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TECHNICAL PAPER

Experimental study on large deflections of perforated composite plates

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Abstract
An experimental investigation on the large deflection of perforated composite plates is performed in this study. The fabrics of the composite plates are considered as unidirectional and woven. The effects of the variations in diameter, number and location of hole on plates are examined. The effects of the fabrics are also examined. One short edge of the composite plate is clamped, and a constant weight is hanged from the other short edge of the composite plate during the experiments. In order to prove the accuracy of the study done in the experiment, the large deflection analysis of the perforated plates is also made by the SolidWorks simulation program. SolidWorks simulation program is capable of performing large deflection analysis based on finite elements. When the results are examined, the large deflection is less in the woven type fabric and the large deflection value in the multi-hole specimens is higher than the single-hole ones. It is also determined that the increase in the distance of the hole position from the clamped end of the plate reduces the large deflection. As a result of the comparison of linear and nonlinear calculations, it is seen that nonlinear calculation should be preferred especially if the applied force is large. When the experimental and the numerical results are compared, it is seen that the obtained results are compatible.

Keywords Large deflection · Composite plate · Perforated plate · Experimental method · Finite element method

1 Introduction

Composite structures are often used in many areas due to their lightness and the ability to adjust their mechanical properties as desired. Many studies have been performed on the structural analysis of composite structures [1–2]. Some of these structures, such as wind turbine blades and helicopter propellers, show large deflection behavior under excessive loads in the environment in which they operate. In order to obtain correct results, such problems should be solved by considering them as geometric nonlinear problems. However, geometric nonlinear problems are often difficult to solve. For this reason, the problem of large deflection in structures has been a research subject for many researchers. As a result of the literature survey, it has been seen that many of the studies on the large deflection behavior of composite structures are theoretical studies. Few studies are related to experimental research. Some of the studies on the large deflection problem of composite structures are summarized below.

Bangxin [3] presented an iterative method to obtain the large deflection values of the laminated composite shallow and plates. The author compared the results obtained with the results obtained from linear analytical and numerical solution. The author proved the accuracy of the results obtained as a result of the comparison. Tanrıöver and Şenocak [4] performed the solution of large deflection of laminated composite plates by using Galarkin method and Newton-Rapson method. They utilized the von Karman plate theory. They used suitable polynomials to solve the governing equations. They compared the results obtained with those obtained from Dynamic Relaxation and Finite Element Methods. Ojeda et al. [5] presented a new technique to find the large deflection of composite plates. They used the Newton–Raphson method to obtain the solution curve. They verified the results obtained with those in the literature. Ovesy et al. [6] studied on the large deflection of composite plates with anti-symmetric angle ply. They used developed finite strip method their study. They took the boundary condition

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of the plate as simple support. They also solved the problem by using finite element method to verify it. Cetkovic and Vuksanovic [7] developed a finite element model of geometrically nonlinear plate using the total Lagrange formulation. They compared the results obtained from their studies with similar results in the literature. Homeijer et al. [8] overcame the solution of displacement of isotropic, axisymmetric plate by using von Karman plate theory. The plate was assumed under transverse pressure and in-plane tensile stress. They used an iterative technique to find a solution of the differential equations. They also solved again the problem by using finite element analysis to verify. Lei et al. [9] studied on the large deflection behavior of the functionally graded carbon nanotube-reinforced composite plates. They used the element free kp-Ritz method. The plates' properties of the material were assumed to be graded through the thickness direction. As a result of their study, the determined the effects of thickness-width ratio and volumetric content of carbon nanotube and boundary conditions. Sitar et al. [10] discussed the large deflections of non-homogeneous, slender beam. They derived the governing equation and solved numerically. They found that the results obtained are in harmony with those found in the literature. Ren and Sun [11] studied on the large deflection of laminated composite beams, which have shape memory alloy fibers. They took into account the geometric nonlinearity of the structure in their work. The nonlinear governing equations were solved by incremental Newton–Raphson method and Galerkin's method. The large deflection analysis on composite skew plates reinforced with functionally graded carbon nanotube resting on Pasternak foundations are investigated by Zhang and Liew [12]. They used von Karman assumption and the first-order shear deformation theory in the study. They presented the effects of carbon nanotube content, skew angle, width-to-thickness ratio, elastic foundation and boundary conditions in their study. Tiar et. al [13] analyzed the large deflections of two dimensional fiber reinforced elastic solids. They proposed a finite element formulation. They solved some examples to show the capabilities of the formulation. Pagani and Carrera [SPS:refid::bib14][14] performed the analysis on the large deflections and post-buckling of the laminated composite beams. They employed the Carrera Unified Formulation in the study. They solved some problems on post-buckling of symmetric cross-ply beams and large deflection of asymmetric laminates. Gholami and Ansari [15] dealt with a large deflection problem on functionally graded multilayer graphene platelet-reinforced composite plates. The plates are assumed under sinusoidal transverse loads. They presented the effects of distribution and geometry of graphene platelet nanofillers, weight fraction, length to thickness ration and boundary conditions on large deflection responses. Akbaş [16] overcome the large deflection problem of a fiber-reinforced composite beam. The author solved the nonlinear problem by using Newton-Rapson iteration method. The author examined the effects of the orientation angle and the volume fraction of the fiber on the large deflection. Rajendran and Mathew [17] investigated on the large deflection of multilayered cantilever beams. They used Da Silva method to solve the problem analytically. They compared the results obtained from the geometrically linear and nonlinear theory. Gönenli et al. [18] studied on the large deflection effect on the natural frequency of pre-stressed laminated composite plates. They used classical plate theory to model the thin curved plate. Al-Shugaa et al. [19] overcame the large deflection problem of anisotropic thin plates. They proposed a formulation based on the Ritz method. They verified the method proposed by comparing the results obtained from the finite element method and the literature.

As aforementioned before, experimental studies on large deflection in the open literature are very limited. Some of the experimental studies encountered are given below.

Minguet and Dugundji [20] investigated the large deflection of coupled composite blades analytically and experimentally. They presented a new model and they solved it by finite difference method. They compared the results obtained with experimental and analytical solutions. Yoo et al [21]. studied the large vibration of a thin clamped plate. The vibration was caused by the weight attached at end point. They presented the ability of the absolute nodal coordinate formulation by comparing to the experiments. Bouadjadja et al. [22] studied on the large deflection of the composite cantilever beam. They performed not only analytical but also experimental studies.

As a result of the literature research, very few studies are encountered on the large deflection problem of perforated composite plates. Especially, when the experimental studies are investigated, it is clearly seen that there is a gap in the literature on this subject. Some of the few theoretical studies performed on large deflection of perforated composite plates in the open literature are given in below.

The large deflection analysis of a circular plate, which have a concentric hole is performed by Banerjee [23]. The author used the von Karman field equations in the analysis. The author compared the results obtained from his study with a study in the literature and found compatible results. Gorji et al. [24] dealt with the large deflection problem of circular and annular plates. They used von Karman theory to solve the problem in their study. Gayanov [25] calculated the deflections of shells with large rectangular holes. He compared their results with those from the net point method and the finite element method. Sun et al. [26] proposed a formula to solve the large deflection behavior of the annular membrane. They solved the problem by using power series method.

When the literature research is evaluated, it is seen that there is a lack in the open literature on the large deflection behavior of perforated composite plates. There are almost no experimental studies on the effect of hole structure and fabric type on the large deflection of composite plates. The experimental study on the large deflection analysis of the composite plates is performed in this study. The effects of hole size, number and location in the composite plate on large deflection are investigated. The effects of the fabrics are also examined. The results obtained from the experimental study are compared with the numerical method. Simulation module of SolidWorks commercial program is used in numerical solution method. When the results are compared, it is seen that suitable results are obtained.

2 Materials

Two type fabrics of fiber materials are used as the reinforced elements of the test specimens. The first of these is unidirectional E-glass fabric and the other is Woven E-glass fabric [27]. They are produced in METYX Composites and FIBROTEKS Weaving Industry (Türkiye), respectively. Furthermore, Epo Kem 1000 is used as epoxy resin and Keh 2000 is used as epoxy hardener. They are supplied from PAG Chemical Industry, Türkiye, are used as epoxy material. Composite plates are produced in ATARD Defense and Aerospace Inc., Türkiye. The plates produced are composed of 8 layers and average dimensions of the plates are 500 mm in width, 1000 mm in length and 2.2 mm in thickness. The mechanical properties of the plates are given in Table 1.

As it is known, in unidirectional fabric, all fibers in the fabric are parallel to each other in the same direction. In this study, fiber directions are along the longitudinal direction of the plate. As for woven fabrics, the fibers within the fabric are bidirectional. In this study, the fibers in the fabric are along the longitudinal and transverse directions of the plate. That is, these fibers in the woven fabric are woven by passing them over and under each other.

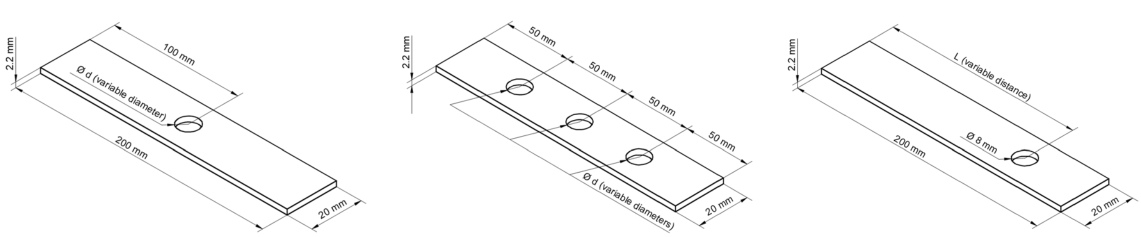
3 Preparation of test specimens

In order to carry out the experiments, 8-layer composite plates are cut in dimensions of 250 mm in length and 20 mm in width. The thickness of specimen is 2.2 mm as aforementioned. The active surface area of the plate used in the experiment is 200 mm × 20 mm. During the large deflection tests, the plate is fixed from the 50 mm part at one end. In this study, three types of specimens are prepared to see the effects of the size, number and location of holes in composite plates on large deflection. Diameter (D), Number (N) and Length (L) types of experimental specimens are shown in Fig. 1, respectively.

In D-type specimens, the hole is in the middle of the plate in both the transverse and longitudinal directions as shown in Fig. 1a. The diameter of the hole is increased in each specimen from 4 to 16 mm in increments of 4 mm to see the effect of increasing the hole diameter in single-hole specimen. N-type specimen is shown in Fig. 1b. As seen in the figure, there are 3 holes in the plate. The diameters of the holes are also increased from 4 to 16 mm in increments of 4 mm as in D-type to see the effects of increasing the hole diameter in multi-hole specimen and increasing the number of holes. As shown in Fig. 1c, the hole diameter is constant in the L-type specimen and it is equal to 8 mm. But the distance of the hole location from the clamped end point of the plate is increased from 25 to 175 mm in 25 mm increments to see the effect of changing the location of the

Table 1 The properties of the composite materials [27]

Fabrics	E_1 [MPa]	E_2 [MPa]	G_{12} [MPa]	$G_{13}=G_{23}$ [MPa]	ρ [g/mm^3]	ν_{12}	$\nu_{13}=\nu_{23}$
Unidirectional	20,443	5184	1856	1113	0.001526	0.36	0.09
Woven	21,651	21,651	1646	988	0.001578	0.35	0.35



(a) D-type **(b)** N-type **(c)** L-type

Fig. 1 Types of experimental specimens hole in single-hole specimen. The photographs of D-, N- and L-types woven composite test specimens are given in Fig. 2.

4 Experimental setup

The schematic and the real representations of experimental setup are given in Figs. 3a, b.

It can be seen from the Fig. 3 that the specimen is fixed one end by a clamp and a precision-measured test weight is hung on the other end of the specimen. The test weights are obtained from small stones placed in a plastic bag. These stone-packed plastic bags are weighed precisely by a precision weighing, PRECISA XB 220A (manufactured by Precisa Gravimetrics AG, Switzerland). Plastic bags filled with stones weighed on a precision scale are shown in Fig. 4. While preparing the weights, they are adjusted according to the desired force according to the F = mg equation.

The precision of the scale shown in Fig. 4 is 0.0001 g. As a result of the measurement with the weighing, weights that will provide a force from 1 to 5 N with 1 N intervals are obtained. This force on the specimen causes a large deflection of specimen. A millimeter paper, which is hung on the reference steel bar, is used to measure the amount of large deflection at the end midpoint of the plate as shown in Fig. 3. The reference point is shown in Fig. 3a. The large deflection value at the end point of the specimen is measured from the reference point. Variations in the large deflections are obtained by determining the x and y coordinates of the large deflection value of the end point of each specimen.

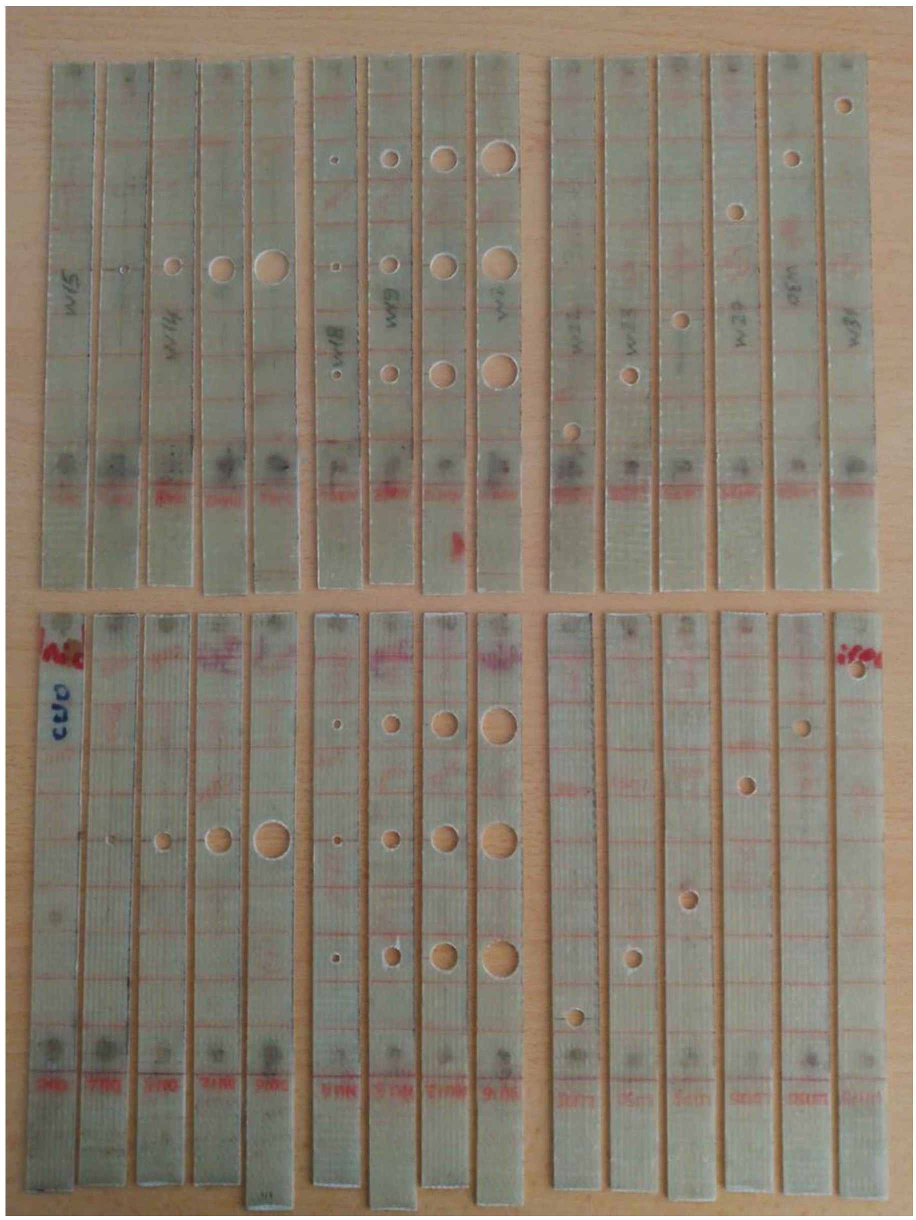
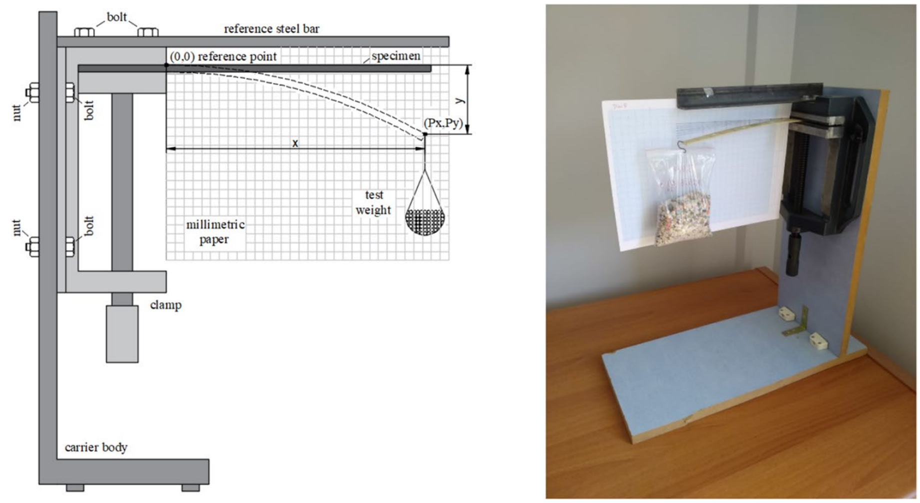


Fig. 2 Real photos of D-, N- and L-types test specimens

Fig. 3 Experimental setup



(a) Schematic view **(b)** Real view

Fig. 4 Precision scale and plastic bag filled with stones

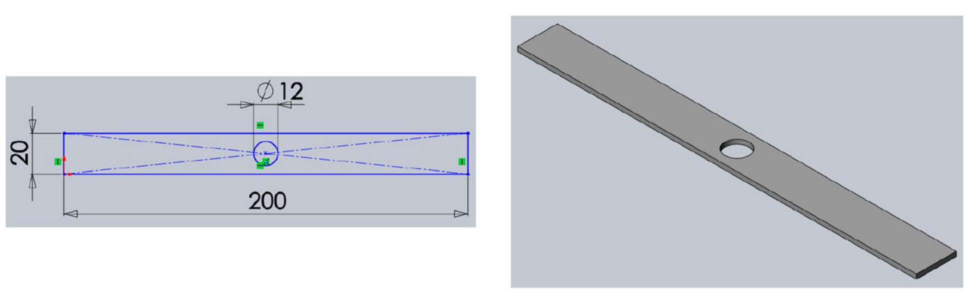
5 Numerical solution

The large deflection analysis of the composite plate is also performed by SolidWorks commercial program (SolidWorks Corp., USA). SolidWorks program is suitable for obtaining solid models of structural elements. Moreover, the simulation module of the program allows structural analysis (static, vibration, thermal, etc.) of structural elements.

In order to perform static analyzes of composite plates, a 2D frame model of each type of specimen is drawn first. 2D frame model of D-type composite plate is shown in Fig. 5a as an example. Then, 3D solid models are extruded from each of these 2D frame models as shown in Fig. 5b. After obtaining the solid model of each specimen, the static analysis module of the program is run. The large displacement option is selected from the options section of the static analysis in order to analyze the large deflections of the plates. The material properties of the model are defined according to the properties given in Table 1.

As can be seen from the Fig. 6a, the clamped boundary condition is applied to one end of the plate. A single force is applied from the middle of the other end of the plate. Then, the model is meshed. For example, the element size after the meshing process of the unidirectional composite plate model with a 12 mm hole in the middle is 2 mm. The total number of nodes in the model is obtained as 18,933. In addition, the total number of elements in the model is 10,730. After the

Fig. 5 Model of composite plate with a hole



(a) 2D frame model **(b)** 3D solid model

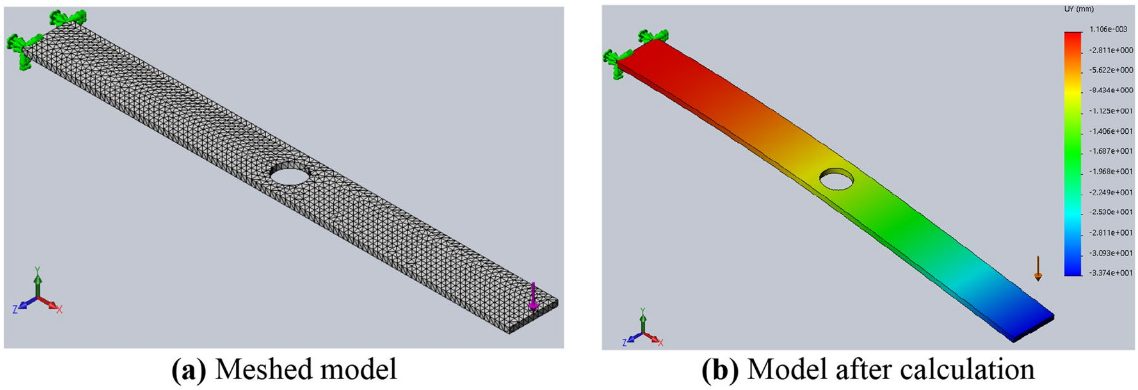


Fig. 6 Model of composite plate during analysis

meshing process, the simulation program is run. The model obtained after the large deflection analysis of the program is shown in Fig. 6b.

6 Result and discussion

The results obtained from experiment are examined from six different aspects. These are the effects of the geometric nonlinearity, different fabrics, increase in the force, increase in the single-hole diameter, increase in the multi-hole diameters, increase in the number of holes and hole location. These effects are examined below, respectively.

6.1 The effects of the geometric nonlinearity

In the static deflection analysis of many engineering problems, the nonlinear equations obtained are linearized to simplify the solution since the deflection values are quite small. However, in some problems, these deflection values are large. Therefore, performing the linearization process causes false results. In the numerical analysis part of the study, nonlinear solution method is preferred in order to obtain more accurate results. The linear and the nonlinear solutions of the deflections in the x and y directions of end point of the unidirectional plate is shown in Fig. 7.

In the linear solution shown in Fig. 7, it is seen that the amount of the deflection increased linearly with increasing force. As expected, in the nonlinear solution, it is seen that the amount of the deflection values also increased with increasing force, but are not linear. Especially, at high force values, the large deflection values are quite far from each other. Therefore, in order to obtain real results in the solution of deflection problems, the solution must be done with nonlinear solution techniques.

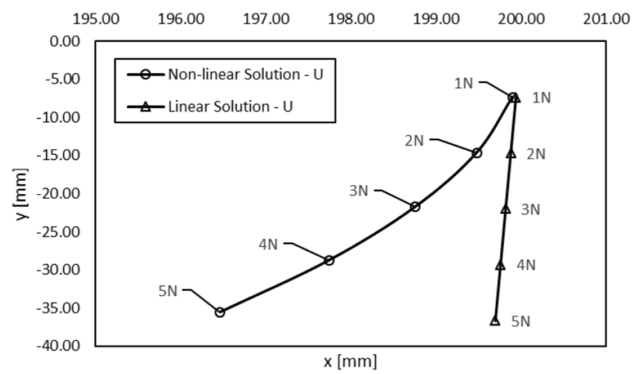


Fig. 7 Linear and nonlinear solutions of the unidirectional plate

6.2 The effects of different fabrics

To see the effect of change in the fabrics, non-perforated specimens are firstly used in the experiment. These specimens have two different fabrics, i.e., unidirectional and woven. Figure 8 shows the large deflection curves of cantilever unidirectional and woven plates.

The curves in Fig. 8 are obtained as a result of the experiments carried out under 5N load. Large deflections are measured at 20 mm intervals in the longitudinal direction of the plate. Due to the application of the force from the end point, the plate gradually deflected toward its free end. It can be seen from the figures that the unidirectional plate is deflected more than woven plate. In the U type specimen, the fiber direction is in the longitudinal direction of the plate, while in the W type specimen, there are fibers in both longitudinal and transverse directions. In that reason, it is seen that the large deflection in the u type specimen is higher than in the w type. In addition, as can be seen from the figures, the results obtained from the experiments and SolidWorks are in good agreement.

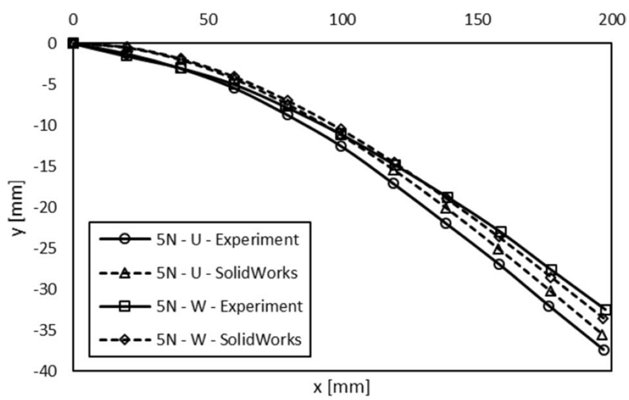


Fig. 8 Large deflections of cantilever non-perforated plates under 5N load

6.3 The effects of increase in the force

Large deflections of cantilever unidirectional and woven plates under different loads are represented in Figs. 9a, b, respectively. The specimens considered are also non-perforated specimens in here. The load is changed from 1 to 5N by 1N increment. Large deflection values are measured at 20 mm intervals from the long edge of the plate, as similar to Fig. 8.

As can be seen from both figures, the amount of deflection at the free end of the plate increased about uniformly with the increasing force, as expected. As also expected, as similar to Fig. 8, the unidirectional plate is deflected more than woven plate under other loads.

6.4 The effects of increase in the single-hole diameter

In order to see the effect of increasing the single-hole diameter, the D-type specimen shown in Fig. 1a is considered. The hole is in the middle of the plate and the hole diameter is increased. The hole diameters are taken as 4 mm, 8 mm, 12 mm and 16 mm. The variation of the coordinate of the end point on the free side of the plate with the increase of the hole diameter under 5N load is given in Fig. 10. Figures 10a, b show the data obtained for the composites which have unidirectional and woven fabrics, respectively.

It can be seen from the Fig. 10a that the deflection of the end point of the plate is increased with increasing the hole diameter. When the data obtained from SolidWorks is examined, it is seen that this increase is almost linear. As for the data obtained from the experiments, it is seen that especially in small hole diameters, the data converge to each other and disrupt the linearity of the curve. Similar curve trends are obtained in the composite specimens with woven fabric as seen in Fig. 10b. Besides, it can be seen from both pictures that the increase in hole diameter increases the large deflection much more. For example, when the hole diameter is increased from 4 to 8 mm, the variation in the large deflection is much more than double compared to the variation in the large deflection obtained when increasing the hole diameter from 8 to 16 mm. The SolidWorks and the experimental data obtained for the composite specimens with woven fabrics are quite close as seen in Fig. 10b. As for the values obtained for the unidirectional fabric, there is some difference between them especially in the x-direction. In numerical analysis, ignoring the effect of gravity and accepting the manufacturing of the sample as ideal may cause small differences between numerical and experimental results.

6.5 The effects of increase in the multi-hole diameters

Figure 11 shows the effects of increasing the multi-hole diameters on large deflection of composite plates. To see the effects of increasing the multi-hole diameter, N-type specimen shown in Fig. 1b is taken into consideration.

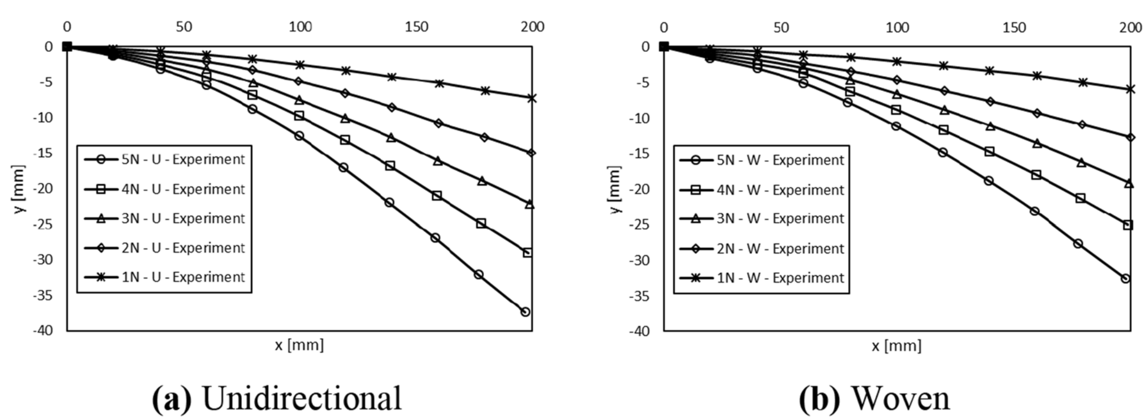


Fig. 9 Large deflections of cantilever plates under different loads

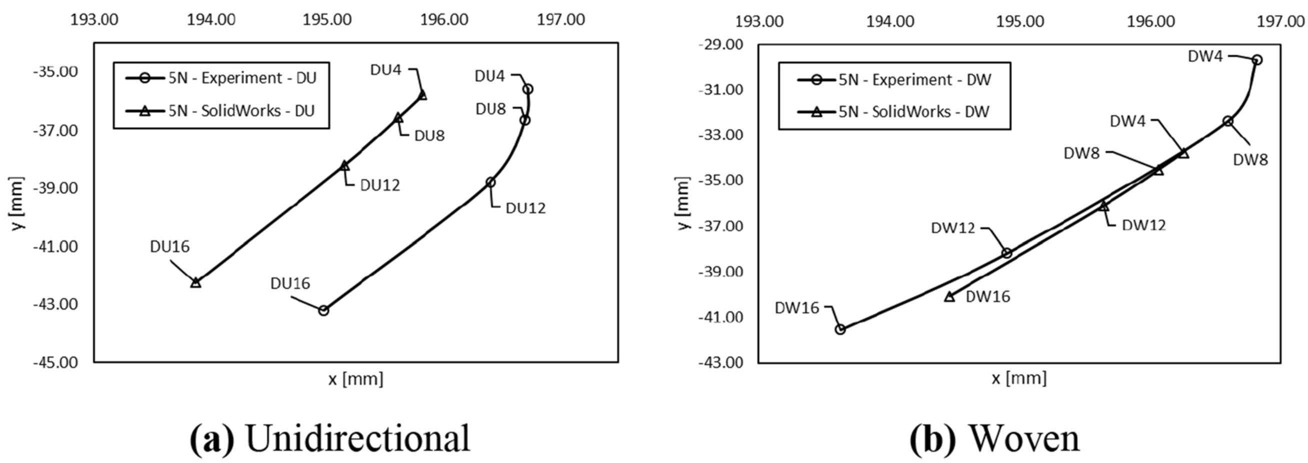


Fig. 10 Large deflections of cantilever plates with different single-hole diameters

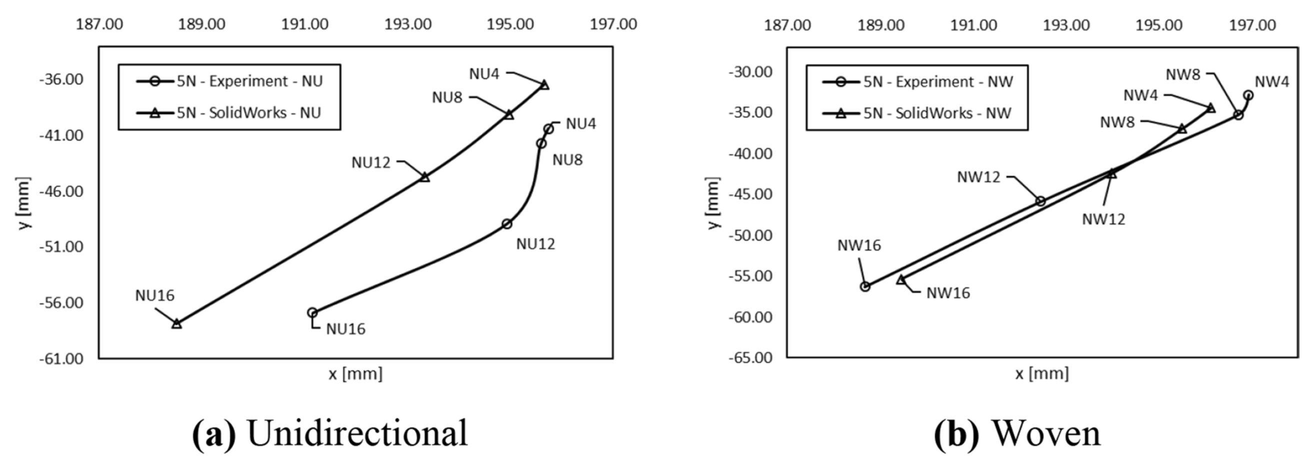


Fig. 11 Large deflections of cantilever plates with different multi-hole diameters

There are three holes in the plate as shown in Fig. 1b. The diameters of these holes are taken from 4 to 16 mm in 4 mm increments. Figures 11a, b show the large deflection of the free end point of the composite plate. It can be seen from the figures that the large deflection values obtained from SolidWorks increased gradually and about linearly with increase in the hole diameters. As for the results of the experiment, it can be seen from these figures that the large deflection values obtained from the experiments also increased with increasing the hole diameters. But, as similar to Fig. 10, it is seen that deflection values get closer to each other and the linearity of the curve deteriorates, in small hole diameters especially. When the experimental and SolidWorks data are examined, the values obtained for woven plate are closer to each other than unidirectional plate. The data obtained for woven plate from SolidWorks and experiment are almost the same. But, there is some difference between them for unidirectional plate especially in the x-direction.

6.6 The effects of increase in the number of holes

In Fig. 12, the curves given in Figs. 10 and 11 are compared. In other words, the specimens with single-hole (D-type) and 3-holes (N-type) in these figures are compared with each other.

When Figs. 12a, b examined, curve trends of D-type and N-type specimens are similar to each other. However, as expected, the large deflection values obtained for composite specimens (N-type) with multi-holes are higher than those for single-hole specimens (D-type). Therefore, the curves obtained for the N-type are larger than those for the D-type. It has already been said that with increasing hole diameter, large deflection values increase for both types.

6.7 The effects of the hole location

The variation of the large deflections of the L-type specimens for unidirectional and woven fabrics are given in

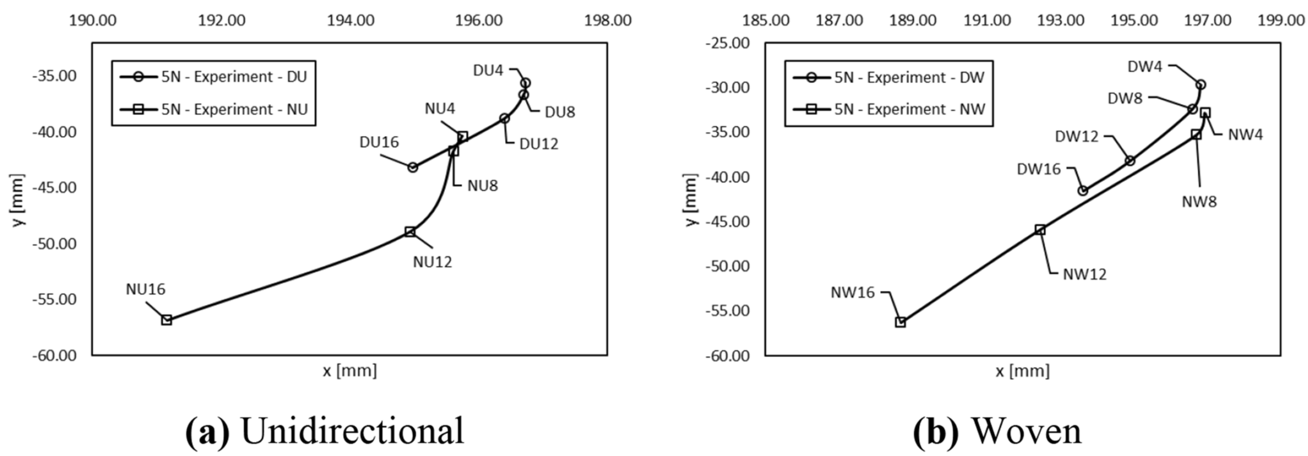


Fig. 12 Large deflections of cantilever plates with different single and multi-hole diameters

Figs. 13a, b, respectively. L-type specimen is represented in Fig. 1c. The hole location is changed in L-type specimens. The distance of the hole location from the clamped end is taken as 25, 50, 75, 100, 125, 150 and 175 mm. The diameter of the hole is taken as 8 mm.

When the values obtained from SolidWorks in Figs. 13a, b are examined, it is seen that the large deflection values of the end point decrease with the increasing the distance of the hole location from the clamped end. The characteristic of the curve obtained from the experimental data is similar to that obtained from SolidWorks, but the obtained values are slightly different. Especially, the values obtained at 125, 150 and 175 mm are close to each other.

7 Conclusion

The large deflection behaviors of the perforated composite plates are investigated in the study. They are discussed in 7 aspects in this study. These are geometric nonlinearity, fabric, force, single-hole diameter, multi-hole diameter, hole number and hole location. In light of the experimental and the numerical studies, the following conclusions are derived.

- To obtain the real deflection results, the nonlinear solution techniques must be preferred.
- The amount of the large deflection of unidirectional plate is more than woven plate. Therefore, if it is desired to reduce the deflection in the plate, composite plate with woven type fabric should be chosen.
- The large deflection value at the free end of the plate increased with increasing force, as expected. The rate of increase in the large deflection is almost directly propor-

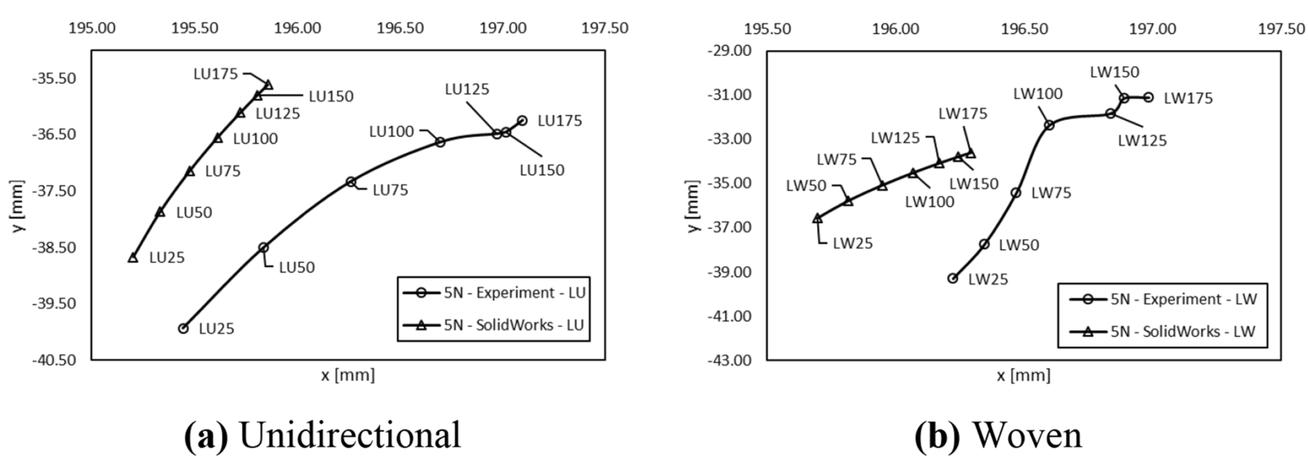


Fig. 13 Large deflections of cantilever plates with different hole locations

tional to the increase in the force. Therefore, it should be known that the increase in force will increase the amount of large deflection almost at the same rate.

- The large deflection value is increased with increasing the single-hole diameter. But this increase is much more than linear increase.
- The large deflection value is increased with increasing the multi-hole diameters as in the single-hole specimen. As expected, large deflection values in multi-hole specimens are greater than those of the single-hole specimens. This increase is not directly proportional as in single hole but much more.
- The large deflection values decrease with increasing the distance of the hole location from the clamped end.

Declarations

Conflict of interest The author did not receive support from any organization for the submitted work. The authors have no competing interests to declare that are relevant to the content of this article.

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