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Effects of Cross-sectional Shape on Mechanical performances of New-designed FRP Sandwich Structures Reinforced with 3D Weft-knitted Spacer Fabrics

Sanaz Hassanzadeh[*], Hossein Hasani, and Mohammad Zarrebini

Department of Textile Engineering, Isfahan University of Technology, Isfahan, IRAN

Abstract

Improving the mechanical performances of technical composite materials along with reduction of their weight, is of the main concern especially in technical applications. 3D sandwich composites are considered as high potential choices to overcome these concerns. 3D spacer weft knitted fabrics due to their individual structure and high flexibility in designing, have found their position in this field. Since the cross sectional shape of these structure would be effective on their mechanical performances, in this paper two different 3D spacer sandwich composites including U-shaped and V-shaped structures was aimed to be compare in terms of their compression and bending strength. The results revealed that the V-shaped 3D spacer weft knitted composites, have higher ability to provide such uniform stresses distribution within the structure than the U-shaped 3D composites.

Keywords: 3D composites, Weft knitting technology, Mechanical performance, glass fibers, structural parameters.

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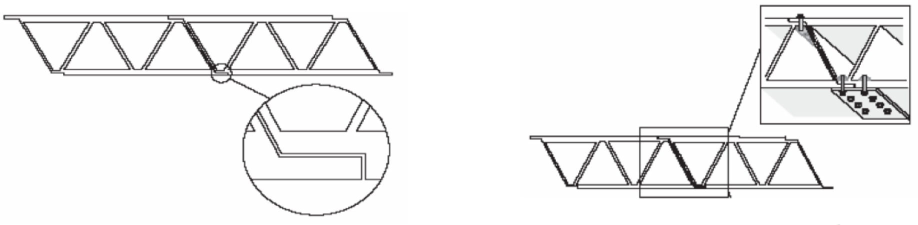
[*] Corresponding author: E-mail: s.hassanzadeh@tx.iut.ac.ir

Introduction

The increasing advancements in civil engineering based on finding new solutions for the deteriorating state of construction infrastructure system, have been led to carry on numerous researches upon the employment of high-performance fiber reinforced polymer (FRP) composites materials as good alternatives for available reinforced concretes (RC) [1-2]. In fiber reinforced systems same as the RCs, the applied loads of pre-designed directions are totally sustained by the fibers embedded into a polymeric medium [3]. FRP materials due to their high-strength, high-stiffness, high-durability as well as low-cost and light-weight advantages, have found wider acceptance especially is construction industries [2].

One of the serious problems concerned by the civil engineers regarding the constructional deterioration is attributed to the transportation infrastructure systems such as bridge [2, 4]. FRP decks with superior mechanical properties have been accepted to be as good candidates for being used in deteriorated bridge rehabilitation [5]. Among two major types of FRP decks including sandwich structure and adhesively bonded shapes, the former is commonly accepted. Despite the adhesively-bonded constructions are easy in manufacturing and provide uniform stress distribution, but the lower fatigue performance and durability of adhesive layers have left them to be considered only in initial research stages [6]. Two different bridge deck structure which are adhesively connected or bolted together and their structural weak spots are shown in Figure 1.



Adhesively bonded connection

Bolted connection

Figure 1. Stress concentration zones of two different bridge decks with adhesively-bonded/bolted connections [4]

Sandwich structures, which are generally comprised of core materials supported by two different surface layers, have attracted lots of technical applications due to their high mechanical strength and stiffness as well as their lightweight properties [3]. Thermal insulation and acoustic performance due to their structural porosity and cellular configuration as well as high energy absorption are considered as some other advantages of sandwich structured materials [1-2]. However, the connection points between the surface layers and the core structure are known as the main stress concentration zones in conventional sandwich structures; this in turn would be resulted in damage propagation during external loading such as impact, tensile, bending and shear forces [7]. Structural delamination as the result of debonding effect applied to the composite's constitutive components, was studied by several researches but most of the proposed solutions are likely to enforce some restrictions and extra cost during composite manufacturing process [8-9].

Development of 3D spacer textile-based preforms as the composite reinforcements due to their individual characteristics, have provided different materials which could solve the problem of skin-core debonding of conventional sandwich materials; on the other hand, these novel-designed textile-based structures would provide a wide range of applications in which the reduction of structural weight is of the main concern [10-12]. In such engineered performs, the cellular-shaped core section of the structure would be formed by the vertical pile yarns or fabric layers which make the connection between the two distinctive surface layers [11-12]. In this case, uniform distribution of loading would be applied to the whole structure which could be resulted in better mechanical performances of FRP 3D-shaped materials in terms of stiffness, strength and service time than other conventional used structures [10, 12].

Mechanical strength of woven 3D sandwich composites have been investigated by different researchers [13-15]. It was revealed that the skin-core debonding resistance of 3D woven sandwich materials as well as their failure strength are much higher than other commonly used sandwich composites. In spite of all advantages considered for 3D woven sandwich preforms, the lack of their flexibility in composite manufacturing with various geometrical shapes has limited their technical applicability. So that, the knitting technology due to their high flexibility in fabricating numerous complex shaped structures, has been developed to overcome this kind of limitation [12]. Along with this issue, the product-ability of 3D weft knitted sandwich structures has been focused by different researchers; although there are limited available reports regarding the researchers' success in fabrication such technical textiles [11, 16-19]. In this regard, Abounaim *et al* [11] provided a single decker 3D knitted preform which was comprised of inlayed reinforcement weft yarns. This structure were then tested for their mechanical performances and found suitable to be employed as thermoplastic composite reinforcement. In our previous work [12], the product-ability of 3D weft knitted spacer fabrics with different cross-sectional shapes was considered. Our reported results were limited to the production of double-decker 3D weft-knitted spacer fabrics used as the newly designed reinforcements for thermoset composite manufacturing. Here in this study, two other 3D weft knitted structures with different cross sections are focused in order to investigate their mechanical behavior under the bending and compression loadings.

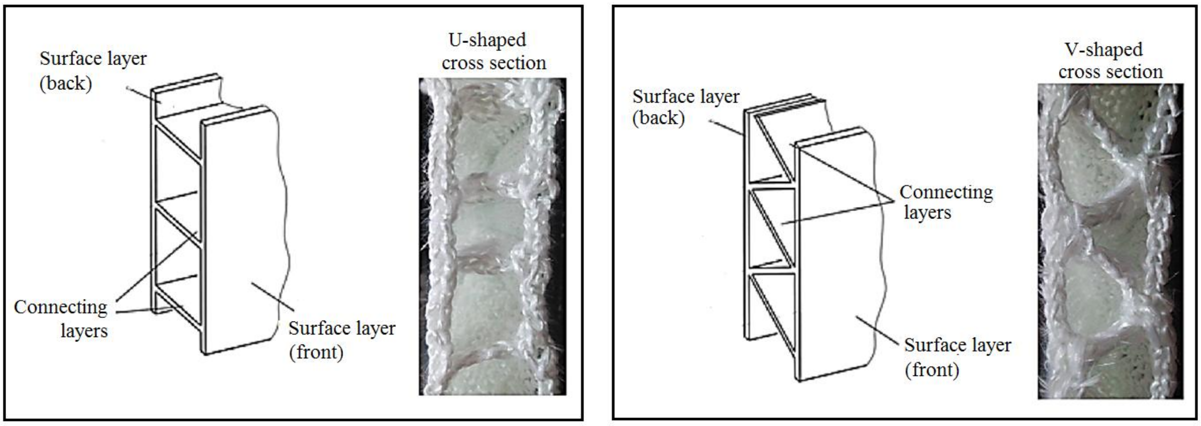
Materials and methods

Sample preparation

Using Stoll flat knitting machine (CMS 400, E5; Germany), two different kinds of 3D spacer weft knitted fabrics (U-shaped and V-shaped) made of E-glass yarns were produced. Because of the glass brittleness nature, production of 100% glass fabrics might be resulted in numerous difficulties such as frequent yarns breakage. For overcoming this problem, four plies of 100_{Tex} glass yarns were twisted with a single-ply 1200_{Denier} ($\approx 130_{Tex}$) intermingled polyester yarn; so that the polyester fibers could play as the wrapping fibers in order to minimize the probable abrasion effect applied to the glass yarn during knitting operating. Detailed information about the glass and polyester fibers are given in Table 1. The schematic drawings and real appearance of the samples are depicted in Figure 2. Table 2 also contains some structural characteristics of the produced 3D spacer knitted fabrics

Table 1. Fibers characteristics

Fiber type	Mechanical properties		
	Tensile strength (*MPa*)	Young's modulus (*GPa*)	Density (g/cm^3)
E-Glass	3400	76	2.58
polyester	570	5.5	1.38



(a) (b)

Figure 2. 3D spacer weft knitted fabrics; (a) U-shaped, and (b) V-shaped samples

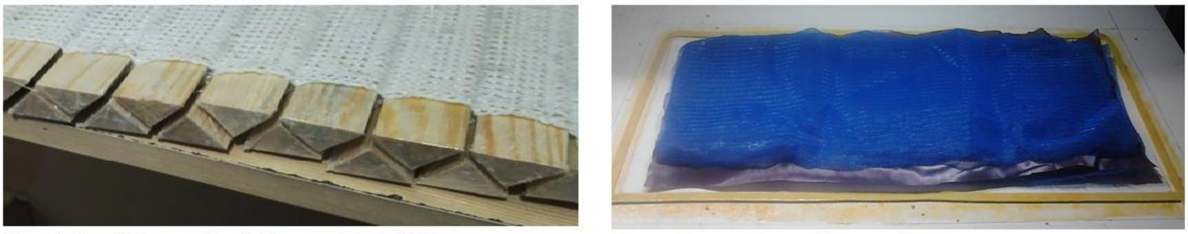
Table 2. 3D spacer weft knitted fabrics characteristics

Fabrics type	CPC (*1/cm*)	WPC (*1/cm*)	Weight (*gram per volume area*)
U-shaped	3.2	2.4	2850 (CV% = 8.8)
V-shaped	2.6	3.2	2980 (CV% = 6.3)

Produced samples were then kept under standard room condition (20±5ºC temperature and 65±5% relative humidity). Using the vacuum bag molding, 3D spacer glass/epoxy composite panels were prepared (epoxy properties: tensile strength = 85_{MPa} and Young's modulus = 10.5_{GPa}). During the composites manufacturing, is should be noticed that spaces formed between the surface and connecting layers must be remained unchangeable; for this aim, some wooden rods with dimensions similar to the fabrics spaces were initially prepared and then inserted into the structure. For better understanding, the composite manufacturing procedure of the V-shaped 3D spacer weft knitted fabrics is illustrated in Figure 3. Before molding process, the wooden rods need to be lubricated by a waxy releasing agent (Meguiar's 8 Max, USA); this, makes it possible to easily pull out all of the supporting rods from the cured final composites. Dimensions of the two different 3D spacer wet knitted composites are compared in Figure 4.

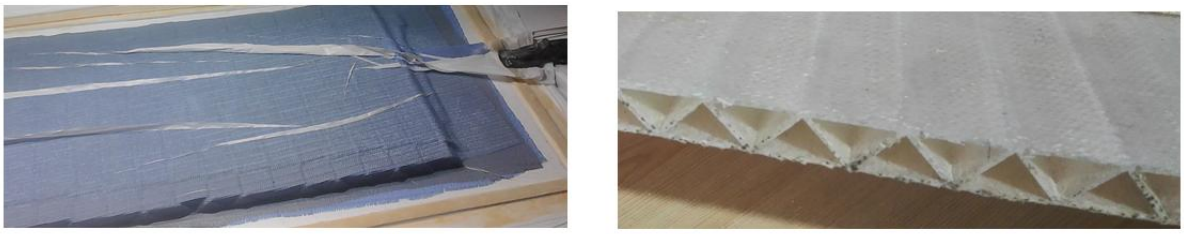
Mechanical test

Composite samples were mechanically tested in order to study their flexural and compression behaviors. Using a Universal tensile tester (DWD-100E, China) bending and compression loads were applied on the samples at a constant rate of 0.5 mm/min considering standard condition (23±3ºC temperature and 50±5% relative humidity).



Step 1: Sample preparation before vacuum molding

Step 2: Vacuum bag molding installation



Step 3: Applying the vacuum in order to transfer resin component

Step 4: Trimming the final composite

Figure 3. Production procedure of 3D spacer weft knitted composites

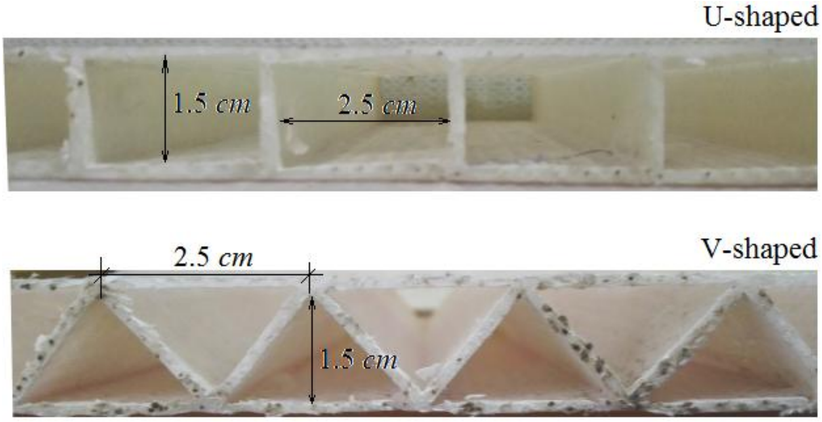


Figure 4. 3D spacer weft knitted reinforced composites (cross-sectional view)

Due to the looped structure of the reinforcing 3D spacer weft knitted fabrics, the values of fiber volume fractions for the composite samples' are expected to be relatively low which could be attributed to the fabrics open structure. Some of the samples characteristics and physical properties are given in Table 3. The U-shaped and V-shaped composite panels are labeled as UC and VC materials, respectively. The given data in Table 3 are the average values of ten measurements.

Table 3. Composite sample characteristics

Sample code	Fiber volume fraction (%)	Weight *(gram per volume area)*
UC	35.8 (CV% = 17.1)	6250 (CV% = 10.3)
VC	38.4 (CV% = 12.9)	6500 (CV% = 9.7)

Flatwise compression tests as well as three-point bending were applied on the samples according to ASTM C364 and ASTM C393. Based on the given standard, $250_{mm}\times60_{mm}$ specimens were prepared for bending test, while $90_{mm}\times90_{mm}$ specimens were chosen for flatwise compression loadings. Figure 5, schematically illustrates two different mechanism of loadings applied on U-shaped and V-shaped 3D weft knitted composites.

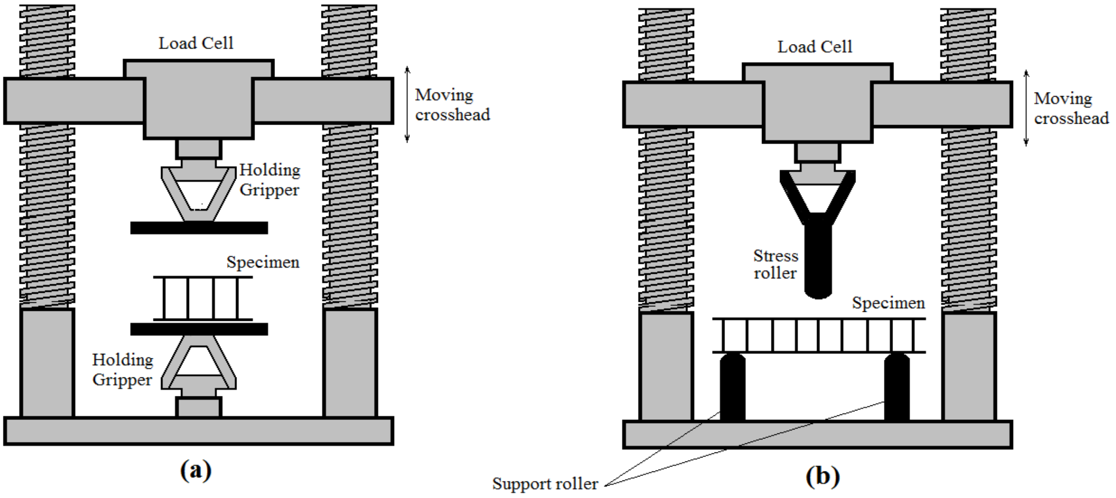


Figure 5. Bending and compression loading; (a) edgewise compression, and (b) three-points bending

Results and discussions

Effect of cross-sectional shapes on compression behaviors of 3D composites

Load-displacement curves of the samples affected by the compression loadings for two different sandwich composite samples, are shown in Figure 6. By assuming the similar thicknesses for the samples, it could be found that the VC samples have higher resistance against the applied loads than the UCs. This could be attributed to the higher number of connection points which are formed between the connecting layers and the face-sheets. The higher connecting points results in uniform distribution of the applied loads within the whole structure [3, 8]. The sudden drop in the curve is corresponded to the sudden buckling of the structure.

Fracture mode of 3D spacer weft knitted composites are considered to be ductile, while the brittle behavior of the glass fibers is well known. This is mainly attributed to the fact that the effect of resin surrounding the reinforcing fibers, plays an important role during the panel flatwise compression [3]. Therefore, it is claimed that the panel yielding as well as ductile behavior of the resin component, are responsible for the structural fracture behavior. Since the fiber volume fractions of the samples are not so much, ductile behavior of the resin component has significant effects on the panel’s structural failure [14].

Specimens show such a linear elastic behavior before the resin cracking, happened. During the matrix cracking, the generated tension within the structure (due to the applied loads) starts to be decreased which is followed by the core yielding. This process would be continued until the connecting layers fail completely at their connecting points, so that the face sheets (surface layers) tend to compress all the piles together.

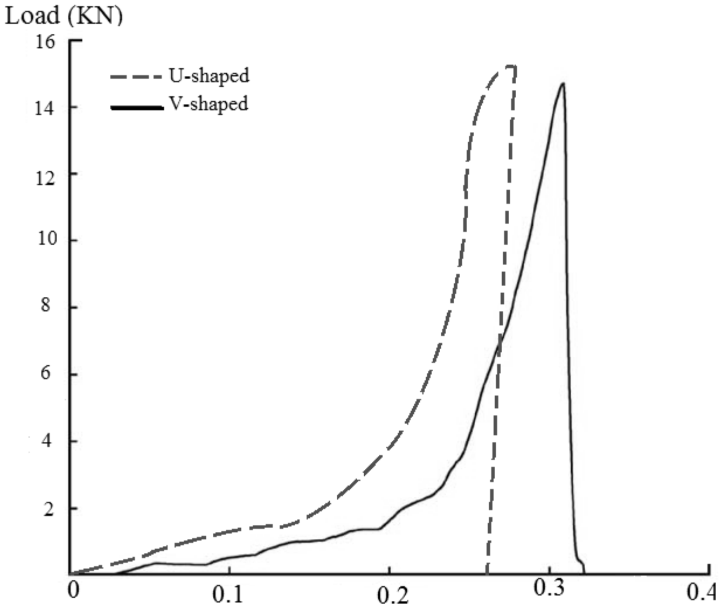


Figure 6. Load-displacement curve of composite samples under the compression loading

It has been reported that the thinner panels show higher compressive stiffness and maximum stress distribution than the thicker structures. This can be justified by this fact that the higher bending moments would be applied at the body of connecting layers as well as the intersection points between the connecting and surface layers, in the case of thicker composites [3]. For the composite samples with the same thickness, it can be claimed that the intensity of the applied bending moment during compression, is affected by the number and the area of bonding regions.

Effect of cross-sectional shapes on bending stiffness of 3D composites

The probability of buckling phenomenon in composite samples with V-shaped structure is expected to be lower than that of the U-shaped composite materials [3]. During bending test, the applied loads as well as the structural deflections, increases linearly until the connecting layers start to be failed under loading. In the case of V-shaped 3D composite panels, the generated stresses within the composite structure could be distributed along two adjacent connecting layers which joint together at the same point, while for the U-shaped structure the fraction of distributed loads through only one connecting layer would be resulted in higher distributed loads at a specific area.

Figure 7, typically shows the load-displacement of the sample under three-point bending condition. The lower value of the maximum loads for the U-shaped structure compared to the V-shaped, reveals the higher bending strength and better mechanical performance of the former structure.

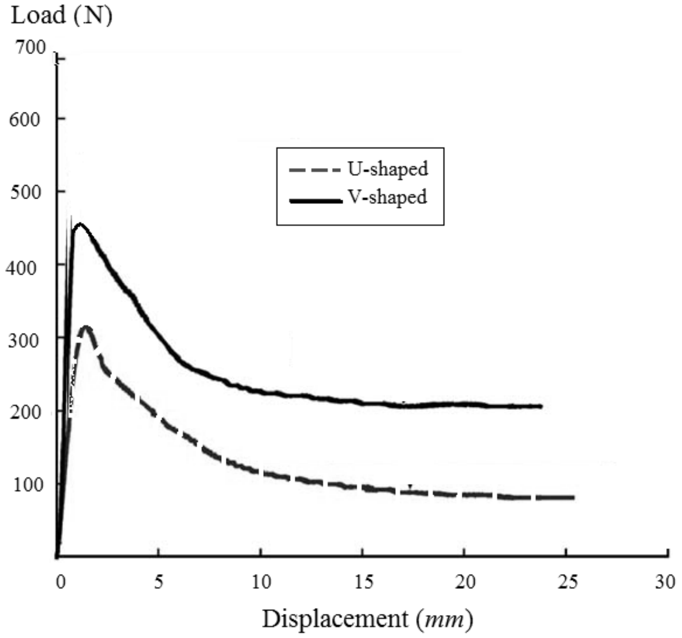


Figure 7. Load-displacement curve of composite samples under the bending loads

Conclusion

3D spacer weft knitted composites show their high potential to be employed in different technical applications. Changing the geometrical shape of the fabrics cross section, have significant effects on their mechanical performances in terms of bending strength and compression stiffness.

Two different kinds of 3D epoxy composite samples reinforced with E-glass/polyester 3D spacer weft knitted fabrics including the U-shaped and V-shaped structures, were considered in this research. The results of bending and compression tests, revealed that the V-shaped composite samples have higher resistance against both bending and compression loadings than the U-shaped structures. This could be contributed to this fact that in the case of 3D composites with triangular-shaped cross section, the generated stresses due to the applied loads could be uniformly distributed through the whole structure. This in turn would increase the ability of the structure to resist more against the applied loads.

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