**Mechanics of Advanced Composite Structures 11 (2024), Serial Number 23, 271 – 280**

Semnan University

**Mechanics of Advanced Composite Structures**

**Journal homepage**: https://macs.semnan.ac.ir/

**ISSN: 2423-7043**

*Research Article*

# Experimental and Numerical Investigation of the Effect of Embedding Steel Wires inside the Foam of GFRP/Foam Sandwich Panel under Three-Point Bending Load

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**ARTICLE INFO**

***Article history:***

Received: 2023-06-25
Revised: 2023-11-03
Accepted: 2023-12-27

***Keywords:***

Sandwich panel;
Three-point bending;
Steel wire;
GFRP;
Foam.

**ABSTRACT**

In this research, the effects of imbedding steel wires into the polyurethane foam of GFRP/Foam sandwich panel under three-point bending has been investigated. For this reason, three samples of non-reinforced, reinforced with two wires above and below and reinforced with three wires above and below the foam inside the GFRP sandwich panel were manufactured by vacuum bagging and tested under three-point bending in order to measure the specific strength of each sample. Moreover, a finite element model (FEM) was utilized using the Abaqus/Explicit package to further observe and analyze the stresses inside the samples. The results showed that imbedding steel wire inside the foam of the GFRP sandwich panel increased the bending strength by 25.2% in the two wire and 56.75% in the three-wire sample and bending modulus by 51.8% in two and 86% in three wire sample respectively. Since the weight of the wires with respect to the whole structure in negligible, the specific bending modulus of the sandwich panel was also improved by 21% in two and 44.8% in the three-wire sample. Finally, the results obtained from the experiments showed to have a decent agreement with the simulated model.

## 1. Introduction

Composite sandwich panels have been extensively utilized in industrial structures such as turbine blades, automotive, pipelines, etc. because of their excellent structural properties in bearing transverse loads with minimum weight (specific properties) [1,2]. Sandwich panels are made up of two skins (backing plates) and a core. The skins are in charge of carrying the bending and the core takes care of the transverse shear load and providing impact resistance etc. [3,4]. Research has been conducted in the past with the intention of further improvement of the performance of the sandwich panels [5–8]. Cores in sandwich panels may be classified into web core, homogenous solid core, foam core, and web cores filled with foam. Also, some cores in the form of honeycomb and corrugated composite/metal and metal truss are known as Ultra-lightweight sandwich panels [9-13]. The manufacturing method can also affect the final property of the sandwich panel which could be observed in the study of Taghavian et al. [14].

Polymeric foams, ceramic foams, and syntactic foams have commonly benefitted as foam cores inside the sandwich panels due to their lightweight [15–19]. Although polymeric foam is the lightest among all other foams, they have the disadvantage of low mechanical properties. It is for that reason that some

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**Cite this article as:**
Amiri, F., Allaee, M. H. and Eskandari Jam, J., 2024. Experimental and Numerical Investigation of the Effect of Embedding Steel Wires inside the Foam of GFRP/Foam Sandwich Panel under Three-Point Bending Load. *Mechanics of Advanced Composite Structures*, 11(2), pp. 271-280

https://doi.org/10.22075/MACS.2023.31055.1526

research has been conducted on the subject to improve the properties of polymeric foams for which one can refer to the study of Gefu Ji et al. [20] where they introduced a new hybrid core for sandwich panels structures using aluminum milli tube in the syntactic foam with two different alignments of tubes in the core (horizontally and vertically). They reported that sandwich panels with the horizontally oriented hybrid core could be viewed as a promising choice for essential structural applications that excel in delamination and impact resistance.

Improving the shock absorption of the sandwich panel has also been investigated. For example, Sun et al. investigated the effect of different SMAs in Glass/epoxy laminated sandwich panels subjected to low-speed impact analysis to improve the impact performance of sandwich panels [21] and Wan et al. [22] used steel wire mesh for low-speed application.

Mohammadkhani et al [23] used five different layouts of steel wires embedded between the layers of Epoxy/Glass face sheets with PU foam core sandwich panel and studied the low-velocity impact both experimentally and numerically and declared using wire between the layers as a delamination problem to the structure.

As discussed, many researchers have investigated the mechanical properties of sandwich panels with wire reinforcements. However, very few studies have been done to evaluate the bending behavior of sandwich panels with embedded wire reinforcement especially in the foam core. In this work, an experimental and numerical analysis is carried out to investigate the bending strength and modulus of GFRP/polyurethane sandwich panels reinforced by stainless steel wires, subjected to a three-point bending load. For that reason, three sandwich panel specimens were made having no wire, two wires, and four wires in the upper and lower side of the core after which, their bending properties were measured and compared in order to inspect the effect of the steel wire in reinforcing the foam and overall, the sandwich panel.

## 2. Experimental Procedure

### *2.1. Materials*

The face sheets of the specimens used in this investigation are GFRP laminates. In these laminates, the fabric used was 220 $g/m2$ woven glass fabric and the resin was Araldite LY5052 epoxy resin with Aradur hardener From Resitan Co, Ltd., Iran.

polyurethane foam contains two parts (Polyol and Isocyanate) from Arian Polyurethane Co, Ltd., Iran with 38 $kg/m3$ density was used for making the sandwich panel cores. Also, to reinforce the core, 1.5 mm diameter Steel wires were used.

Tables 1 and 2 show the properties of the matrix and fabric used and steel wire alternatively. Table 3 indicates the property of the GFRP face sheet under the tensile test which is used in the numerical section. Also, polyurethane foam's property is shown in Table 4 which is gained from the experimental test.

**Table 1.** Resin properties [24]

| Property | value |
|---|---|
| Density(kg/m$^3$) | 1170 |
| Flexural strength (MPa) | 2.96 |
| Flexural modulus (MPa) | 117 |
| Elongation at flexural strength, % | 5.8 |
| Tensile strength (MPa) | 0.07 |
| Tensile modulus (GPa) | 3 |

**Table 2.** Fibers and steel wire properties [25]

| Property | E glass | Steel wire |
|---|---|---|
| Density (kg/m$^3$) | 2550 | 7800 |
| Weave pattern | Plain | - |
| Diameter (mm) | 0.2 | 1.5 |
| Tensile modulus (GPa) | 52 | 203 |
| Percent elongation | 4.7 | 4.5 |

**Table 3.** Material properties of the E-Glass/Epoxy composite laminate

| Property | Symbol | Value |
|---|---|---|
| Density | $P$ | 1650 kg/m$^3$ |
| Young's modulus in the longitudinal direction | $E_{11}$ | 26 GPa |
| Young's modulus in transverse direction | $E_{22}$ | 26 GPa |
| Out-of-plane Young's modulus | $E_{33}$ | 10 GPa |
| Poisson's ratio | $\upsilon_{12}$, $\upsilon_{13}$, $\upsilon_{23}$ | 0.2 ,0.1 ,0.1 |
| In-plane shear modulus | $G_{12}$, $G_{13}$ | 1.7 GPa |
| Out-of-plane shear modulus | $G_{23}$ | 1.6 GPa |

**Table 4.** Material properties of the PU foam [25,26]

| Property | value |
|---|---|
| Density (kg/m$^3$) | 38 |
| Water absorption (%) | 0.5 |
| Thickness (mm) | 40 |
| Tensile modulus (GPa) | 0.0054 |

### *2.2. Sandwich Panel Manufacturing*

In this study, three different samples of non-reinforced (Fig. 1(A), reinforced with two wires above and below (Fig. 1(B)) and reinforced with three wires above and below (Fig. 1(C)) are manufactured and compared under three-point bending.

These different categories of samples are named RS2, RS3, and NS by the reinforcement difference, in which the number stands for the number of wires inside the core, “S” means sandwich panel and R and N illustrate the reinforced and non-reinforced samples.

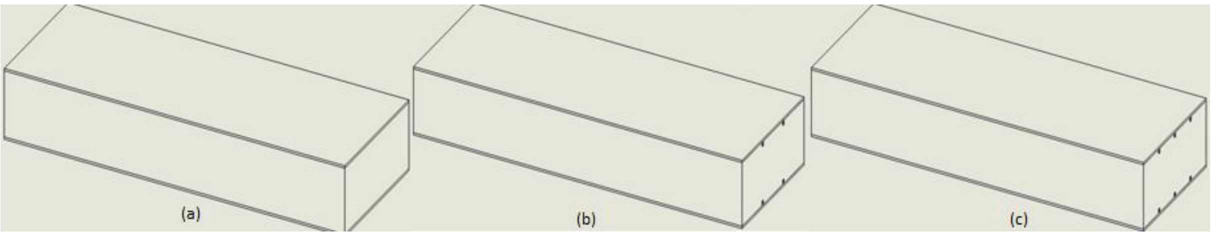


**Fig. 1.** Schematic figures of the A) non-reinforced (NS), B) reinforced with two wires (RS2), and C) reinforced with three wires (RS3)

In all the above-mentioned sandwich panel samples, the GFRP face sheets used consist of four layers of GFRP composites on each side. To make the samples, first, the glass fabrics were cut into 210×75 mm$^2$ according to ASTM C393 standards. In the next step, the foams were cut into 210×75× 40 mm$^3$ and the place for the reinforcing wires was made by the use of a hot wire cutter. In the next step, the surface of the wires was cleaned with acetone and then sanded with 80-grit silicon carbide paper and cleaned again with acetone. Finally, after preparation of the flat glass mold (the surface was cleaned, the release again was applied and the whole glass was bordered by a sealing tape), the matrix material LY5052 epoxy resin and Aradur hardener were combined in the ratio of 100:40, and applied using hand layup. At first 4 four glass fabrics were hand-laid on the mold, after which the foam was placed and again the next four layers were laid. For the samples containing the steel wire, before the foam was placed on the wet fabrics, the wires were coated with the epoxy resin and placed inside the preform slots, as shown in Fig. 2.

**Fig. 2.** Wire placement into the foam core

After the layup was complete, a Dacron layer and a breathable layer were placed and finally the vacuum bag was connected to the vacuum pump by a hose. The samples were cured under room temperature and vacuum pressure for one day.

### 2.3. Three-point Bending Test

One of the important flexural properties of the sandwich panels is bending stiffness, and in order to detect the effect of the reinforcing wires, a three-point bending test was conducted using the SANTAM STM-150 universal testing machine. For this reason, the three-point bending load was applied to the sandwich panel according to ASTM C393. According to this standard, three-point bending tests were accomplished with a 145 mm support span. Fig. 3 shows a three-point bending test setup for the reinforced foam sandwich panel. The type of loading was displacement control with a speed of 0.5 mm/min.

Overall, three sets of samples were made for each class of sandwich for conducting the experimental tests.

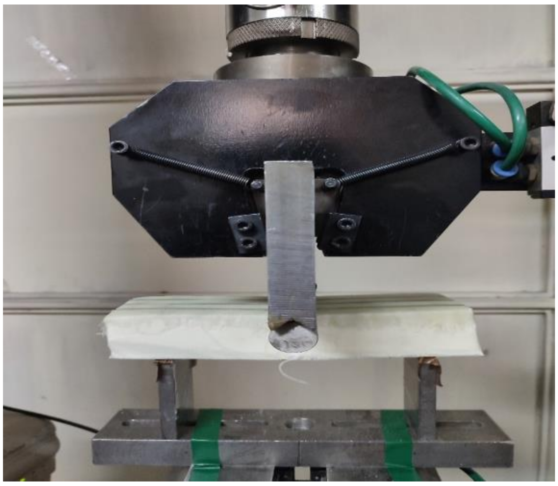


**Fig. 3.** Three-point bending setup

According to ASTM C393, facing stress is expressed as Eq (1):

$$\sigma = \frac{P_{max}\,S}{2t(d+c)b} \tag{1}$$

In the above equation, σ, $P_{max}$, $t$, $S$, b, d, and c denote facing stress, the maximum force carried by the test specimen before failure, facing thickness, span length, specimen width, sandwich thickness, and core thickness respectively.

## 3. Numerical Modeling

For the numerical analysis, “Abaqus CAE 6.14” was utilized to model the flexural bending of the sandwich panel as the static finite element analysis program. The GFRP face sheets of the panels were modeled with [0/90] fabricated layering. Three different C3D8R mesh configurations [27] with an approximate global size of 5, 2.5, 1.5 and 1mm named Mesh-i, Mesh-ii, Mesh-iii, and Mesh-iv (Figure 4) were considered in the convergence analysis of the S215 specimen (Figure 5).

Finally, with the purpose of saving time in the simulations, Mesh-iii with an approximate number of 278000, and 28000 elements respectively for foam core and composite face sheets were selected.

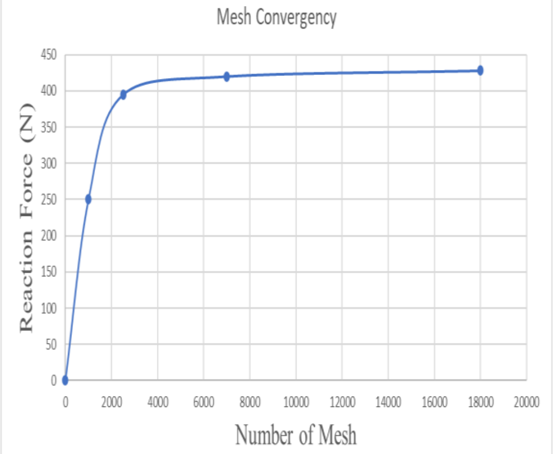


**Fig. 5.** Mesh convergence study

For a general static simulation, a duration of 1 s and a loss energy fraction of the automatic stabilization of 0.0002 were set [28]. Complete interconnection and cohesive bonding contact between the composite skins, the cores, and the wires were considered and a general contact algorithm with a coefficient of friction of 0.15 was defined [29]. The measurement procedure was performed for each of the correct elements in the finite element method with a smooth increase in time for less than 1e-20 s and a maximum number of increments of 100000.

Figure 6 indicates the model of the sandwich panel specimen (RS2) for the study.

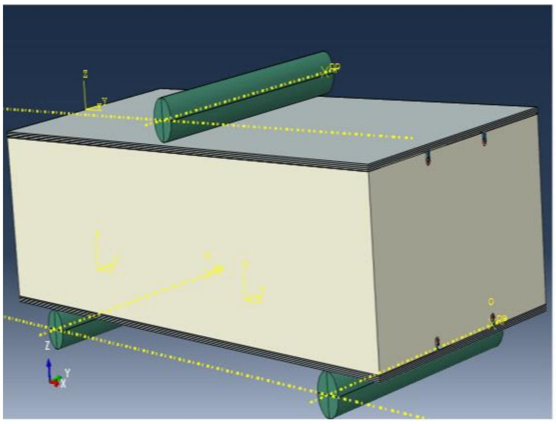


**Fig. 6.** The model considered for the numerical analysis

It was assumed that the model's parts such as faces, wires, and the core are perfectly glued together by using tie constraint, so it would be an ideal condition for the three-point bending test.

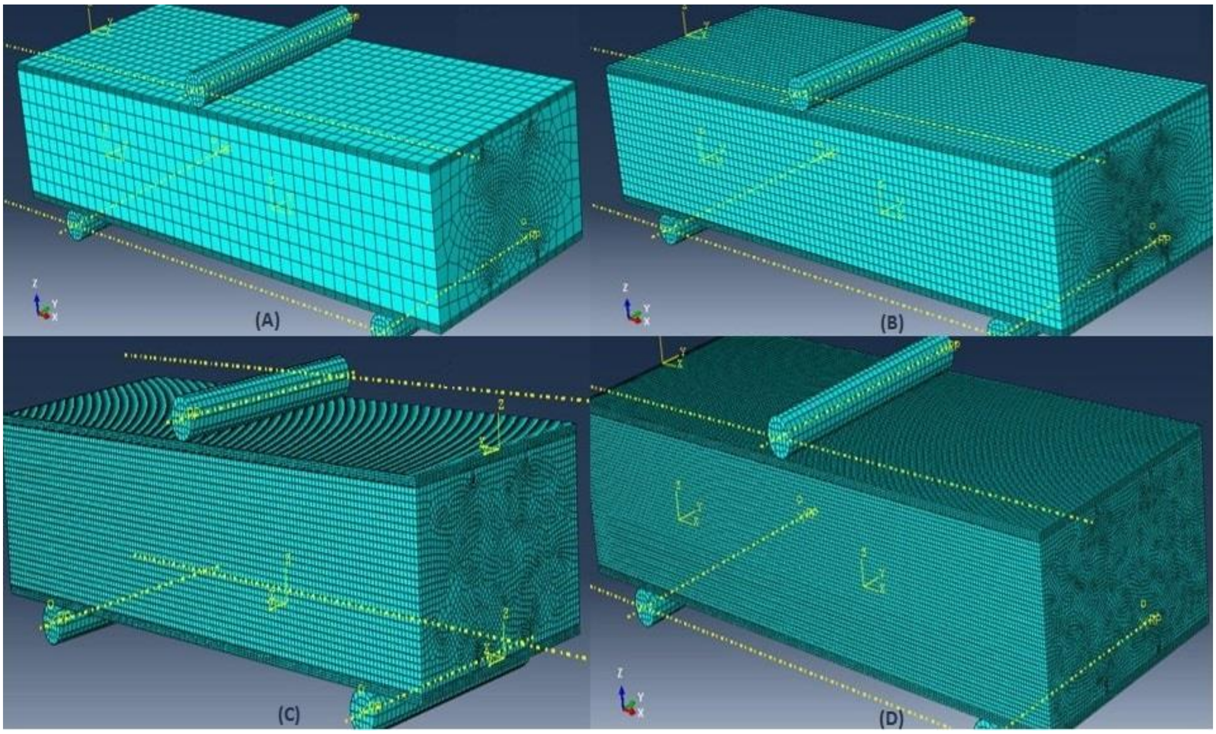


**Fig. 4.** Four different sizes of mesh were used in convergence analysis with approximate global A) mesh-i, B) mesh-ii, C) mesh-iii, and D) mesh-iv

## 4. Discussion and Result

### 4.1 Three-point Bending Test Results

To examine the effect of using wires in foam core on the flexural behavior of the samples, the load-displacement graph achieved from a three-point bending test that was performed on three different types of specimens (NS, RS2, and RS3) and for each category, three samples were made and tested under three-point bending load. Figure 7 shows bending test results for non-reinforced sandwich panels. It shows an elastic region up to 3-4 mm displacement and a peak load of 489 N at displacement of 6–9 mm.

For the RS2 samples, the force–displacement figure in this test showed an elastic region up to 4 mm displacement and a peak load of 610 N at the displacement of 4–7 mm that is observable in Figure 8, but further, it decreased to 512 N at the displacement of 30 mm.

The load-displacement diagram For the RS3 samples (Fig.9) in this test has a similar trend to RS2 and a maximum load of 801 N but further, it decreased to 597 N at the displacement of 30 mm.

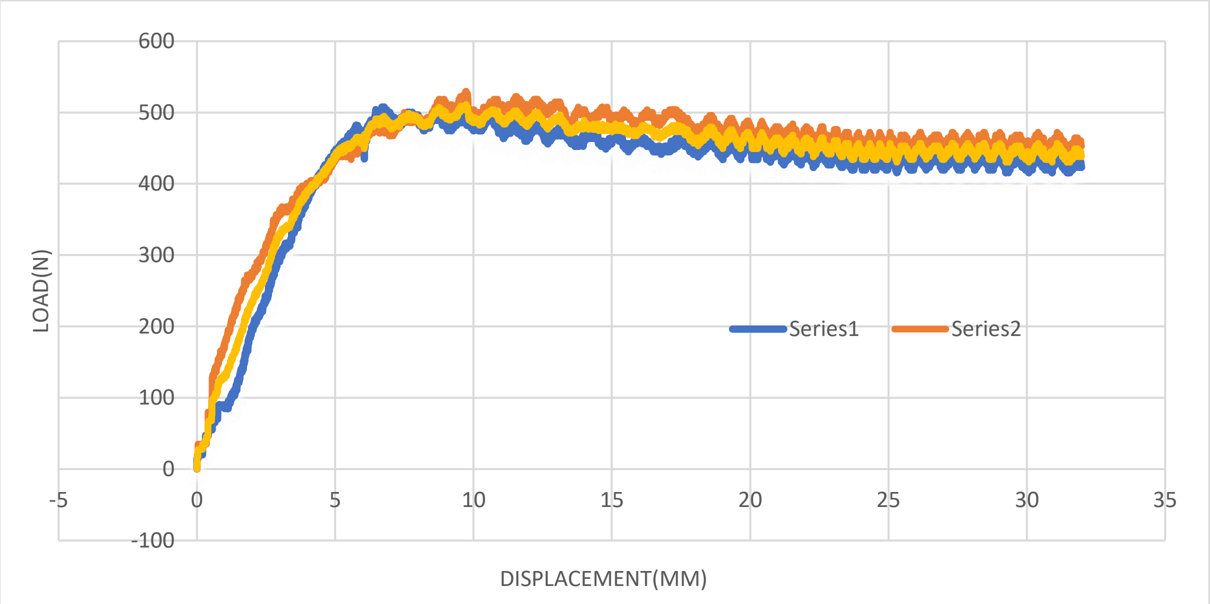


**Fig. 7.** Load-displacement diagram for NS sample (non-reinforced Sandwich panel)

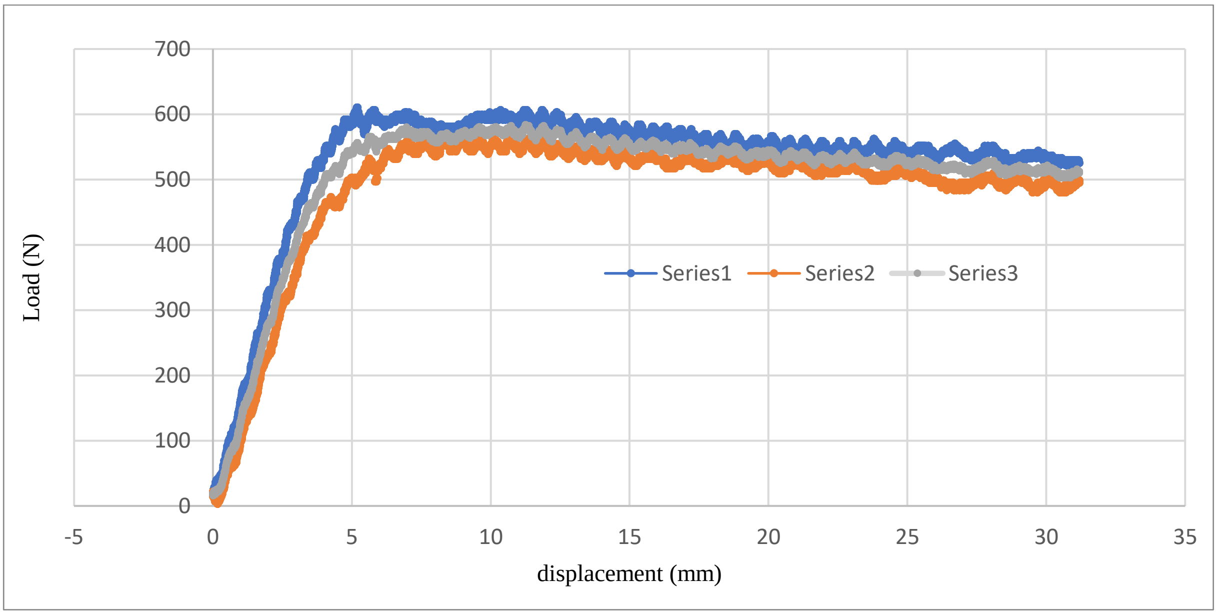


**Fig. 8.** Load-displacement diagrams for RS2 sample (reinforced Sandwich panel with 2 wires)

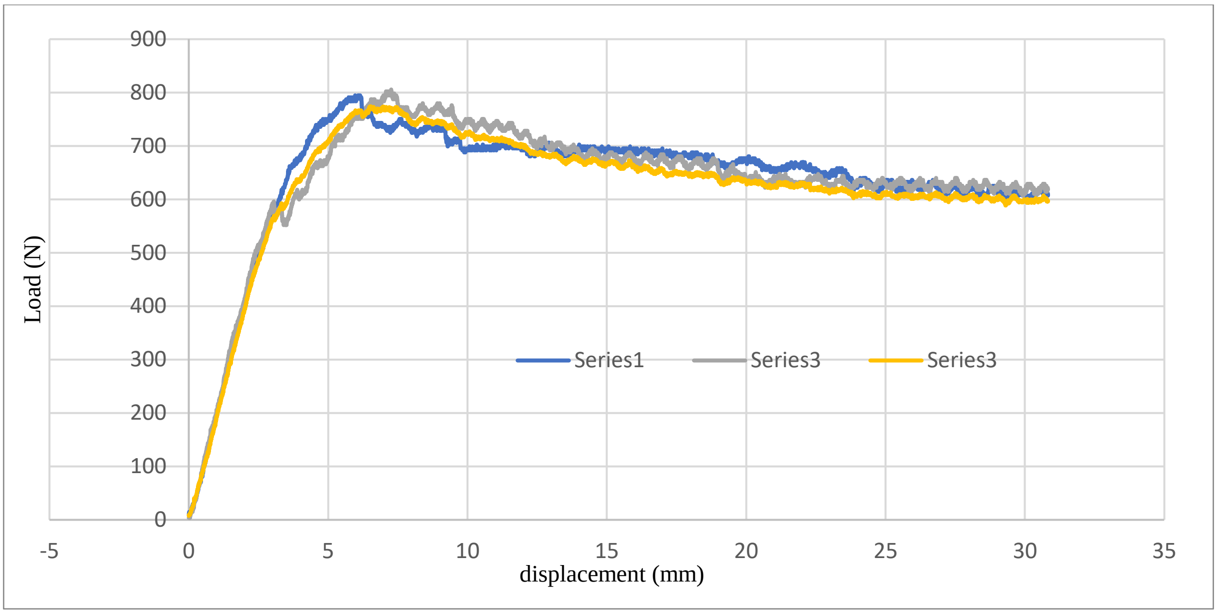


**Fig. 9.** Load -displacement diagrams for RS3 sample (reinforced Sandwich panel with 3 wires)

Figure 10 shows the sum of diagrams for reinforced and non-reinforced sandwich panels (NS, RS2, and RS3) for comparison. According to Figure 10, it can be observed that steel wires had a major effect on improving the flexural strength of the sandwich panels. By embedding 2 and 3 wires (on each side) into the cores, the samples meet an increase of about 40% and 61%, respectively (RS2 and RS3) in flexural strength, compared to the NS samples.

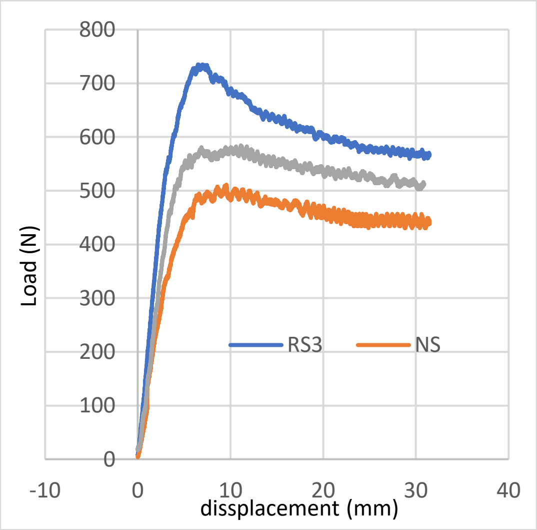


**Fig. 10.** Average Load-displacement diagrams for all samples

Table 5 shows the summary of the results including the strength (maximum load), stiffness, weight, the specific strength and stiffness (divided by weight), and the percent of enhancement of properties of RS3 with respect to NS. The stiffness of the specimens was obtained from the initial slope of the linear load–displacement curves (the linear elastic region). It can be observed from the table that the incorporation of wires inside the foam increases the stiffness of the NS sample (99.33 N/mm) to 150.83 N/mm in RS2 and 185 N/mm in the RS3 sample.

As it is observed, reinforcing the foam with wires improves the flexural strength and stiffness but adds to the weight of the foam. So, as to evaluate the percent of improvement in the properties with the added weight, the specific strength, and stiffness of the three samples were measured. By comparing these results in Table 5, it can be concluded that the added weight of the wires is negligible to the percent of improvement of the properties of the foam as there was 17.54 % improvement of specific strength of RS3 with respect to NS and 44.8 % improvement in the specific stiffness. Finally, it can be observed that (table 5) the wires have a more stiffening effect in the flexural bending of the foam core sandwich panels than in strengthening them.

**Table 5.** Summary of the results

| Specimen | Strength (N) a | Stiffness (N/mm) | Weight (gr) | Specific strength (N/gr) | Specific Stiffness (N/mm.gr) |
|---|---|---|---|---|---|
| NS | 511 | 99.33 | 51.5 | 9.92 | 1.92 |
| RS2 | 640 | 150.83 | 61.8 | 10.35 | 2.4 |
| RS3 | 801 | 185 | 66.5 | 12.05 | 2.78 |
| Enhancement (RS3 and NS) | 56.75 % | 86% | 29.1% | 21.47% | 44.8% |

### *4.1.2 Failure Mode*

Failure and damage mechanism of the specimen under a three-point bending test were examined by visual inspection (Figure 11). The results of the comparison between the failure modes show that in the entire non-reinforced sandwich panels, (in the NS samples) the failure occurred at the foam site resulting in separation of the shell from the core. However, in the case of the reinforced panels with steel wire, in all six cases for RS2 and RS3, the failure occurred from the skin area (center of the specimen) where no trace of Foam failure was found and the sample failed due to the local bending. This is the reason for the increase in flexural strength of RS2 and RS3 as compared to NS. This type of failure also prevents the foam from breaking and, as a result, sudden deformations.

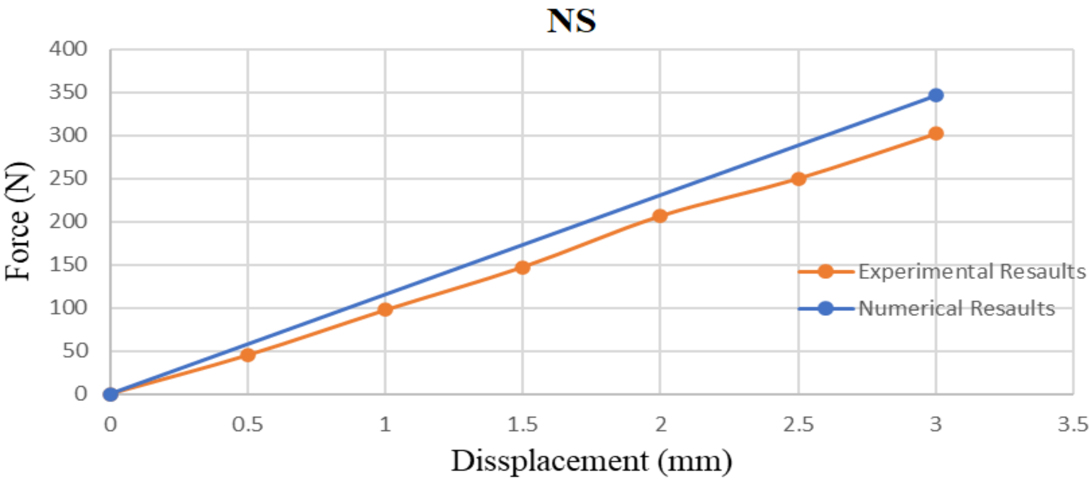
## *4.2. FEM Results*

As observed in the experimental testing of the specimens, the linear portions (elastic region) were observed till the displacement of 3–4.5 mm. In this study, in order to have a more conservative and exact situation, FE analyses were performed up to a displacement of 3 mm (elastic range), where the bending stiffness of the samples was measured.

In Figure 12, the results of simulation and experimental investigation are verified with appropriate accuracy and compared. In the sandwich panel's flexural test, there is about a 10% discrepancy between the numerical and experimental results.

The mentioned disagreement between numerical and experimental results is due to unwanted production issues such as the approximate geometry of the panels and considering ideal conditions in numerical investigations. Sandwich structures took different loads depending on the number of wire reinforcements, of which RS2 specimens proved to be weaker than RS3 due to having fewer steel wires.

**Fig. 11**. Failure and damage mechanism of the sandwich structure subjected to three-point bending test A&C) NS panels and B) RS3 panel



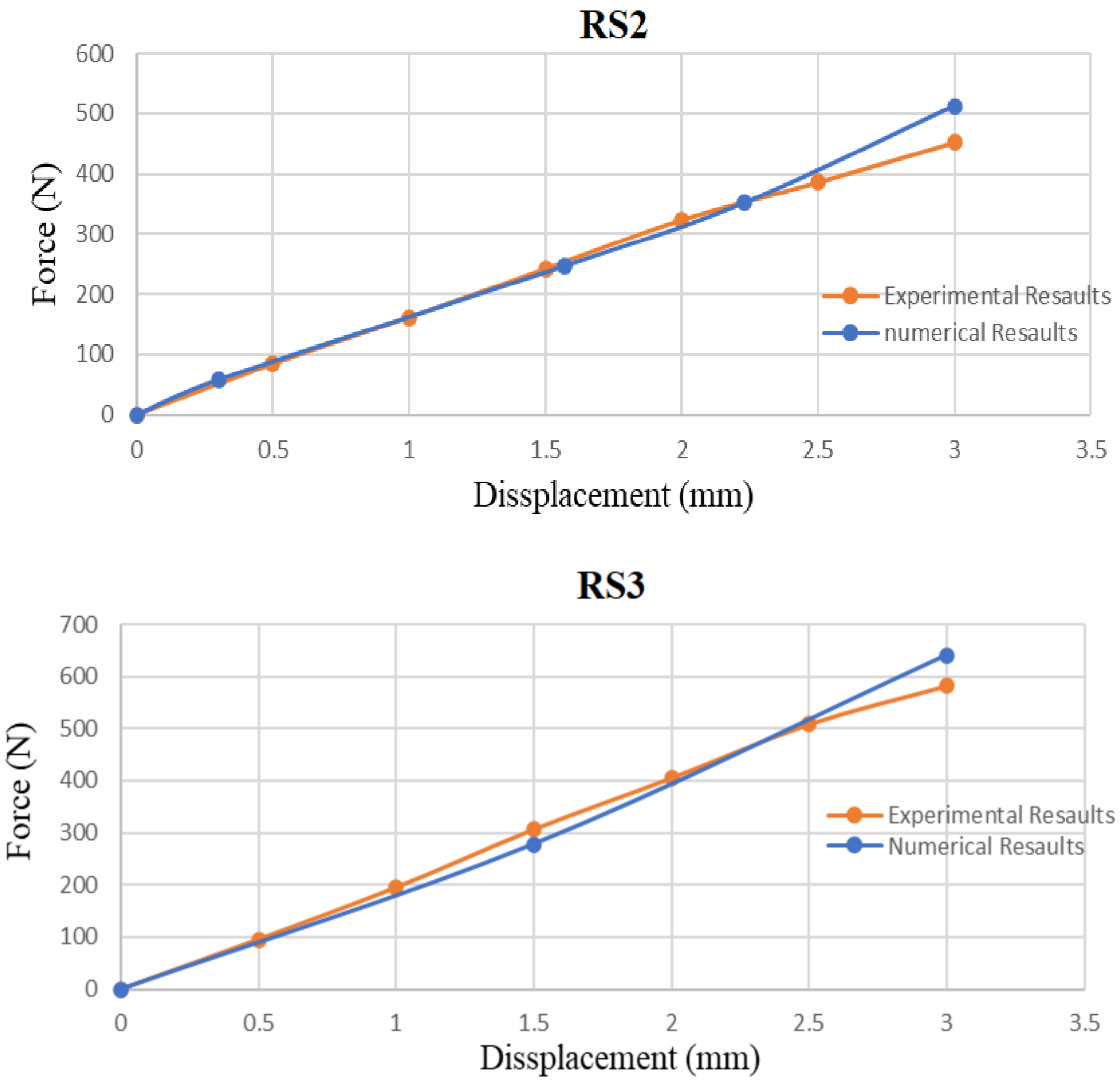


**Fig. 12**. Comparison between the experimental and the numerical results for NS, RS2, and RS3 samples

## 5. Conclusions

In this paper, the effect of reinforcing the foam of a GFRP composite panel was investigated experimentally and theoretically. In conclusion:

The presence of steel wires inside the polyurethane foam core improves the flexural Bending strength of the sandwich panel by 25.2% in RS2 and 56.75% in RS3. Steel wires also improve the flexural bending stiffness of the sandwich panel by 51.84% in RS2 and 86.24% in RS3. Although increasing the number of wires increases the weight of the sandwich panels the improvement of the flexural strength and stiffness is higher which results in overall improvement in the flexural strength and stiffness-specific properties. This does not necessarily mean that using a greater number of wires can further improve the specific properties and for that more investigations are required. Also, this style of using wires fixed the delamination problem. The failure of the reinforced samples all occurred in the middle of the top skin, but in the case of non-reinforced sandwich panels, the failure occurred in the foam area, which shows that the use of steel wires can prevent core failure and as a result, catastrophic failure of the structure. It was found that the effect of using these reinforcements on the flexural stiffness of the sample is greater than its flexural strength. The numerical results showed to have a good agreement with the experimental result which is used in our further study for optimizing the pattern and number of wires inside the sandwich panels.

## Funding Statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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