# Edgewise Compression Behavior of Three-Dimensional Integrated Woven Sandwich Composite Panels

Hooshang Nosraty*, Abolfazl Mirdehghan, Mahshid Barikani, and Mehdi Akhbari

*Abstract*- **This paper is concerned with the study of edgewise compression properties of newly developed sandwich panels denoted as 3D integrated woven sandwich composites (IWSCs). IWSC panels consist of two fabric faces that are interwoven by pile yarns and therefore, a very high skin-core debonding resistance is obtained. To qualify the mechanical properties of this structure, in this study, 3D woven samples with different pile heights and pile distribution densities were fabricated and then after the impregnation by resin, the effect of panel thickness, pile density, sample size, and types of resin on the edgewise compression behavior of IWSC panels were experimentally investigated. The results showed that edgewise compression properties of IWSC panels are increased with the increase of core heights as well as core pile density. Compared with the core height of 20 mm (H1), the peak load values of 30 mm panel thickness (H2) increase between 18 and 36%. Also, as the pile density increases from 2.1 cm$^{-2}$ (D1) to 4.3 cm$^{-2}$ (D3), the peak load values of samples increases about 6% to 14%. Furthermore, the composite produced by epoxy resin showed about 300% better compression properties than the composite fabricated by polyester resin. Warp and weft direction properties as well as size dependency of IWSC panels in edgewise compression test were also studied. The difference between the maximum load values for the warp and weft directions in the samples varies from 10% to 40%.**

***Keywords*: three-dimensional woven fabric, edgewise compression, glass fabric, sandwich panel, composite**

## I. INTRODUCTION

In the recent decades, considerable research works have been devoted to composites reinforced with three-dimensional fibrous structures [1-4]. For instance, a modified face-to-face carpet-weaving machine was used to produce 3D integrated woven sandwich panels [5]. Three-dimensional integrated woven sandwich composites (IWSC) consist of two woven fabric faces. These two parallel faces are bonded together using pile yarns, which keep a defined distance between the top and bottom skins, thus forming integrated woven sandwich composites [6-8]. Sandwich composite panels have found increasing applications in structures where high mechanical properties at low weight are desired [9-11]. Due to the dissimilarity of the face-sheet and core materials, the connection between the skin and core is a crucial important concern in traditional core sandwich structures [12-14]. The material similarity and integrated connection between the face-sheet and hollow core in the IWSC panels provide a through-the-thickness reinforcement during impact, shear and bending loads and therefore, core-skin delamination of 3D sandwich composites has been entirely prevented [15,16].

To qualify the mechanical properties of these structures, the edgewise compression properties of 3D integrated woven sandwich composites have been examined by some researchers. Li *et al.* [17] have studied the edgewise compression response of 3D integrated woven spacer composites with thickened face-sheets. The results indicated that due to additional layers in the face-sheets, edgewise compression and impact properties had been improved significantly than those of composites without thickened face-sheets. Also, they indicated that there is no face-sheets fracture for edgewise compression, while the local shear fracture occurs on the thickened face-sheets. Deformation, strength and failure modes of 3D integrated woven sandwich composite panels were investigated by Hu *et al.* [18]. They studied the strength of warp and weft direction of IWSC sandwich panels in the edgewise compression test and concluded that when the height is smaller than 60 mm, the strength of compressed panels has few variations, progressive crushing, and bending fracture are two observed post-failure modes.

Zhao *et al.* [19] have examined the edgewise compression test on the 3D integrated woven spacer composites with

H. Nosraty, A. Mirdehghan, and M. Barikani
Textile Engineering Department, Amirkabir University of Technology, Tehran, Iran.

M. Akhbari
Textile Engineering Department, Kashan Branch, Islamic Azad University, Kashan, Iran.

Correspondence should be addressed to H. Nosraty
e-mail: hnosraty@aut.ac.ir

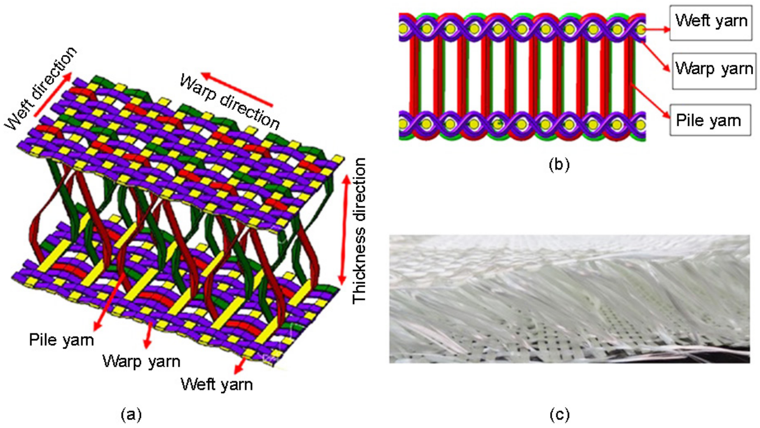



Fig. 1. (a) Schematic display of the 3D fabric structure, (b) schematic cross-sectional view of 3D fabric in the warp direction, and (c) produced sample of 3D fabric.

different core thickness. The failure mechanism under the edgewise compression test is the face-sheets rupture and dislocation between the top and bottom face-sheets that dominate the failure of the composites. Wang *et al.* [20] have investigated the effect of additional glass weaves at the skin-sheets of 3D integrated woven spacer composites on the edgewise compression properties. They studied the effect of various factors such as the additional layer number, the design of glass weave, and the lay-up type. Their results indicated that additional weaves could significantly improve the composite performance. In addition, in order to predict the mechanical properties of IWSC panels, a number of researchers [15,21] provided numerical approaches based on the finite element methods.

In the present study, the simultaneous effect of different parameters on the edgewise compression behavior of IWSC panels has been investigated. For this purpose, 3D composite samples were produced with two different core thicknesses, three different pile densities and two different resin types and then subjected to the edgewise compression test. Warp and weft directions as well as size dependency of IWSC panels in edgewise compression were also investigated.

## II. EXPERIMENTAL

### *A. Materials and Specimens Preparation*

#### *A.1. 3D Integrated Woven Fabrics*

The 3D woven fabrics have been fabricated by a modified face-to-face carpet-weaving machine. Figs. 1a and 1b show the schematic representation of a 3D integrated woven spacer fabric. The structure consists of three distinct layers, two face-sheets with plain weave fabrics, which are integrally connected to each other by pile yarns. The pile yarns are connected to the face-sheets in the warp direction and can be seen in the form of the “8” shape where in the weft direction resembling the “c” shape. In this study, all fabrics are identical in terms of their top and bottom woven fabrics. The warp, weft, and pile yarns in all samples are fabricated by E-glass fiber roving with linear density of 600 tex (supplied by Syna Fiber Delijan Co., Iran). The detailed information of glass fiber provided by the manufacturer is summarized in Table I and the produced sample of 3D woven fabric is shown in Fig. 1c.

#### *A.2. Fabrication of Sandwich Composite*

In order to produce sandwich composite panels, all prepared woven fabrics were fabricated by the hand lay-up technique. The samples were impregnated with two different resin types. The first resin type was epoxy resin (ML-506) with hardener (HA-11) (supplied by Mokarrar Engineering Materials Co., Iran) where, resin-hardener was mixed in a ratio of 100:15 by weight, as recommended by the manufacturer. The second resin system was unsaturated orthophthalic polyester resin (BUP-690) (supplied by Bonyan Kala Chemie, Iran). The initiator was 2% methyl ethyl ketone peroxide (MEKP) (supplied by Iran Peroxide Co.) and the curing agent used was 0.5% cobalt naphthenate (commercial grade). The detailed information of epoxy and polyester resin, which are provided by the mentioned manufacturers, is summarized

TABLE I
MECHANICAL PROPERTIES OF GLASS FIBER [6]

| Fiber type | $E_{11}^f$ (GPa) | $E_{22}^f$ (GPa) | $G_{12}^f$ (GPa) | $G_{32}^f$ (GPa) | $\nu_{12}^f$ | $\sigma_u$ (MPa) |
|---|---|---|---|---|---|---|
| E-glass | 72 | 72 | 27.7 | 27.7 | 0.3 | 1500 |

TABLE II
SOME PROPERTIES OF EPOXY AND POLYESTER RESINS USED IN THE CURRENT STUDY

| Characteristic | Epoxy resin (ML-506) | Polyester resin (BUP-690) |
|---|---|---|
| Density (g/cm³) | 1.11 | 1.12 |
| Tensile strength (MPa) | 75 | 65 |
| Tensile modulus (GPa) | 2.735 | 0.944 |
| Gel time (min) | 24 | 9 |
| Curing time (min) | 25 | 8 |

in Table II.

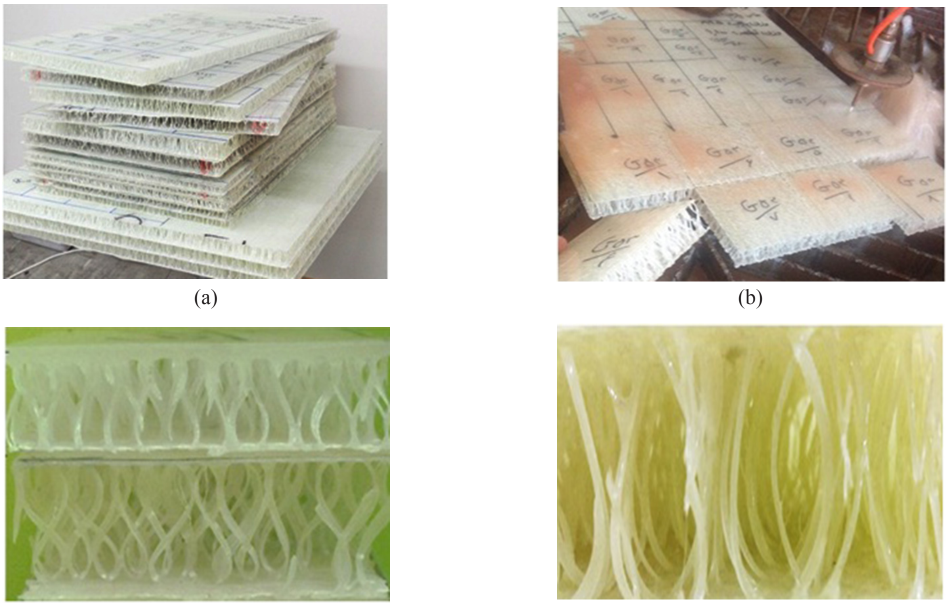
For hand lay-up process, the mold was first polished with releasing agent, then about 40% of resin was applied on the mold evenly and the fabric was placed over it. After the fabric was impregnated with the resin, the remaining 60% of the resin was applied over the top face-sheet. Special care was taken to control the fiber volume fraction fabric impregnation by controlling the ambient temperature and viscosity of resin in which the resin content of the produced panels was about 55% by weight. Then, all samples were kept in ambient temperature for 24 h to complete the curing process.

Fig. 2a shows the picture of produced panels. The detailed characteristics of all samples are summarized in Table III. The composite differences are in their pile density (D1, D2, and D3), panel thickness (H1 and H2), and resin type (Epoxy (E) and Polyester (P)). Since the core section of sandwich panels is hollow, the fiber weight fraction has been reported rather than theoretical fiber volume fraction. In order to reveal the size influence, the samples were cut with two different sizes by a waterjet cutting machine (see Fig. 2b). Besides, the specimens were tested in both warp and weft directions. The cross-sectional view of the composite in the warp and weft directions is illustrated in Figs. 2c and 2d, respectively.

*B. Test Method*

*B.1. Edgewise Compression Test*

The in-plane compression properties of the sandwich composites panels (compressive properties in a direction parallel to the face-sheets of sandwich panels) were measured using the edgewise compression test. For this purpose, all the specimens were prepared and subjected to a compression test according to the standard test method, ASTM C364. The compression test setup is shown in Fig. 3a. As can be seen in this figure, the ends of the sample were



(a) (b) (c) (d)

Fig. 2. (a) Produced IWSC panels, (b) sample cut by water jet machine, and cross-sectional view of the composites in the (c) warp direction, and (d) weft direction.

TABLE III
MAIN SPECIFICATIONS OF THE PRODUCED COMPOSITE PLATE

| Sample code | Type of resin | Composite thickness (mm) | Pile density (1/cm$^2$) | Pile length (mm) | 3D dry fabric weight (kg/m$^2$) | Composite weight (kg/m$^2$) | Fiber volume fraction (%) | Fiber weight fraction (%) |
|---|---|---|---|---|---|---|---|---|
| E-H1D1 | Epoxy | 20 | 2.1 | 24 | 1.552 | 3.505 | 25.8 | 44.3 |
| E-H1D2 | | 20 | 3.2 | 24 | 1.687 | 3.748 | 26.3 | 45.0 |
| E-H1D3 | | 20 | 4.3 | 24 | 1.816 | 4.035 | 26.3 | 45.0 |
| E-H2D1 | | 30 | 2.1 | 34 | 2.158 | 4.796 | 26.3 | 45.0 |
| E-H2D2 | | 30 | 3.2 | 34 | 2.261 | 5.026 | 26.3 | 45.0 |
| E-H2D3 | | 30 | 4.3 | 34 | 2.047 | 4.549 | 26.3 | 45.0 |
| P- H1D2 | Polyester | 20 | 3.2 | 24 | 1.532 | 3.738 | 23.5 | 41.0 |
| P- H2D2 | | 30 | 3.2 | 34 | 2.313 | 4.918 | 28.2 | 47.0 |

smoothed and put vertically between two parallel rigid steel surfaces. The specimens were fully clamped at two opposite edges. The fixture contains side supports at the edgewise sides for the gripping of sandwich structures during the experiment. The fixture prevents the rotation of the specimen and localized buckling failure. Special care was given to the alignment of the sample in the test rig. All tests were carried out on a universal testing machine, Santam (STM 150), at a test speed rate of 1 mm/min via 20 kN load cell capacity. Five samples of each specimen were tested.

## III. RESULTS AND DISCUSSION

### *A. Mechanical Properties*

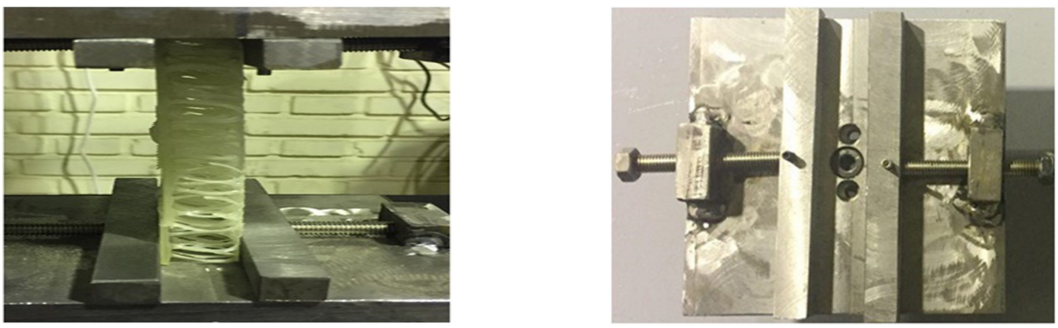
#### *A.1. Load–Displacement Curves*

The load-displacement curves of the edgewise compression test for all samples in the warp and weft directions are illustrated in Fig. 4. The general trend of all curves is similar, but there are differences between their details, which are originated from the core pile structure and the properties of panels. It is useful to note that each of the presented experimental curves was selected among at least four compression test results, in the manner that its maximum force was the nearest to the mean value of specimen in order to assure that the presented graph is the best representative for that specimen. It can be seen from Fig. 4 that in the elastic stage, the panels exhibit a linear behavior up to the failure. However, after the maximum load, the curves decline dramatically because of face-sheets buckling and the composites show clear brittle failure manner in this stage. The non-linear trend of curves after the peak load is different, which indicating the difference between the extents of damage occurs for the panels.

The detailed results of the edgewise compression test are reported in Table IV.

#### *A.2. Warp and Weft Direction*

The maximum compression load values of IWSC panels in the warp and weft directions are given in Fig. 5. It is clear that, all peak force values of composites in the warp direction are higher than those in the weft direction. According to these results, the difference between the



(a) (b)

Fig. 3. (a) Edgewise compression test setup and (b) fixture designed in this study.

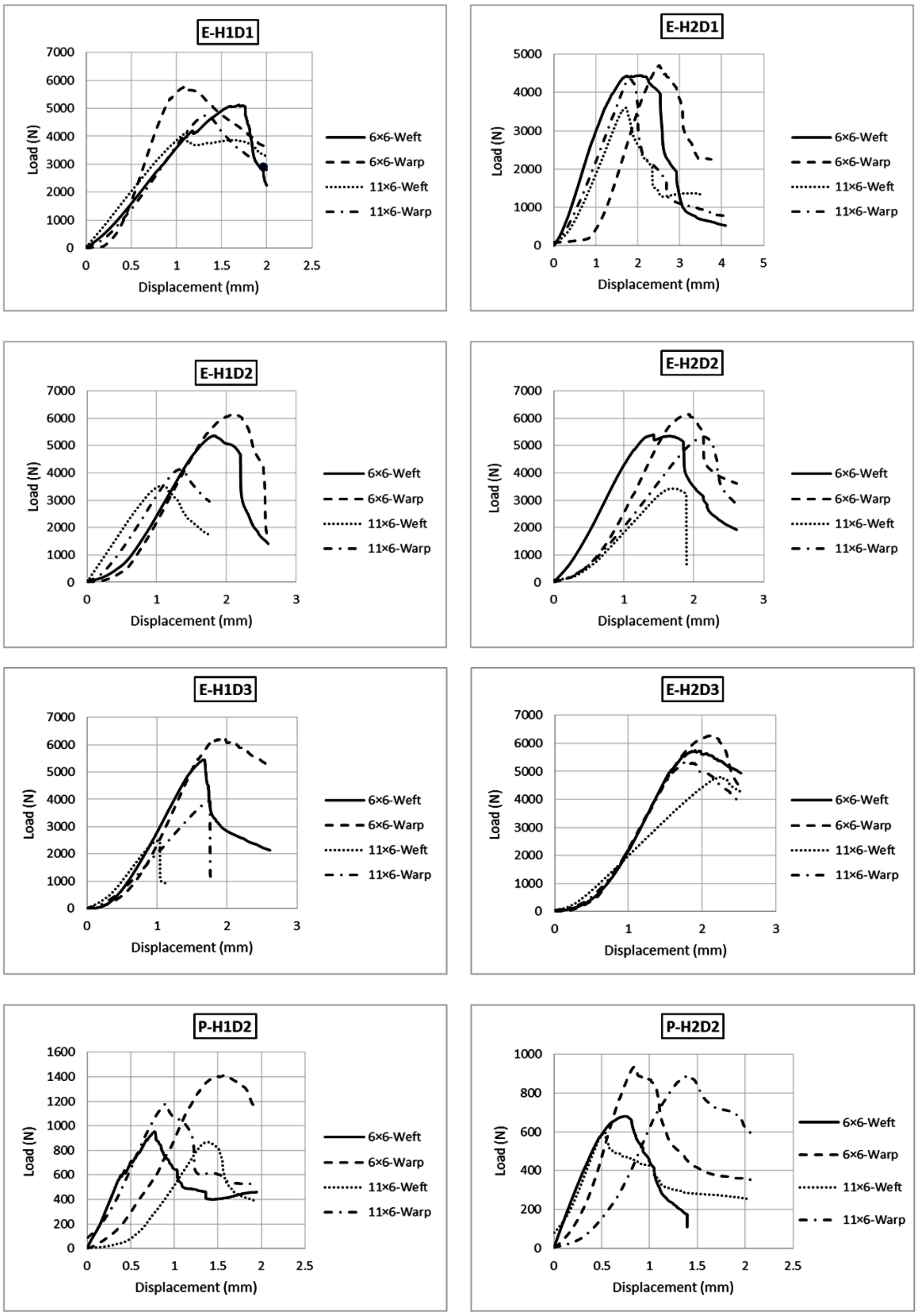



Fig. 4. Load-displacement curves of IWSC specimens under the edgewise compression test.

maximum load values for the warp and weft directions in the samples varies from 10% to 40%. As can be seen in Figs. 1 and 2, the pile yarns are connected to the skins in the warp direction and can be seen in the form of the “8” shape, while in the weft direction they resemble the “c” shape. This particular arrangement is one source of the difference in the warp and weft direction properties of this structure.

In addition, as the warp and weft densities of face-sheet fabrics are nearly identical, the difference between the peak load values of the weft and warp directions is also a result of the difference in pile density in these two directions. The pile density in the warp direction is more than that in the weft direction. Therefore, when the composites are loaded in the weft direction, as the distance between the two rows of piles is larger than that in the warp direction, the

TABLE IV
DETAILED RESULTS OF THE EDGEWISE COMPRESSION TEST OF IWSC PANELS

| Sample code | Compression load (N) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Warp direction | | | | Weft direction | | | |
| | Size: 6×6 | CV% | Size: 11×6 | CV% | Size: 6×6 | CV% | Size: 11×6 | CV% |
| E-H1D1 | 5111 | 3.4 | 3779 | 2.3 | 4621 | 1.5 | 3205 | 3.4 |
| E-H1D2 | 5318 | 4.7 | 3918 | 4.5 | 4820 | 6.4 | 3379 | 5.7 |
| E-H1D3 | 5588 | 6.4 | 4307 | 6.1 | 4931 | 5.3 | 3546 | 4.3 |
| E-H2D1 | 6052 | 1.9 | 5125 | 3.9 | 5176 | 3.8 | 4353 | 6.9 |
| E-H2D2 | 6400 | 7.2 | 5348 | 3.2 | 5493 | 4.6 | 4623 | 5.3 |
| E-H2D3 | 6672 | 3.4 | 5442 | 4.1 | 5693 | 5.3 | 4904 | 2.9 |
| P-H1D2 | 1312 | 5.1 | 1203 | 3.8 | 939 | 4.2 | 886 | 4.2 |
| P-H2D2 | 1620 | 1.7 | 1503 | 5.8 | 1250 | 6.9 | 1106 | 7.1 |

face-sheet is less supported by piles and is buckled much easier in the space between the pile rows. Similar results have been reported in the literature [21]. However, higher buckling load in the warp direction is not a general rule. Some researches indicate that the weft direction buckles under higher loads in edgewise compression test than the warp direction [17,20]. It arises from the fact that structural and geometrical parameters of this structure such as pile yarn, pile density, tilt angle of the piles and the degree of pile stretching determine that which direction shows higher mechanical properties [6].

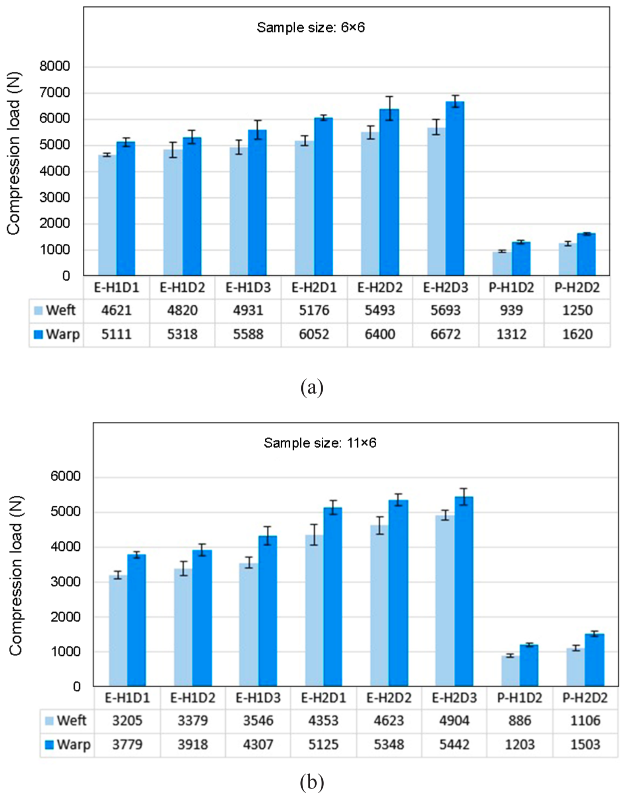



Fig. 5. Compression peak load values of composites in the warp and weft directions: (a) sample size 6 cm×6 cm and (b) sample size 11 cm×6 cm.

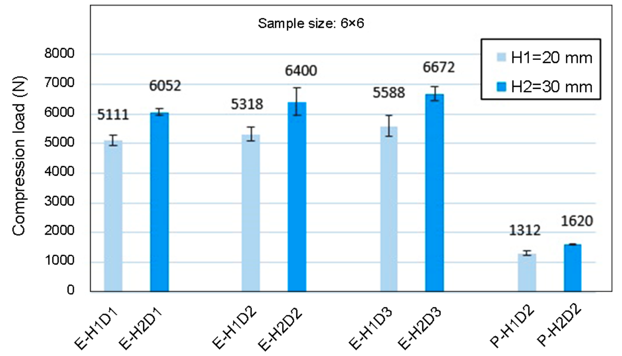
The obtained results have been statistically evaluated with the ANOVA test at a 95% confidence interval. The ANOVA test results indicate that the panel direction has a statistically significant effect on the variation of the compression strength.

It needs to be stated here that, as the edgewise compression properties in the warp direction are better than those in the weft direction, therefore for brevity, in the following sections, only the results of samples in the warp direction are compared.

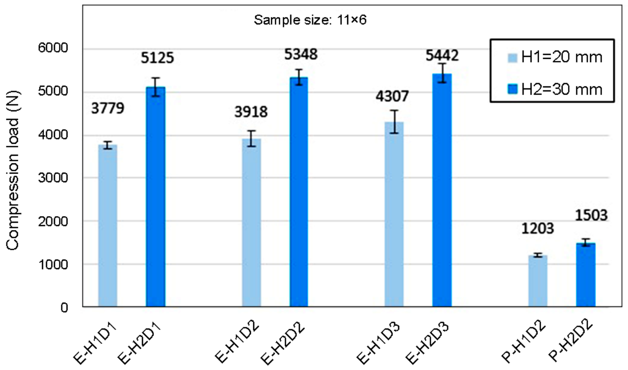
### *A.3. Panel Thickness*

In order to investigate the influence of panel thickness, emanated because of the difference in pile height, on the edgewise compression performances of IWSC panels, composites with two different panel thicknesses (20 and 30 mm) were fabricated. The results of the panel thickness variation on the peak load values of composite samples in the warp direction are shown in Fig. 6.

It can be conclude that by increasing the panel thickness, the maximum load values of compression test increases significantly. Compared with the core height of 20 mm (H1), the peak load of 30 mm panels thickness (H2) in the warp direction increases between 18% to 23% for sample size 6 cm×6 cm and 24% to 36% for sample size 11 cm×6 cm. Similar results have been reported in the literature [19]. Zhao *et al.* [19] reported that edgewise compression




(a)




(b)

Fig. 6. Effect of panel thickness on the edgewise compression load in the warp direction: (a) sample size 6 cm×6 cm and (b) sample size 11 cm×6 cm.

strength of panels with 30 mm thickness increases about 152.6% compared with core height of 5 mm.

The results indicated that the panel thickness has an important influence on the maximum load, which was in agreement with the Euler formula about the critical load. The Euler buckling load for the sandwich panels in the case of elastic buckling is expressed as the following equations [17]:

$$P_{cr} = \frac{\pi^2 D}{L^2} \tag{1}$$

Where, L is the unsupported length of column and D is the flexural rigidity, which is calculated by:

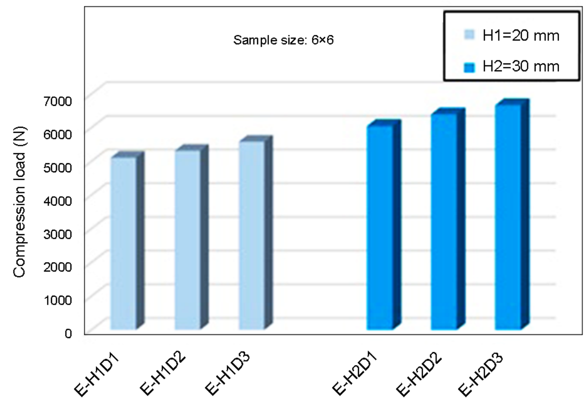
$$D = \frac{E_f b t d^2}{2} \tag{2}$$

Here, $E_f$ is the Young's modulus of face-sheets, b is the width of the sandwich column, t is the face-sheets thickness, and d is the core thickness. Based on the above equations, the buckling force of the specimen is directly related to its thickness. The higher the core thickness, the higher the moment of inertia, and the material has better stability under compressive loading [17,18], which is consistent with experimental results in the current study.

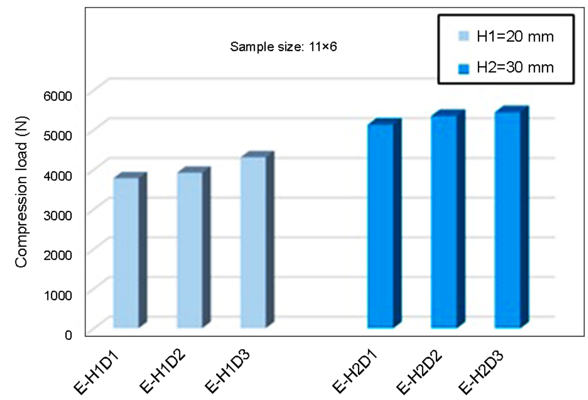
The obtained results have been statistically evaluated with the ANOVA test at a 95% confidence interval. The findings indicate that the panel thickness has a statistically significant effect on the variations of the compression strength.

### *A.4. Pile Density*

To study the influence of pile density on the compression performance of IWSC panels, composite samples were produced with three different pile densities, as stated in Table III. As shown in Fig. 7, the results indicate that the edgewise compressive strength increased with increasing the pile density. The peak load values of samples with pile density of 2.1 $cm^{-2}$ (D1), compared to those with the 4.3 $cm^{-2}$ (D3) increased about 6% to 14%. When the composite panel is under the compression load, the face-sheets are supported by pile yarns, which restrict the lateral deformation. Therefore, the pile density plays a significant role in lateral connection between two face-sheets and bearing the compression and shear loads. As the pile distribution density is increased, this support is considerably increased, and because of delay in buckling,




(a)




(b)

Fig. 7. Effect of pile density on the edgewise compression load in the warp direction: (a) sample size 6 cm×6 cm and (b) sample size 11 cm×6 cm.

load bearing capacity of face-sheets is increased.

The obtained results have been statistically evaluated with the ANOVA test at a 95% confidence interval. The findings indicate that the pile density has a statistically significant effect on the variation of the edgewise compression strength.

### *A.5. Size Effect*

With the objective of evaluate the sample size effect on the compression strength of IWSC panels, two different sample sizes were used. The dimension of samples was 6 cm×6 cm and 11 cm×6 cm. It should be noted that the selected dimensions were within the standard recommended dimension for sample prepared for edgewise compression test. The reason for choosing these two sizes was only to observe the effect of sample height variation and it was possible to select other sizes, which were excluded in this study.

Based on the Fig. 8, it can be said that as the height of the sample under the compression load increases, the sample will be able to withstand lower compressive strength. For panels with lower height (6 cm×6 cm), the compression strength is about 7%-35% larger than the sample with a higher dimension (11 cm×6 cm) in the warp direction. This phenomenon is justified by the Euler equation as was discussed in the previous sections. According to these results, it can be concluded that the edgewise compression strength of the sandwich panels is related to their size. In this context, Hu *et al.* [18] reported that both strength and stiffness of the IWSC panels are related with their size.

The obtained results have been statistically evaluated with the ANOVA test at a 95% confidence interval. The findings indicate that the sample size has a statistically significant effect on the variation of the edgewise compression strength.

### *A.6. Type of Resin*

In order to assess the effect of resin type on the edgewise compression behavior of IWSC panels, two samples

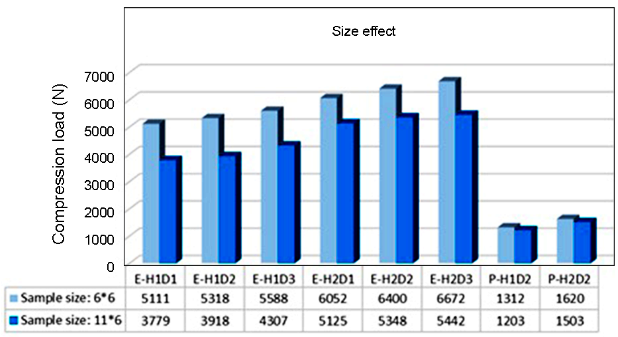
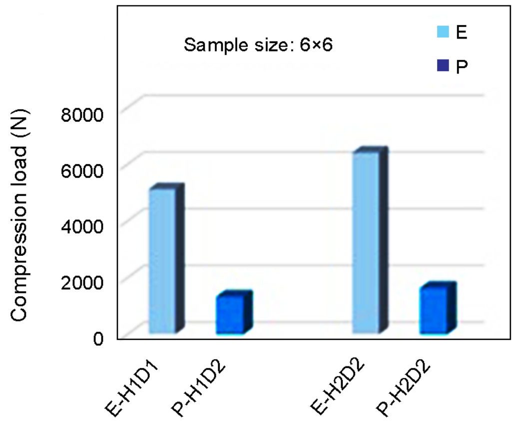
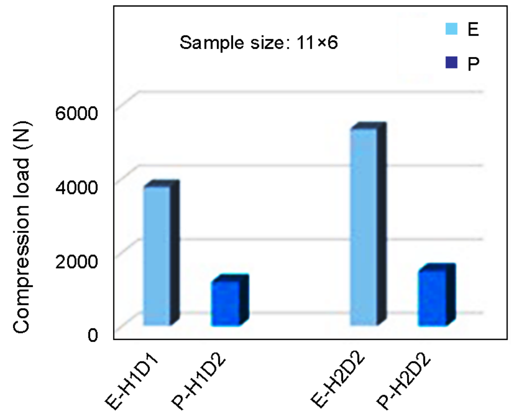



Fig. 8. Effect of sample size on the edgewise compression load in the warp direction.




(a)




(b)

Fig. 9. Effect of resin type on the edgewise compression load in the warp direction:(a) sample size 6 cm×6 cm and (b) sample size 11 cm×6 cm.

(H1D2 and H2D2) were fabricated with polyester resin as well as epoxy resin. Fig. 9 compares the results of edgewise compression properties of IWSC panels fabricated with epoxy and polyester resins. The results showed that the type of resin noticeably affected the compressive properties of the composites. In this case, the compression properties in the polyester samples are less than those in the epoxy samples. Comparing the data shows that the compression load in the epoxy resin samples is about 300% higher than that in the polyester resin, which can be interpreted in terms of the Euler buckling formula [22]. The compression strength of the sandwich composite depends primarily on the face-sheet mechanical properties and secondly on the resistance of core pile yarn to the compression and shear loads. As was reported in Table II, epoxy resin has considerably superior tensile modulus (or Young's modulus) than polyester resin (2.735 GPa versus 0.944 GPa) [22]. So, refer to Euler buckling formula (Eqs. (1) and (2)), the Young's moduli of face-sheets in the polyester samples is lower than that in the epoxy composite. Therefore, compared with epoxy-

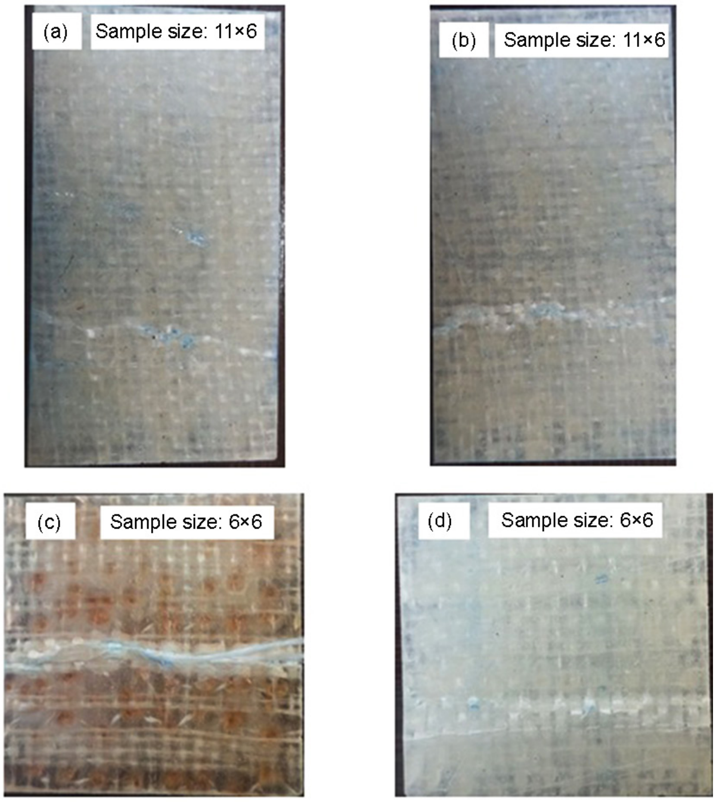



Fig. 10. Fracture photographs of composites after edgewise compression test: (a) epoxy composite sample in the warp direction, (b) epoxy composite sample in the weft direction, (c) polyester composite sample in the weft direction, and (d) epoxy composite sample in the weft direction.

based composite, the IWSC panels produced by polyester resin have lower edgewise compression load. In a study conducted by Abdil *et al.* [23] the samples fabricated with epoxy and polyester resins were analyzed and significant changes in flexural behavior of the IWSC panels prepared with epoxy resin were shown.

The obtained results have been statistically evaluated with the ANOVA test at a 95% confidence interval. The findings indicate that resin type has a statistically significant effect on the variation of the compression strength.

### *B. Failure Mechanism*

Fig. 10 represents the view of damage regions of samples after the edgewise compression test. The photographs of the surface damage were taken using a digital camera. For edgewise compression test, it is found that although the breakage shapes looked different, but the types of damage in all samples are approximately identical. It is useful to note that, the IWSC panels consist of integrated woven structure. The face-sheets are tightly connected by pile yarns, which eliminates the delamination, is the prevalent mode of failure of foam and honeycomb conventional sandwich composite panels.

For the edgewise compression test, skin strength to shear and compressive loading, primarily determines the size of the composite damage. As can be seen in Fig. 10, the face-sheets are destroyed due to the skin cracking and rupture, which dominate the failure of the samples as was reported by other researchers [18-20]. In addition, the fracture occurs in the space between neighboring core piles, where the mechanical properties of IWSC panels are the weakest.

As the distance between the pile yarns in the weft direction is larger than that in the warp direction, when the panel is compressed, the damaged area of samples in the weft direction is larger than that in the warp direction. In addition, in the polyester samples, the extent of occurred damage was greater than that in the epoxy composites.

## IV. CONCLUSION

In the present study, the simultaneous effect of different parameters on the edgewise compression behavior of IWSC panels was investigated. Based on the results, it can be concluded that the maximum compression load values of composite samples in the warp direction are higher than those in the weft direction. According to these results, the difference between the maximum load values for the warp and weft directions in the samples varies from 10% to 40%. Differences in pile density in these two directions, as well as particular arrangement of pile yarn in the warp and weft directions are the sources of difference in the warp and weft direction properties.

The results showed that by increasing the panel thickness, the maximum load values of edgewise compression were increased significantly. Compared with the core height of 20 mm (H1), the peak load values of 30 mm panel thickness (H2) in the warp direction increased between 18 and 23% for sample size of 6 cm×6 cm and 24 and 36% for sample size of 11 cm×6 cm. Base on the Euler buckling formula about the critical load, the buckling force of the specimen is directly related to its thickness. The higher the core thickness, the higher the moment of inertia and the material has better stability under compressive loading.

The edgewise compression strength increased with increasing the pile density and it decreased with reducing pile distribution density. Compared with the samples with the pile density of 2.1/cm$^2$ (D1), the peak load values of 4.3 pile/cm$^2$ (D3) samples increased about 6% to 14%. As the pile distribution density is increased, this support is considerably increased, and because of delay in buckling, load bearing capacity of face-sheets is increased.

According to the results, as the height of the sample under the compression load increases, the sample will be able to withstand lower compressive strength. For panels with lower height (6 cm×6 cm), the compression strength is about 7%-35% larger than the samples with higher dimension (11 cm×6 cm) in the warp direction. The results showed that the type of resin noticeably affected the compressive properties of the composites. In this case, the compression properties in the polyester samples are less than those in the epoxy samples. Comparing the data shows that the compression load in epoxy resin samples is about 300% higher than that in polyester resin. For edgewise compression, it is found that although the breakage shapes looked different, but the mode of failure in all samples is approximately identical and is the face-sheets cracking and rupture. Also, the face-sheets and the core are tightly connected by pile yarns, which eliminate the delamination.

ACKNOWLEDGEMENT

The authors would like to acknowledge the Noavaran Sanate Sialk Kashan Co. for their technical assistance, production of fabric preforms, and sandwich composite panels.

REFERENCES

[1] A.P. Mouritz, M.K. Bannister, and P.J. Falzon, "Review of applications for advanced three dimensional fiber textile composites", *Compos. A*, vol. 30, no. 12, pp. 1445-1461, 1999.

[2] R. Kamiya, B.A. Cheeseman, and P. Popper, "Some recent advances in the fabrication and design of three dimensional textile preforms: a review", *Compos. Sci. Technol.*, vol. 60, no. 1, pp. 33-47, 2000.

[3] K. Bilisik, "Multiaxis three-dimensional weaving for composites: a review", *Text. Res. J.*, vol. 82, no. 7, pp. 725-743, 2012.

[4] J. Hu, *3D Fibrous Assemblies: Properties, Applications and Modelling of Three-Dimensional Textile Structures*, 1st ed, Woodhead Publishing, 2008.

[5] A.W. Van Vuure, J.A. Ivens, and I. Verpoest, "Mechanical properties of composite panels based on woven sandwich fabric preforms", *Compos. A,* vol. 31, pp. 671-680, 2000.

[6] A. Mirdehghan, H. Nosraty, M.M. Shokrieh, M. Akhbari, and R. Ghasemi, "Micro-mechanical modelling of the compression strength of three-dimensional integrated woven sandwich composites", *J. Ind. Text.*, vol. 48, no. 9, pp. 1399-1419, 2019.

[7] M. Li, S. Wang, and W. Zhang, "Effect of structure on the mechanical behaviors of three-dimensional spacer fabric composites", *Appl. Compos. Mater.*, vol. 16, pp. 1-14, 2009.

[8] M. Karahan, H. Gul, and N. Karahan, "Static behavior of three-dimensional integrated core sandwich composites subjected to three-point bending", *J. Reinf. Plast. Compos.*, vol. 32, no. 9, pp. 664-678, 2013.

[9] S.W. Choi, M. Li, and W.I. Lee, "Analysis of buckling load of glass fiber/epoxy-reinforced plywood and its temperature dependence", *J. Compos. Mater.*, vol. 48, no. 18, pp. 2191-2206, 2014.

[10] M.G. Toribio and S.M. Spearing, "Compressive response of notched glass-fiber epoxy/honeycomb sandwich panels", *Compos. A*, vol. 32, no. 6, pp. 859-870, 2001.

[11] C.H. Park, W.I. Lee, and W.S. Han, "Multi-constraint optimization of composite structures manufactured by resin transfer molding process", *J. Compos. Mater.*, vol. 39, no. 4, pp. 347-374, 2005.

[12] J.M. Mirazo and S.M. Spearing, "Damage modeling of notched graphite/epoxy sandwich panels in compression", *Appl. Compos. Mater.*, vol. 8, no. 3, pp. 191-216, 2001.

[13] J.G. Ratcliffe and J.R. Reeder, "Sizing a single cantilever beam specimen for characterizing facesheet-core debonding in sandwich structure", *J. Compos. Mater.,* vol. 45, no. 25, pp. 2669-2684, 2011.

[14] C. Berggreen, B.C. Simonsen, and K.K. Borum, "Experimental and numerical study of interface crack propagation in foam-cored sandwich beams", *J. Compos. Mater.*, vol. 41, no. 4, pp. 493-520, 2007.

[15] A.W. Van Vuure, J. Pflug, and J.A. Ivens, “Modelling the core properties of composite panels based on woven sandwich fabric preforms”, *Compos. Sci. Technol.*, vol. 60, pp. 1263-1276, 2000.

[16] H. Judawisastra, J. Ivens, and I. Verpoest, “Determination of core shear properties of 3D woven sandwich composites”, *Plast. Rubber Compos.*, vol. 28, no. 9, pp. 452-457, 1999.

[17] D.S. Li, N. Jiang, L. Jiang, and C.Q. Zhao, “Static and dynamic mechanical behavior of 3D integrated woven spacer composites with thickened face sheets”, *Fiber Polym,* vol. 17, no. 3, pp. 460-468, 2016.

[18] Y. Hu, W.X. Li, H.L. Fan, and N. Kuang, “Experimental investigations on the failures of woven textile sandwich panels”, *J. Thermoplast. Compos. Mater.*, vol. 30, no. 2, 2015. http://dx.doi.org/10.1177/0892705715598357.

[19] C. Zhao, D. Li, T. Ge, L. Jiang, and N. Jiang, “Experimental study on the compression properties and failure mechanism of 3D integrated woven spacer composites”, *Mater. Design*, vol. 56, pp. 50–59, 2014.

[20] S. Wang, M. Li, Z. Zhang, and B. Wu, “Mechanical reinforcement of three-dimensional spacer fabric composites”, *Mater. Sci. Forum*, vol. 65, pp. 2604-2607, 2010.

[21] M. Sadighi and S.A. Hosseini, “Finite element simulation and experimental study on mechanical behavior of 3d woven glass fiber composite sandwich panels”, *Compos. B*, vol. 55, pp. 158-166, 2013.

[22] M. Barikani, “Investigation of the edgewise compression properties of 3D woven glass fibre composites (in Persian)”, Msc Thesis, *Dept. Text. Eng.*, Amirkabir University of Technology, Tehran, Iran, 2017.

[23] A. Kus, I. Durgun, and R. Ertan, “Experimental study on the flexural properties of 3D integrated woven spacer composites at room and subzero temperatures”, *J. Sandw. Struct. Mater.*, vol. 20, no. 5, pp. 517-530, 2018.