mainly used to mechanically reinforce concrete structures in tension and shear. This represents an alternative solution for steel reinforcement that benefits from the advantageous properties of fiber products, such as weight-to-strength ratio, flexibility, and thermal resistance (specific types of fibers). Continuous fibers exist in various forms. The most common type of continuous fiber reinforcement is fiber-reinforced polymer (FRP) rebars, usually used as a substitute for steel reinforcement [28–34]. They provide lighter, corrosion-resistant concrete structures. Similarly, carbon fiber composite cables are used as a pre-stress reinforcement in concrete structures” [35–38].

Moreover, “another type of continuous fiber reinforcement is textile-reinforced concrete (TRC). The practical use of TRC was highlighted by the invention of Concrete Canvas (CC), which is a flexible form of cement-impregnated fabric, capable of hardening into any given shape and forming a thin, durable, waterproof, fire-resistant concrete shell. This could be used to produce inflatable emergency shelters that are easily transported and erected in a short period of time. Understanding the mechanical behavior of TRC composites is important to the development and construction of TRC structures. Another advantage of TRC was its resistance to impact loading compared to HPFRC [39–42] and the ability to produce impact-resistant concrete panels [43]. The term textile reinforced concrete, or the abbreviation TRC, is often and internationally used for composites made of a cementitious matrix and continuous fibers as reinforcement. The fibers can be in the form of a weave or be unidirectional and just stitched together with a yarn in the perpendicular direction. During the second half of 2002, a technical committee called “Textile Reinforced Concrete” (TRC) was established by RILEM. It replaces steel rods with non-corrosive textile structures to reduce the amount of concrete needed in construction. This nearly halves the global warming potential of traditional steel-reinforced concrete, which is the largest producer of CO_2 emissions in the building industry” [5,38,44,45].

Recently, roving fiber has been investigated as the main reinforcement to replace steel reinforcement. Many researchers investigate TRC structural members as sandwich sections (beams or panels) [46,47] and using TRC in thin-walled structures [48] and TRC I-beam [49–51]. Moreover, other researchers used TRC as the main reinforcement in reinforcing flexural concrete beams [52] and in TRC-reinforced concrete slabs [23,27,53,54]. The findings of all previous researchers have shown conformity about the effect of the number of TRC layers inside concrete members on overall structural behavior [55–61].

Today, “there is an increasing awareness of the need to reduce resources and energy intensity. TRC is being explored as a sustainable solution. Its design not only enhances durability but also helps minimize the use of concrete. This new composite material has been extensively researched for over a decade [62–66]. TRC was found to be able to make thin, light, modular, freeform structures that eliminate the risk of corrosion [67], waste, and consumption, especially in the building industry” [38].

This paper investigates utilizing continuous non-woven textile carbon bundles as shear reinforcement in concrete beams as an alternative to the traditional steel stirrups to achieve a sustainable, durable, and lightweight reinforcement solution as explained previously. For the comparison, two reference reinforced concrete beams were taken, one without shear reinforcement (stirrups), and the other with shear reinforcement to illustrate the effect of using steel stirrups in the shear zone on the load capacity and mode of failure. For bond requirements and to prevent debonding of the carbon bundles, there should be an adequate overlap distance at the end of the closing loop of the yarn’s bundles. Furthermore, as there was no previous work regarding utilizing continuous or long carbon fiber in the same manner as this work, the overlap distance was taken as a variable to be explored in this study. Logically, increasing overlap would provide a higher bond, failure delay, and higher load capacity, but the overlap should not exceed 100% as it would be an additional loop, i.e., an additional calculated area of carbon. The overlap, therefore, was taken at 30%, 60%, and 100% (as a maximum percentage) of the single loop length. To resemble the stirrup spacing, the same spacing distance between carbon bundles was taken at 130 mm in the reinforced concrete beam. To inspect the effect of spacing, a concrete beam with carbon bundles having a different spacing of 90 mm was added, and the spacing was taken to be the second variable considered in this work. The carbon fiber has a smooth surface, and with the fact that failure types related to using textile fibers or even FRP sheets are slipping fracturing, and debonding, the bond between carbon bundles and surrounding concrete should be considered. Therefore, the last variable was adding micro-steel fiber to the surface of the carbon fiber to enhance the bond, thereby delaying the failure, and increasing the load-carrying capacity. Moreover, the angle of inclination was also investigated, taking two different angles 45 and 60°.

Table 1
Concrete mix constituents [38].

“Designation C40	
Cement (kg/m^3)	450
Sand (kg/m^3)	860
Gravel (kg/m^3)	860
Water (kg/m^3)	252
Superplasticizer	0.33%
Water cement ratio	43%
Slump (mm)	150 mm”

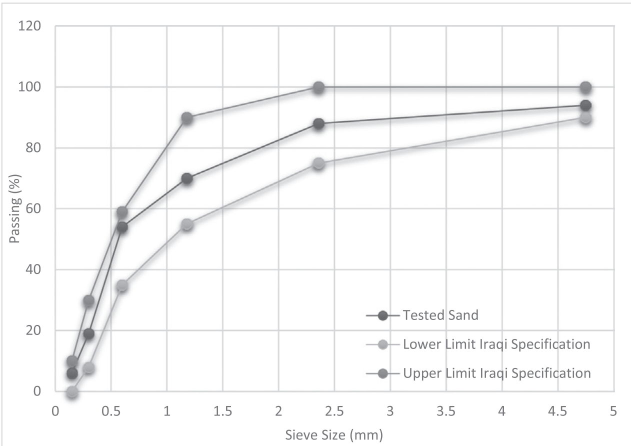
2. Materials and methods

2.1. Concrete mix

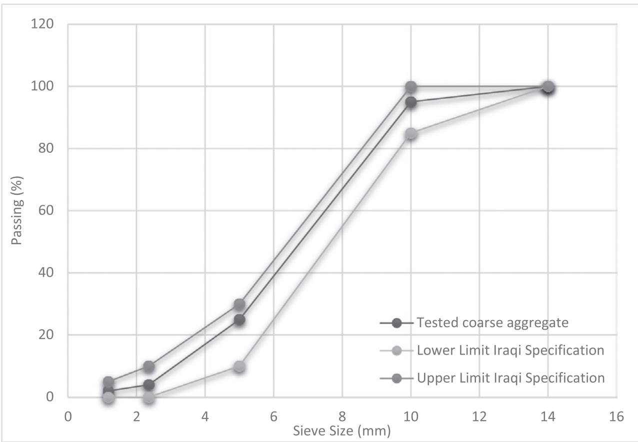
The characteristic compressive strength (f_{cu}) for the mix used throughout this work was 40 MPa with a 150 mm slump value. Table 1 shows the mixed proportions. The ingredients of the concrete mix were Ordinary Portland Cement (OPC) conformed to the Iraqi specification No. 5/1984 [68], natural sand of 4.75 mm maximum size was used as fine aggregate, and coarse aggregate with a max size of 10 mm conformed to Iraqi specification No. 45/1984 [69]. Fig. 1 shows the grading curve of fine and coarse aggregate. Also, mixes included is a superplasticizer (Sika viscocrete®−5930 L) that satisfies the ASTM-C-494 [70] requirements for types G and F.

2.2. Steel fiber

Steel fibers with a diameter of 0.8 mm and a length of 15 mm straight cross-section were used. "Steel fiber is a metal reinforcement. Steel fiber for reinforcing concrete is defined as short, discrete lengths of steel fibers with an aspect ratio (ratio of length to diameter) of about 20–100, with different cross-sections, and that are sufficiently small to be randomly dispersed in the concrete mixture using the usual mixing procedures" [38]. The short steel fibers were used to improve the bond between the carbon yarn bundle stirrups and the concrete. Steel fiber was added to about 500gr (almost 0.5% volumetric ratio) of the mortar to enhance the bond between textile yarn bundles and the concrete. Fig. 2 shows steel fiber, while Table 2 lists the properties of steel fiber.



a. fine aggregate



b. coarse aggregate

Fig. 1. Grading curve of aggregate.

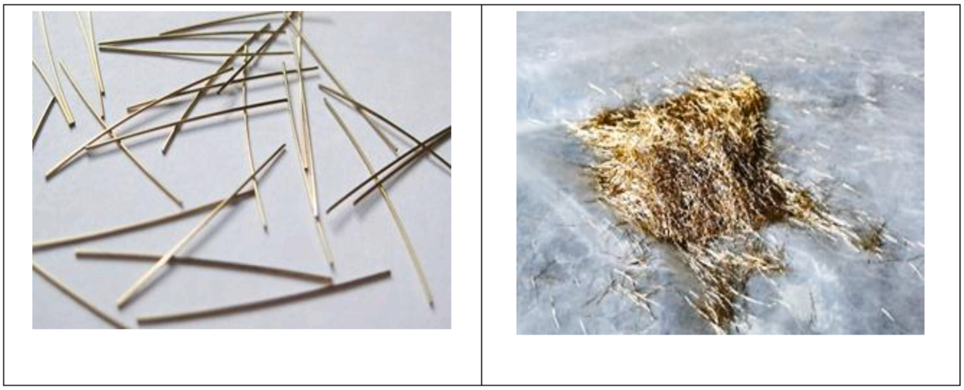


Fig. 2. Steel fibers.

Table 2
Properties of steel fiber.

Type of fibers	Steel fibers (straight ends)
Length (mm)	15–16
Diameter (mm)	0.2 ± 0.02
Density (kg/m^3)	7800
Aspect ratio (L/D)	40–80
Tensile strength (MPa)	2000

2.3. Textile carbon bundles

The other type of reinforcement that is used as "shear reinforcement instead of steel reinforcement in this study is the textile carbon yarn, which is characterized by excellent mechanical characteristics" [38]. "It was supplied by the Chinese company (Jiaxing) as shown in Table 3. The longitudinal carbon yarns were taken only from the textile grid to be used for web reinforcement as shown in Fig. 3."

It is difficult to use the textile mesh as it is in wrapping the main reinforcement at the shear zone, so it was suggested to extract the long continuous carbon fiber bundles from the mesh to use them easily. Moreover, the textile carbon yarns were impregnated in a flowable cement paste for the purpose of increasing the bond (providing a rough surface) between the yarns and the surrounding concrete and preventing slipping, as shown in Fig. 4.

2.4. Flexural and shear reinforcement

Table 4 shows the deformed "steel bars with different sizes used in reinforcing the beams in shear and bending, ∅ 8 mm is used as stirrups,∅ 16 as flexural reinforcement, and 2 ∅ 12 is placed at the compression zone to stabilize the steel and carbon" yarn stirrups.

2.5. Experimental setup

The ordinary wood of 25 mm thickness was molded into beam specimens with dimensions of 200 × 300 × 1500 mm. "The mold's internal walls and base were oiled in order to inhibit the adhesion of concrete to them. The first control beam was reinforced by bending by the steel reinforcement without shear reinforcement, and the other was with steel stirrups as shear reinforcement. The first specimen was tested to determine the actual shear strength of the concrete and was also used as a reference specimen to compare with beams reinforced in shear by a textile carbon yarn bundle to clarify the contribution of the textile yarns to shear strength. However, the

Table 3
Properties of carbon textile fibers [38].

"Material	12 k carbon fiber
Weight (g/m^2)	160 ± 10(g)
Width (mm)	1000
Thickness (mm)	0.2
Mesh size (mm)	3
Tensile strength (MPa)	3530
Tensile Modular (GPa)	230
Color	Black"

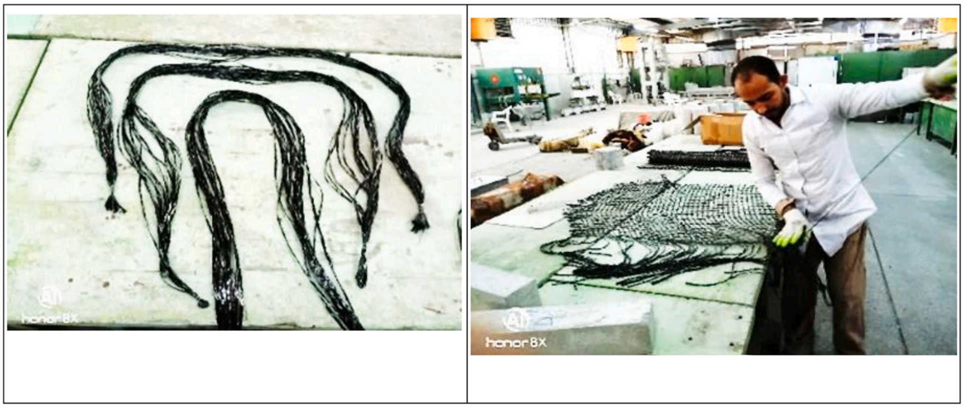


Fig. 3. Production of continuous carbon yarn bundles from textile mesh.

Fig. 4. Impregnation of textile Carbone yarns in a flowable cement paste.

Table 4
Properties of Reinforcing Steel Bars.

Nominal Diameter (mm)	Cross-section Area (mm2)	*fy* (MPa)	*fu* (MPa)	Elongation (%)
8	50.24	530	880	13
12	113.04	425	700	13.5
16	200.96	650	907.5	12.1

second control specimen was adopted to achieve the comparison between the traditional steel stirrups and the textile carbon yarn bundle. The dry carbon yarn bundles were immersed in a flowable cement paste to increase and improve the adhesive bond with concrete. The area of the carbon yarn bundles was adopted from the equivalent area of steel stirrups, taking into consideration the high tensile strength of the carbon yarn and its bond with concrete" [38]. The six specimens of carbon yarn bundles were distributed as one control beam B12 in which the carbon bundles were placed at the same spacing that was adopted in the beam with steel stirrups. As a

result, this beam had 130 mm of spacing between carbon bundle stirrups and 60% length overlap. 60% represents the ratio of overlap length to the effective depth, at 90° of inclination, and without steel fibers. The other five beams were: two beams B11 and B13 with 30% and 100% overlap length, the beam B3 with 90 mm spacing between carbon bundle stirrups, the beam B2 with 45° of inclination, and the last beam was the same as B12 with steel fiber bonding added to the mortar. Table 5 shows the details of the beam specimens. Fig. 5 shows a sketch of the reinforcement details for the specimens.

3. Results and discussion

3.1. Load carrying capacity

A general view of the obtained results indicates that the beams with shear textile yarn stirrups gave a significant increase in the load-carrying capacity with different overlap lengths as compared with those with and without shear steel stirrups. There is a clear improvement in the shear behavior of the beams reinforced by yarns as shear stirrups. As a result, the ultimate load of B11TYL30% 130 mm decreased by 16%, while that of B12TYL60%90° 130 mm, B13TYL100%130 mm, B3TY11L60%90 mm, B2TYL60% 45°130 mm, and B5TYLS60%130 mm increased by 1.5%, 24.5%, 13.6%, 54.8%, and 3%, respectively, compared to the reference beam RCWS. However, the reduction in the overlap length to 30% leads to a decrease in the ultimate load by 18%, while the 100% overlap length causes an increase in the load carrying capacity valued at 22.7% as compared with the B12TYL 60% 90° 130 mm specimen. This is attributed to the increase in the longitudinal bond of the textile yarn stirrups. Consequently, when using textile yarns as shear reinforcement, the 100% overlap length must be used as the best length of overlap at which the slipping between yarn filaments themselves and between yarns and concrete is prevented. On the other hand, the load-carrying capacity increased by about 12% when the spacing between the textile yarn stirrups was decreased from 130 mm to 90 mm. The reason for the reduction in the spacing between the yarn stirrups is that it leads to better utilization of the yarn filaments by improving the bond with the concrete. The ultimate load is thus increased, i.e., more contact area with the surrounding concrete results in more internal strengthening of the concrete and increases its load capacity. Furthermore, the inclination of the textile yarn stirrups by 45° leads to an increase in the ultimate load by 52.5% as compared with that of 90°. However, this difference is attributed to the mechanical anchoring of the textile yarns that is achieved by 45° inclination. Hence, the number of activated yarns is increased. The comparison between B12TYLW M60% 130 mm and B5TYLWMS60%130 mm demonstrates that the beam with bonding (steel fiber + mortar) attains a higher ultimate load than that of the other beam due to the ability of the dispersed steel fibers to achieve the bridging mechanism that restricts the development of the shear crack. This agrees with Parmentier, Cauberg and Vandewalle [71], who observed a significant improvement in the beam's shear capacity when the span ratio is between 0.5 and 2.5.

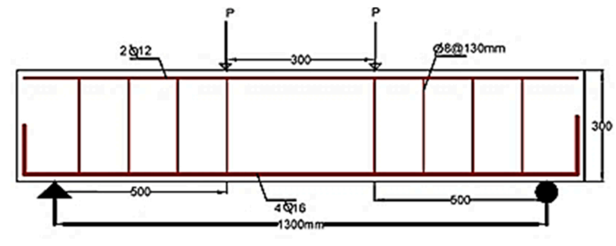
However, the concrete's mechanical properties like the tensile strength can be improved by steel fiber incorporation as noted by Européen [72]. Since the diagonal tension dominates the shear strength, the addition of the dispersed steel fibers leads to an increase in the shear capacity of the reinforced concrete members. Table 6 shows the test results for the tested beams. The deflection at the ultimate load showed a clear increase in the seven beams that contained the steel and textile yarn stirrups as compared to those without shear reinforcement (RCWOS) due to the higher shear strength that the seven beams yield as compared with the latter. On the other hand, the beam with traditional steel stirrups showed the highest deflection as compared to the beams of textile yarn stirrups, in spite of their higher shear strength compared with the former. Accordingly, the beams with 100% overlap length and 45° inclination showed higher ultimate load with a lower deflection in comparison with the RCWS. As a result, despite the slight increase in shear strength, the B4TYL S60%130 mm yields a clear increase in deflection valued at 26.7% when compared to the B12TYL 60% 90° 130 mm. The use of inclined shear reinforcement has not been popular in the industry due to the difficulty of fabrication. However, the diagonal cracking pattern of shear failure in RC beams supports the fact that the inclined position is more effective in resisting the shear [73] compared with the use of vertical position as recommended by ACI 318–14 [74]; the actual shear reinforcement configuration was in an inclined position.

3.2. Load-deflection behavior

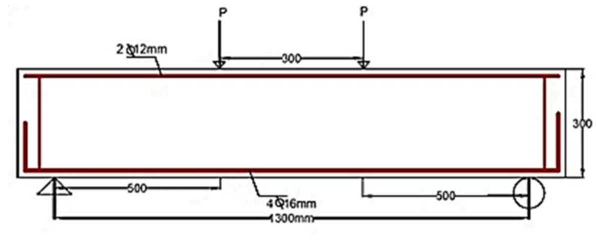
The load-deflection behavior of the structural member is "represented by a relation between the deflection at mid-span and the ultimate load. Generally, the structural behavior of the beams is indicated by the load-deflection curves in this study. The curves of load versus deflection identify three specific regions: the first one is the linear elastic region until the crack occurrence, followed by the

Table 5
Details of the tested beams [38].

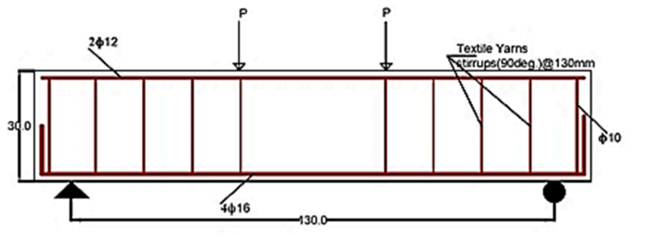
"Specimen	Shear Reinforcement Material	Description	Specimen Type
RCWOS	Without steel	–	Control beam
RCWS	Steel	Using ∅8 steel stirrups mm at 130 mm	Control beam
B_{11}TYL 30%130 mm	Textile Yarns	Using yarns bundle with 30% overlap at 130 mm	
B_{12}TYL 60% 90° 130 mm		Using yarns bundle with 60% overlap at 130 mm	Control beam
B_{13}TYL 100% 130 mm		Using yarns bundle with 100% overlap at 130 mm	
B_3TYL 60% 90 mm		Using a yarns bundle with a spacing of 90 mm	
B_2TYL 60% 45° 130 mm		Using yarns bundle with 45° inclination at 130 mm	
B_4TYL S60%130 mm		Improving bonds by steel fibers"	



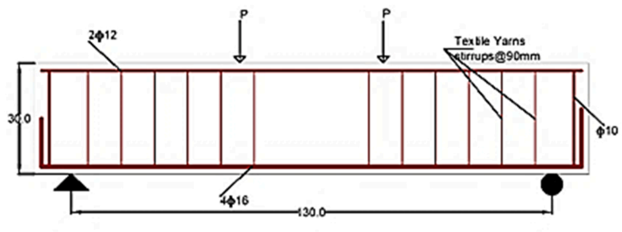
a: with shear reinforcement



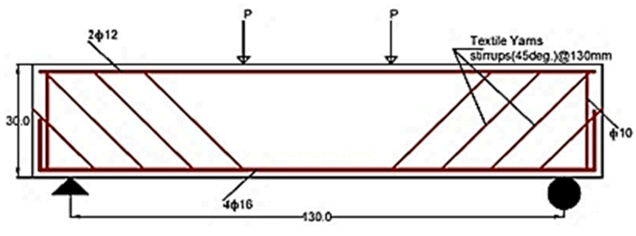
b: without shear reinforcement



c: with textile yarns at 130 mm



d: with textile yarns at 90 mm



e: with textile yarns at 45°

Fig. 5. Reinforcement details of the specimens.

nonlinear stage, which is represented by the dominance of the reinforcement on the beam behavior and terminated either by yield in the case of steel reinforcement or by a rupture in the case of elastic reinforcing materials" [38]. Steel reinforcement is characterized by plastic deformation, which evidently occurs beyond the yield, while textile reinforcement exhibits elastic behavior until failure. The concrete is responsible for the behavior until the cracking; therefore, the slope of the linear elastic portion refers to the stiffness (flexural rigidity) of the beam. While the flexural rigidity of the beam gradually decreases with increasing load as a result of the transition from an uncracked to a partially and fully cracked state. The last transition is accompanied by a continuous decrease in the

Table 6
Test results of the eight beams.

Specimen	Ultimate load (kN)	Δ_u (mm)	Ultimate load (%)		Δ_u (%)
RCWS	330	13.2	-	24	-
RCWOS	266	7.29	-20	–	44.7
B_{11}TYL30%130 mm	275	7.87	-16	3.3	40.3
B_{12}TYL 60% 90° 130 mm	335	9	1.5	26	31.8
B_{13}TYL100%130 mm	411	12.4	24.5	54.5	6
B_3TY$_{11}$L60%90 mm	375	9.22	13.6	50	30.1
B_2TYL60%45°130 mm	511	12.8	54.8	92	3
B_5TYLS60%130 mm	340	11.4	3	27.8	13.6

depth of the compression zone; hence, the moment of inertia is reduced progressively. Accordingly, the deflection of the beam increases with load development since it represents a function of loads, spans, and stiffness. Fig. 6 shows the load-deflection behavior for the beam specimens. However, "as it is observed that the load-deflection curve of all specimens initiated by a linear portion is identical in all of them, the following region showed a clear separation between the curves of these specimens. Accordingly, the beam with steel stirrups gave lower flexural stiffness, while the beams with textile yarn stirrups showed higher flexural stiffness" [38]. However, increasing the length of the overlap and the addition of the steel fibers showed no clear effect on the post-cracking stiffness while reducing the spacing between the textile yarn stirrups to 90 mm and the inclination of the stirrups by 45° showed an obvious improvement in the post-cracking behavior.

3.3. Shear ductility

The ductility of the material can be defined as the ability to deform without a substantial reduction in the bending capacity [75]. "The shear ductility index was defined by the shear ductility index 1, which is computed by the ratio of the area under the load-deflection curve response up to 0.75 of the ultimate loads (0.75 Pmax) in the descending portion to the area up to the ultimate load (Pmax). Table 7 shows the shear ductility values for all beam specimens. It can be seen that the shear ductility is clearly improved by using textile yarns as shear reinforcement instead of the traditional steel stirrups" [38]. As a result, the shear ductility of the beams B11TYL30%130 mm, B12TYL60%90° 130 mm, and B13TYL100%130 mm increased by about 38%, 13.2%, and 17.3%, respectively, when compared to the reference beam (RCWS). However, the reduction in the length of the overlap to 30% and 100% of the effective depth leads to an increase in the shear ductility. "It can be observed that the shear ductility index is influenced by the first drop in the load-deflection curve beyond the ultimate point. Specifically, if this part of the load-deflection curve shows perfect descending, then the shear ductility index is reduced, while if this part exhibits ascending, the shear ductility index increases" [38]. The B11TYLWM30%

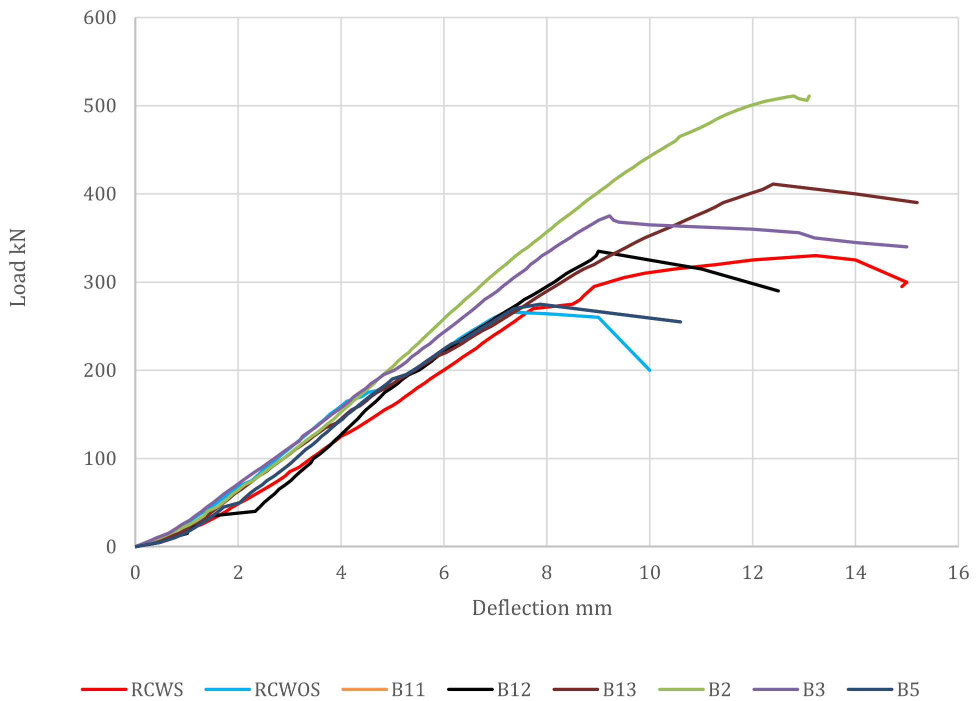


Fig. 6. Load-deflection behavior for the beam specimens.

Table 7
The shear ductility index for all specimens.

Specimen	Ultimate load (kN)	Deflection Δu (mm)	Shear ductility index (μ1)	Ductility index (μ1) (%)
RCWS	330	13.2	1.21	–
B_{11}TYL30%130 mm	275	7.87	1.67	38
B_{12}TYL 60% 90° 130 mm	335	9	1.37	13.2
B_{13}TYL100%130 mm	411	12.4	1.42	17.3
B_3TY_{11}L60%90 mm	375	9.22	1.14	-6
B_2TYL60%45°130 mm	511	12.8	1.03	-14.8
B_5TYLS60%130 mm	340	11.4	1.32	9

130 mm yields the higher value of this index since it shows the lower gradient in the stage beyond the peak point of the load-deflection curve. Furthermore, the shear ductility index of B3TY11LWM60%90 mm decreased by 31.7% as compared with B11TYLWM30% 130 mm. This reduction is attributed to the decrease in the spacing between the yarn stirrups, which leads to a decrease in the number of yarns in each bundle, diminishes slipping of the filaments, and activates a high number of filaments, hence the brittleness is increased. On the other hand, the shear ductility index decreased when the angle of stirrups was changed from 90° to 45° with respect to the horizontal main reinforcement by about 24.8%, which is the reason for the excessive rupture of the yarn filaments due to the mechanical anchoring. However, the addition of steel fibers to the textile yarn stirrups leads to a decrease in the shear ductility index by 3.6%, despite that this addition is supposed to improve the shear ductility since steel is a ductile material, while the excessive damage of filaments caused by the intersection of these fibers leads to more brittleness.

3.4. *Cracking behavior*

The cracking details for all beams are presented in Table 8. When the load is applied on these beam specimens, the first crack is formed at 16.66%, 15%, 17.9%, 17.2%, 18.67%, 14.67%, and 20.6% of the ultimate load of RCWS, RCWOS, B11TYL30%130 mm, B12TYL 60% 90° 130 mm, B13TYL100%130 mm, B3TYL60%90 mm, B2TYL60%45°130 mm, and B5TYLS60% 130 mm, respectively. However, the cracking load is clearly increased when steel or textile yarn stirrups are used instead of (RCWOS). Moreover, the reduction in the length of the overlap to 30% led to a decrease in the first crack load by 21.67%, while increasing the length of the overlap to 100% increased the cracking load by 18.33% as compared to the reference beam with an overlap of 60%. On the other hand, reducing the spacing between the textile yarn stirrups from 130 mm to 90 mm and the addition of steel fibers showed a similar increase in the cracking load by 16.67% as compared with the B12TYL 60% 90° 130 mm, while the inclination of the textile yarns at 45° showed the higher improvement in the cracking load. “The textile yarns exhibit the bridging mechanism, which is evidenced by the yarn filaments that inhibit the development of the micro-cracks and resist their initiation and propagation” [38]. However, the bond between the concrete and the yarns has greatly influenced this process. Consequently, the increase in the overlap length, the reduction of the spacing between the yarn stirrups, the change in the angle of the inclination to 45°, and the addition of steel fibers improved the bond and increased the cracking strength. The table also shows the crack width at the advanced loading stage. The increase in the overlap length and reducing the spacing to 90 mm led to a reduction in the crack width, while the 45° inclination showed a clear increase in the crack width for the reason of its highest load-carrying capacity and the addition of steel fibers led to the wider cracks since the damage occurred. Fig. 7 shows the crack pattern for beams.

3.5. *Weight of beams*

On a weighing scale, the beam was weighed prior to testing. As indicated in Table 9, the weight of beams reinforced using textile yarns as shear stirrups rather than standard stirrups fell by approximately 12%, 11.77%, 11.11%, 6.6%, and 12% compared to the reference beam (RCWS) for the beams. The reason for this decrease is mainly due to the different proportions and densities of materials.

4. Conclusions

The results collected from this work revealed the following:

1. The use of the textile yarn as a shear reinforcement showed excellent results in “terms of load-carrying capacity, load-deflection behavior, shear ductility, cracking strength, and crack width. However, these results promote the use of this type of reinforcement instead of conventional steel stirrups. This can serve sustainability in terms of resistance to corrosion and other aggressive materials and environmental conditions”.
2. The gradual increase in the length of the textile yarn “overlaps by 30%, 60%, and 100%, which leads to an increase in the load-carrying capacity, increases the ultimate deflection and improves the post-cracking stiffness.”
3. Reducing the spacing between the textile yarn stirrups from 130 mm to 90 mm leads to improved load carrying capacity, increases the deflection, enhances the bond between the concrete and the textile shear stirrups by reducing the congestion of the yarns, increases the cracking load, and increases the number of cracks. It also reduces the crack width and causes.

Table 8
The cracks details for all specimens.

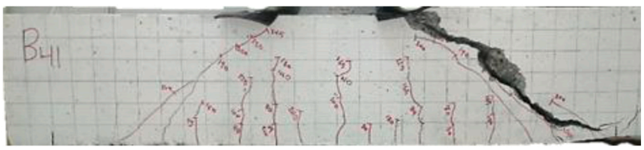
Specimen	Crack load Pcr (kN)	Ultimate load Pu (kN)	Pcr/Pu (%)	Ultimate crack width Wu (mm)
RCWS	55	330	16.66%	0.065
RCWOS	40	266	15%	0.21
B_{11}TYL30%130 mm	47	275	17%	0.12
B_{12}TYL 60% 90° 130 mm	60	335	16.11%	0.0704
B_{13}TYL100%130 mm	71	411	17.2%	0.066
B_3TY_{11}L60%90 mm	70	375	18.6%	0.066
B_2TYL60%45°130 mm	75	511	14.6%	0. 22
B_5TYLS60%130 mm	75	340	20.5%	0.77

a: Crack pattern for RCWS

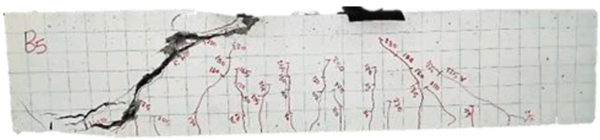
b: Crack pattern for RCWOS

c: Crack pattern for B11TYL30%130mm

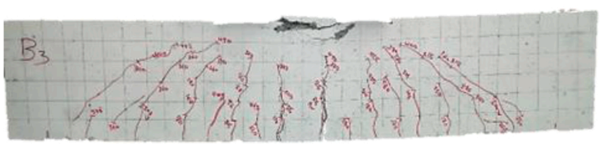
d: Crack pattern for B12TYL60%130mm



e: Crack pattern for B3TY11L60%90mm



f: Crack pattern for B5TYLS60%130mm



g: Crack pattern for B2TYL60%45°130mm

Fig. 7. Crack pattern for all beams.

Table 9
The weight of all specimens.

Specimen	Weight (Kg)	Diff. of Weight
RCWS	225	–
RCWOS	195	–
B11TYLWM30%130 mm	198	-12%
B12TYLWM60%130 mm	198.5	-11.77%
B13TYLWM100%130 mm	200	-11.11%
B2TYLWM60%45°130 mm	210	-6.6%
B3TY11LWM60%90 mm	198.5	-12%
B4TYLWMS60%130 mm	207	-8%

4. The inclination of the textile yarn stirrups at 45° leads to "an increase in the load-carrying capacity, increases the deflection, and increases the cracking strength by reducing the crack width and changing the mode of failure from shear to flexure, which is accompanied by crushing of the concrete in the bending zone."
5. The impregnation of the textile yarn stirrups in the cement paste with short steel fibers increases the cracking strength, load-carrying capacity slightly, deflection, and crack width slightly.
6. "The weight of beams that were reinforced with bundles of textile yarns gave less weight by 12% as compared with the reference that was reinforced with steel stirrups."

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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