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RESEARCH ARTICLE

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Investigation of bending behavior of foam core sandwich plates with different face and core materials at different layer thicknesses

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Abstract

Sandwich plates consist of a total of three layers with a thick core layer between two thin face layers. While the face layers provide resistance against bending, the core layer provides resistance against shear. General purpose finite element software programs are one of the most convenient and widely used analysis procedures for investigating the behavior of structures. Many design parameters can be easily examined by these analysis programs. In this study, the bending of simply supported sandwich square plates on four sides with a ratio of core layer thickness to face layer thickness between 7 and 9 was investigated by using the general purpose finite element software program. The effect of the thickness change was investigated by changing the face and core layer thicknesses of the sandwich plates with a fixed total thickness. At the same time, the face and core materials were changed and the most suitable design in bending behavior was revealed. For this purpose, 110 analyzes were performed with 2 different face materials, 5 different core materials, 11 different thickness ratios, and the results were presented with graphics. It was concluded that the elasticity modulus of the material used in the face layer is a parameter that directly affects the midpoint deflection value. In sandwich plates, when the elasticity modulus of the face layer increases the resistance to bending also will increase.
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Keywords**:** *Finite element method, Foam-core sandwich plate, Mid-point deflection, Thin plate, Static analysis.*

1. Introduction

Sandwich plates are widely used in civil engineering, offshore, marine and military fields, construction, aviation, automobile, aerospace, marine, etc. It is used in the construction of various structures in these areas. Also, they are also preferred for construction of filters, sports cars, wind turbine blades, aircrafts, boats, defense vehicles, etc.

The sandwich plates consist of two face sheets at the bottom and top and a core layer. As shown in Figure 1, an adhesive layer is used to bond the thin and rigid face sheets to the thick and light core layer. [1]. While the core layer of the structure increases the rigidity of the structure by carrying shear loads, the face sheets carry the bending stresses [2].

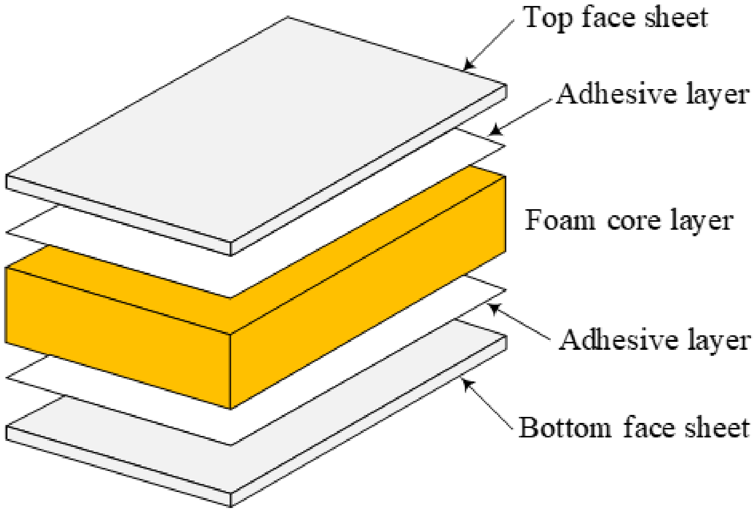

Fig. 1. Sandwich plate.

Insulating qualities, light weight, durability, impact resistance, damage and fatigue resistance are the advantages of sandwich plates.

Joints of the sandwich plates usually decrease the efficiency, and this is one of the disadvantages of sandwich plates. When cutting the sandwich plates, they can be easily damaged. They also require additional surface treatment.

Light materials such as honeycomb, balsa wood, EPS (expanded polystyrene), and foam are used as core materials. Carbon fabrics, glass fiber, GRP (glass reinforced polyester), FRP (fiber reinforced polymer), FRC (fiber reinforced composite) or isotropic materials such as steel and, aluminum are used as face sheet materials.

Many researchers have conducted studies on sandwich structures, which are special types of composite materials and economical, durable, very light materials. Garg et al. published a detailed study about sandwich structures made with functionally graded materials. In their study, a literature survey has been carried out for different theories and methods for static, vibration, and buckling analysis [3]. Xiong et al. investigate the developments and characterizations of sandwich structures with different core types in their review study [4]. Altunsaray, investigated the static deflections of sandwich plates. In the study, carbon/epoxy material used for the face sheets and balsa wood material used for the core. The obtained results were compare with the finite element method solutions [2]. Demirhan and Taşkın, presented static analysis of sandwich plates with foam cores. They derived the governing equations and found the numerical results from the Navier's method [5]. Taşkın and Demirhan analyze the bending of simply supported porous sandwich plates by using the four-variable shear deformation theory. In their study, equilibrium equations are derived from the virtual displacement principle [6]. Some researchers have experimentally studied the bending behavior of sandwich plates. Moreira and Rodrigues investigate the static and dynamic analysis of soft core sandwich panels numerically and experimentally. For this purpose they formulate a new finite element by applying spring concept. They validate the numerical solutions with experiment results. Heywood et al. studied about the profiled sandwich panels with deep foam cores in flexure experimentally. And also they were developed numerical model and compare the results [7-8]. Li et al. developed a new model for functionally graded material sandwich plate in their study. They deduce the governing equations by using the static equilibrium method and verify the results with solutions solved with Navier approach [9]. Liaw and Little developed the governing equations for bending of multilayer sandwich plates in their study by variational methods [10]. Carbas investigated the static behavior of sandwich plates with different boundary conditions numerically and experimentally in thesis study [12].Mota et al. investigate the mechanical behavior of a sandwich plate with aluminum foam core in their study [15]. Yazdani et al. investigate the bending of composite sandwich plates using generalized differential quadrature method based on first order shear deformation theory [16]. Fan et al. investigate the nonlinear bending of sandwich plates with graphene nanoplatelets under various loads and boundary conditions [17].

In this study, static analyzes of uniformly distributed loaded foam core sandwich plates with different core materials and different layer thicknesses were investigated by using the general purpose finite element software program. The plates are simply supported on all four sides. The effect of materials and layer thickness in bending of sandwich plates are investigated. For this purpose, a simply supported square sandwich plate was considered, and uniformly distributed loads were applied to the plate. The sandwich plates with 11 different face and core layer thicknesses are modeled to investigate the effect of layer thickness. As a result of these analyzes, the effect of foam core material on foam core sandwich plates with the same conditions was investigated. The effect of the layer thickness for the design of the sandwich plates under bending has been determined.

2. Materials and methods

The classical laminated plate theory which is a pure plane stress model is used for the sandwich plates. The transverse rigidity of the material in the core layer of sandwich plates is lower than the transverse rigidity of the material in the face layers.

For sandwich plates, the mid plane deflection is considered to be small, and the following assumptions are made based on plate theory [11].

- The thicknesses of the face layers are thin compared to the core layer thickness.
- The face bending stiffness was ignored.
- The torsional and bending moments are carried by the top and bottom face layers.
- The shear stresses are carried by the core layer
- The shear stresses do not change throughout the thickness.

An example sandwich plate section is shown in Figure 2.

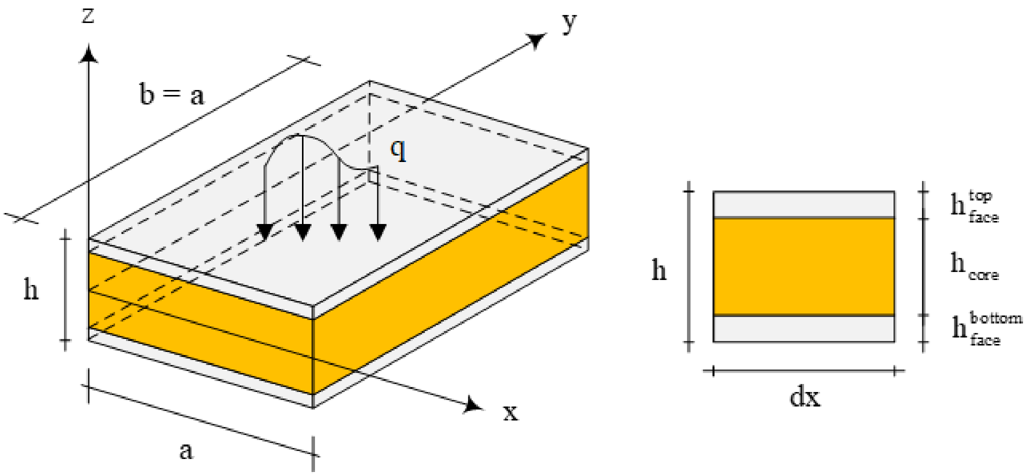

Fig. 2. Geometry and cross section of a rectangular sandwich plate.

In Figure 2, the thickness of the core part of the sandwich plate is shown as h_{core}, the upper layer thickness is shown as $h_{topface}$, and the bottom layer thickness is shown as $h_{bottomface}$.

Bending and torsional stiffnesses of sandwich plates are expressed by moments and derivatives of deflection [12]. These rigidities can be described as follows:

$$D_x = -\frac{M_x}{\partial^2 w / \partial x^2} \quad D_y = -\frac{M_y}{\partial^2 w / \partial y^2} \quad D_{xy} = -\frac{M_{xy}}{\partial^2 w / \partial x \partial y} \tag{1}$$

The transverse stiffnesses D_{Qx} and D_{Qy} are expressed by shear forces and shear strains [13]:

$$D_{Qx} = \frac{Q_x}{\gamma_{xz}} \quad D_{Qy} = \frac{Q_y}{\gamma_{yz}} \tag{2}$$

Poisson's ratios are described as[13]:

$$\nu_x = \frac{\partial^2 w / \partial y^2}{\partial^2 w / \partial x^2} \quad \nu_y = -\frac{\partial^2 w / \partial x^2}{\partial^2 w / \partial y^2} \tag{3}$$

There is a relationship between bending rigidities and Poisson ratios as $\nu_x D_y = \nu_y D_x$.

Bending curvatures and torsional curvatures are expressed as follows [13]:

$$\begin{aligned}
\frac{\partial^2 w}{\partial x^2} &= -\frac{M_x}{D_x} + \nu_y \frac{M_y}{D_y} + \frac{1}{D_{Qx}} \frac{\partial Q_x}{\partial x} \\
\frac{\partial^2 w}{\partial y^2} &= -\frac{M_y}{D_y} + \nu_x \frac{M_x}{D_x} + \frac{1}{D_{Qy}} \frac{\partial Q_y}{\partial y} \\
\frac{\partial^2 w}{\partial x \partial y} &= -\frac{M_{xy}}{D_{xy}} + \frac{1}{2D_{Qx}} \frac{\partial Q_x}{\partial y} + \frac{1}{2D_{Qy}} \frac{\partial Q_y}{\partial x}
\end{aligned} \tag{4}$$

The moment expressions used in the equilibrium equations for sandwich plates are as in Equation 5 [13]:

$$\begin{aligned}
M_x &= -\frac{D_x}{1-\nu_x \nu_y} \left[\frac{\partial}{\partial x} \left(\frac{\partial w}{\partial x} - \frac{Q_x}{D_{Qx}} \right) + \nu_y \frac{\partial}{\partial y} \left(\frac{\partial w}{\partial y} - \frac{Q_y}{D_{Qy}} \right) \right] \\
M_y &= -\frac{D_y}{1-\nu_x \nu_y} \left[\frac{\partial}{\partial y} \left(\frac{\partial w}{\partial y} - \frac{Q_y}{D_{Qy}} \right) + \nu_x \frac{\partial}{\partial x} \left(\frac{\partial w}{\partial x} - \frac{Q_x}{D_{Qx}} \right) \right] \\
M_{xy} &= -\frac{D_{xy}}{2} \left[\frac{\partial}{\partial x} \left(\frac{\partial w}{\partial y} - \frac{Q_y}{D_{Qy}} \right) + \frac{\partial}{\partial y} \left(\frac{\partial w}{\partial x} - \frac{Q_x}{D_{Qx}} \right) \right]
\end{aligned} \tag{5}$$

By substituting these expressions in the equilibrium equations, differential equilibrium equations are obtained for sandwich plates. The equilibrium equations are as follows [13]:

$$\begin{aligned}
\frac{\partial M_{xy}}{\partial y} + \frac{\partial M_x}{\partial x} - Q_x &= 0 \\
\frac{\partial M_{xy}}{\partial x} + \frac{\partial M_y}{\partial y} - Q_y &= 0 \\
\frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} + q &= 0
\end{aligned} \tag{6}$$

For an isotropic simply supported uniformly distributed loaded square plate mid point deflection value can be calculated as follows [13]:

$$w_{\max} = \frac{4qa^4}{\pi^6 D} \tag{7}$$

In this equation D is the flexural rigidity of the plate and can be calculated with the mechanical properties of isotropic material (Poisson's ratio and modulus of elasticity) and thickness of the plate h as below:

$$D = \left(Eh^3\right) \Big/ \left(12\left(1-\upsilon^2\right)\right) \tag{8}$$

Table 1 shows the mechanical properties of the materials used in this study.

Table 1. Mechanical properties of sandwich plate materials.

Type	**Material**	**E (MPa)**	**G (MPa)**	**K (MPa)**	**ν**
Face Sheet 1	Steel	206000.000	79300.000	171666.667	0.300
Face Sheet 2	Aluminum	69000.000	25940.000	68986.203	0.333
Foam Core 1	PVC H200	230.000	86.466	225.494	0.330
Foam Core 2	PVC H60	45.000	20.737	18.072	0.085
Foam Core 3	linear PVC foam (Airex R63.80)	56.000	21.000	56.000	0.333
Foam Core 4	AIREX® R82.110 High Performance Structural Foam	83.000	30.000	118.571	0.383
Foam Core 5	CoreLite PVC 100 Closed-Cell PVC Foam Sheet	89.980	37.000	52.795	0.216

In Table 1, ν is the Poisson's ratio, K is the bulk modulus, G is the shear modulus, and E is the elasticity modulus.

The calculation results of the examples discussed in this study were obtained using the ANSYS finite element package program. The three-dimensional Figure 3 shows the solid finite element, SOLID186 from the ANSYS element library, used in the study.

The SOLID186 element is a high-order three-dimensional 20-node solid element with second-order displacement behavior. Each of the 20 nodes of this element has three degrees of freedom. It supports properties such as plasticity, hyperelasticity, stress hardening, large displacement and large strain.

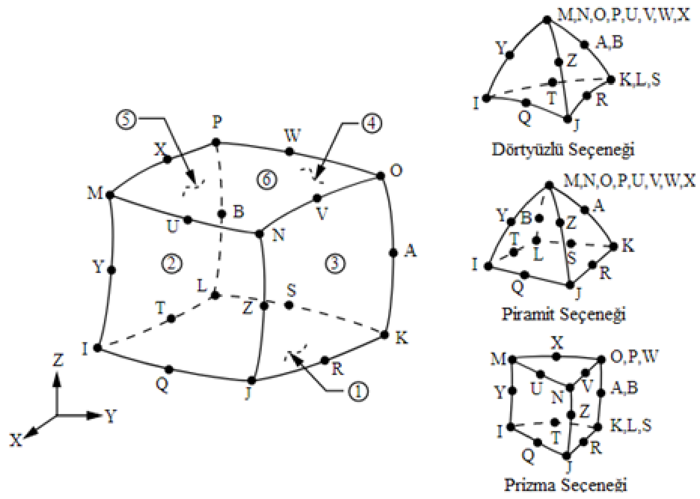

Fig. 3. SOLID 186 element [14].

3. Example problems

In this study, static analyzes of square sandwich plate models with 1000 x 1000 mm plane width with different layer thicknesses with same total thickness, which are formed by using two different rigid materials in the face layer and five different foam materials in the core layer performed. The sandwich plates were subjected to uniformly distributed load of q = 100 kN/m^2. The materials used in the sandwich plate examples were shown in Table 1.

Boundary conditions of the plates are simply supported on all four sides. In the analysis, combinations of three different parameters, namely Layer Thickness Effect (k), Face Material Effect (F), and Core Material Effect (C), will be discussed

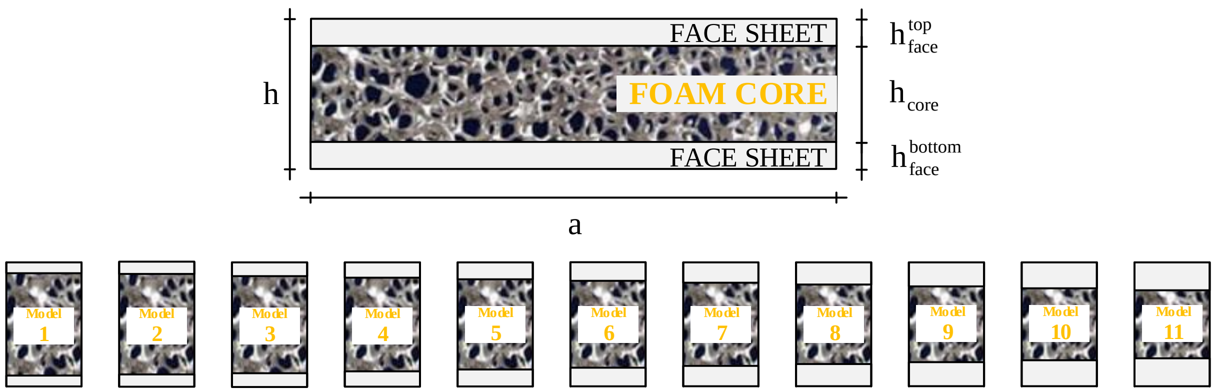

Fig. 4. Cross-sectional scheme of the 11 sandwich plate models.

In order to ensure the thin plate assumptions, the slenderness ratio of the plate was taken constant as a/h = 100. Accordingly, the total thickness of the square plate was taken as 10 mm in the 1000 mm x1000 mm samples. In the samples, the face thicknesses were taken as equal. Plates of the same total thicknesses were obtained by increasing the core thicknesses and decreasing the face thicknesses with the $k = h_{core} / h_{face}$ equation. Different 11 sandwich plate models with k constants between 7 and 9 are considered as illustrated in Figure 4. The geometric properties of the examined plates are shown in the Table 2 below.

Table 2. Geometric properties of sandwich plates (mm).

model no	k	a	h	h_{face}	h_{core}
1	9.0	1000	10	0.91	8.18
2	8.8	1000	10	0.93	8.14
3	8.6	1000	10	0.94	8.12
4	8.4	1000	10	0.96	8.08
5	8.2	1000	10	0.98	8.04
6	8.0	1000	10	1.00	8.00
7	7.8	1000	10	1.02	7.96
8	7.6	1000	10	1.04	7.92
9	7.4	1000	10	1.06	7.88
10	7.2	1000	10	1.08	7.84
11	7.0	1000	10	1.11	7.78

4. Results and discussion

In the uniformly loaded simply supported square sandwich plates, the critical deflections occur at the mid point of the plate. Different models were analyzed to demonstrate the effect of the thickness and material changes of the layers on the critical deflection value for the sandwich plate.

A total of 55 problems (11 models for each 5 core materials) have been considered to investigate the Layer Thickness Effect (k) and Core Material Effect (C) by selecting the face material as steel. Mid point deflections vs layer thickness effect (k) for uniformly loaded square sandwich plates with the steel face are plotted in Figure 5 with different 5 core materials.

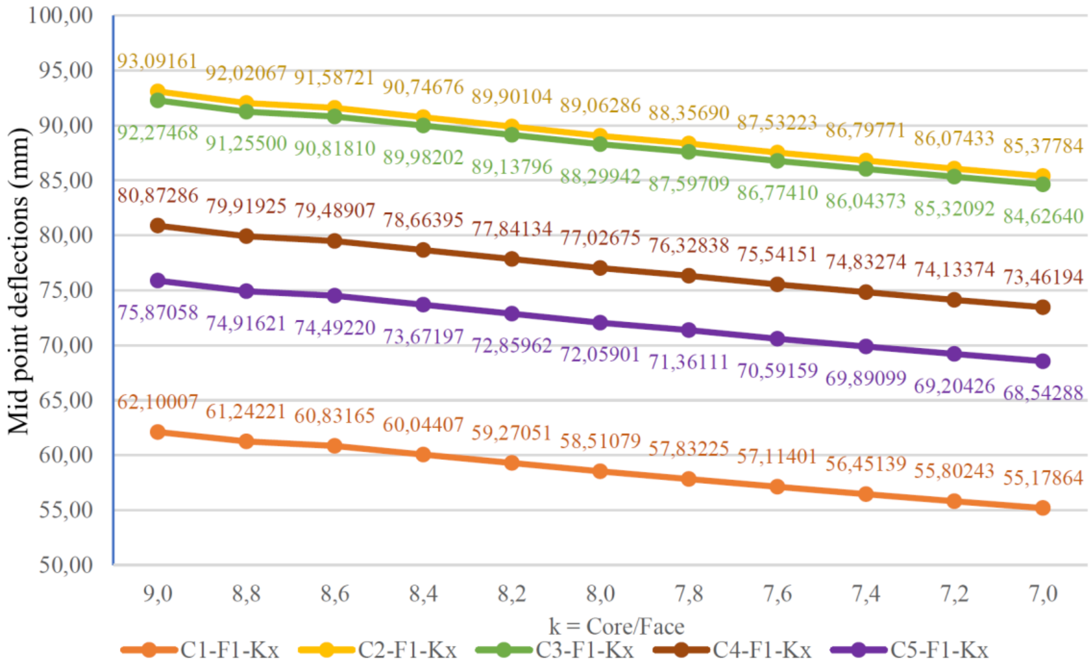

Fig. 5. Mid point deflections vs layer thickness effect k for steel face sandwich plates.

As can be seen from the Figure 5, the maximum deflection value of the sandwich plate decreases as the face layer thickness increases.

The elasticity modulus of the face layer is much higher than that of the core layers. So the strength of the core layer to the distributed load is very low compared to the face layer. For this reason, as the face layer's thickness increases and the core layer's thickness decreases, the sandwich plate's mid point deflection will decrease.

A total of 55 problems (11 models for each 5 core materials) have been considered to investigate the Layer Thickness Effect (k) and Core Material Effect (C) by selecting the face material as aluminum. Mid point deflections vs layer thickness effect (k) for uniformly loaded square sandwich plates with the aluminum face are plotted in Figure 6 with different 5 core materials.

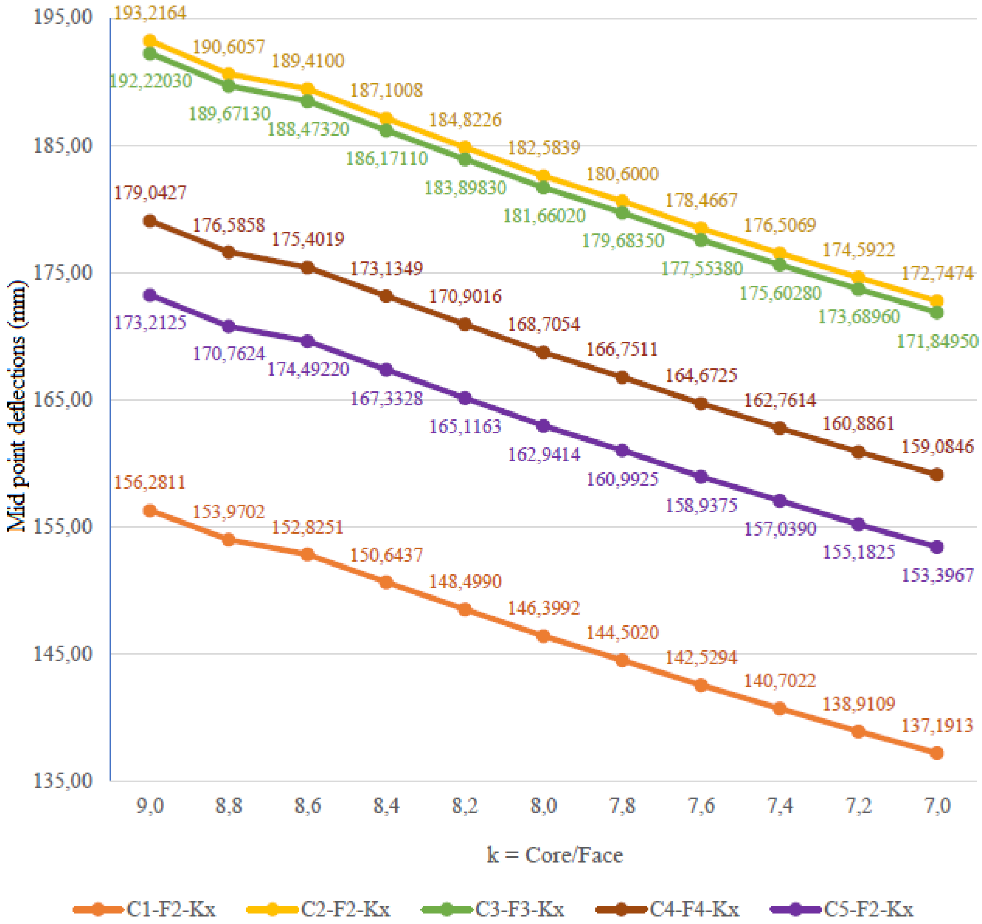

Fig. 6. Mid point deflections vs layer thickness effect k for aluminum face sandwich plates.

As can be seen from the Figure 6, the maximum deflection value of the sandwich plate decreases as the face layer thickness increases.

The elasticity modulus of the aluminum face layer is much higher than that of the core layers. So the strength of the core layer to the distributed load is very low compared to the face layer. For this reason, as the face layer's thickness increases and the core layer's thickness decreases, the sandwich plate's mid point deflection will decrease.

In Figure 7 mid point deflection according to the layer thickness effect k variation of sandwich square plates with both steel and aluminum faces is shown.

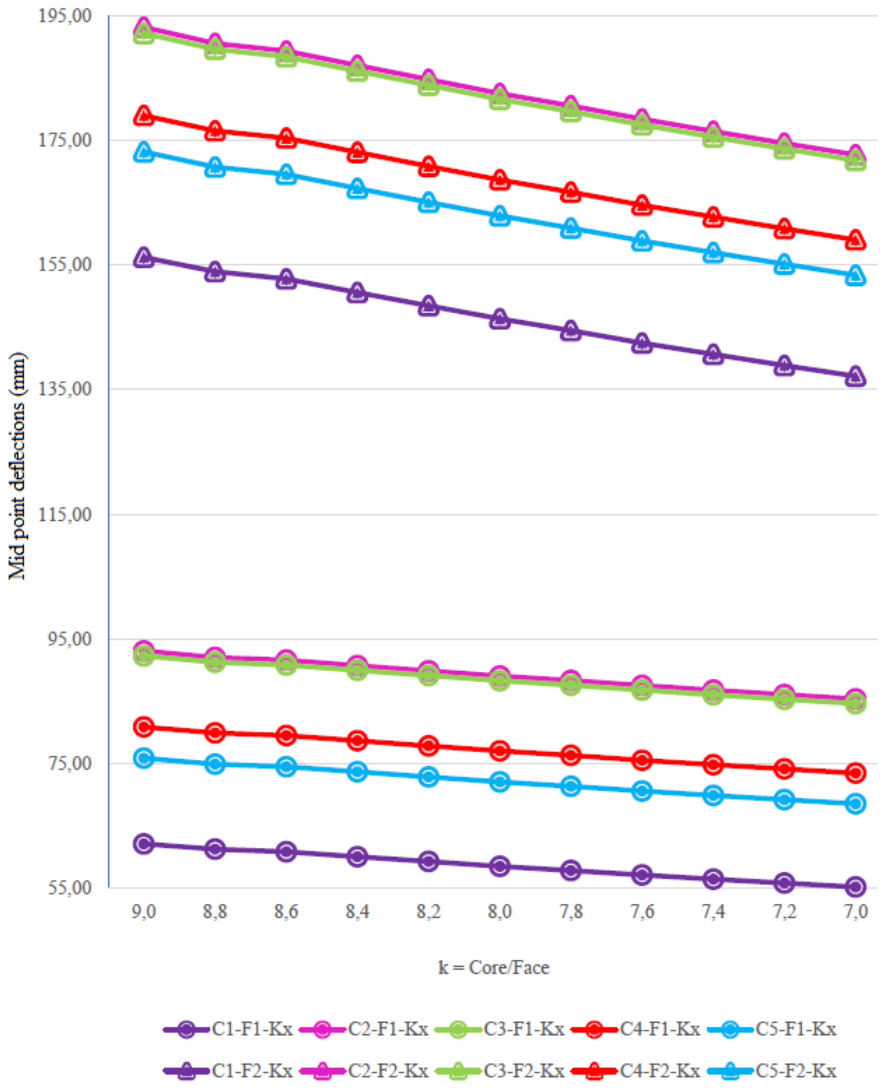

Fig. 7. Mid point deflections vs layer thickness effect k for steel and aluminum face sandwich plates.

As can be seen from the Figure 7, when the k value decreases mid point deflection also decreases. Also, as the elasticity modulus of the core layer material used in sandwich plates increases, the critical deflection that occurs at the midpoint of the sandwich plate decreases accordingly. As the elasticity modulus decreases, the critical deflection value occurring at the midpoint of the sandwich plate increases.

In the models that has steel face layer, mid point deflection varies between 55 and 93 mm dependent to core material. But these values are changes between 137 and 193 mm for aluminum face layered sandwich plates. The midpoint deflection value order according to the core material is similar in both face layer materials.

5. Conclusions

In this study, uniformly distributed loaded, 110 sandwich square plates simply supported on all four sides, consisting of different face and core thicknesses with different materials were investigated by using a finite element package program.

As the face layer thickness is increased and the core layer thickness is decreased, the maximum deflections that occurred at the midpoint of the plate were decreased (Figure 5-7).

When different materials are used, minimum midpoint deflection occurs in the model with the highest material modulus and a more rigid structure is obtained.

As the thickness of the face layer increases and the thickness of the core layer decreases, the bending resistance of the sandwich plate increases further. When the face layer is steel, the maximum mid-point deflection of the square sandwich plate changes between 93 mm and 55 mm approximately, but 193mm and 137 mm for the aluminum face layers. The mid point deflection is a parameter that depends on the material quality as well as the layer thickness.

As a result of the analysis, it was concluded that the face material is more dominant than the core material in the design of the uniformly distributed loaded simply supported sandwich square plates with constant thickness, and the sandwich plates with higher face layer thickness are more rigid.

Acknowledgments

This study was derived from the master's thesis.

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