

## Failure Analysis of Low-density Polymer Foam Core Sandwich Structures under Three-point Bending Loading

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### Abstract

In this study, low-density polymer foam core sandwich beams, non-existent in the literature, having woven carbon/epoxy face sheets in different core thicknesses and specimen lengths were fabricated and then subjected to three-point bending tests. The bending behavior of the sandwich beams were scrutinized experimentally. The effects of both core thickness and specimen length were revealed. As the ratio of face sheet to core decreases, transferring of shear forces between the face sheets decreases and the face sheets also become weaker. Hence, the failure mode changes from core shearing to indentation and the sandwiches have become tendency to fail by indentation. The theoretical models available in the literature was also utilized to predict the failure mode and collapse forces. The results indicated that both analytical calculations and experimental findings are compatible with each other.

**Keywords:** Core shear, Failure mode, Indentation, Sandwich structures, Three-point bending

### Üç Nokta Eğilme Yükleme Altındaki Düşük Yoğunluklu Polimer Köpük Sandviç Yapıların Hasar Analizi

### Öz

Bu çalışmada, örgü dokuma karbon/epoksi yüzeylere sahip, literatürde yer almayan, düşük yoğunluklu polimer köpük çekirdek sandviç kirişler, farklı uzunluk ve çekirdek kalınlıklarında üretilmiş üç nokta eğilme testlerine tabi tutulmuştur. Sandviç kirişlerin deneysel olarak eğilme davranışları incelenmiştir. Hem numune uzunluğunun hem de çekirdek kalınlığının etkisi ortaya çıkarılmıştır. Yüzey tabaka kalınlığının çekirdek kalınlığına oranı azaldıkça, yüzeyler arasındaki kayma kuvvetlerinin transferi azalmaktadır ve yüzeyler de zayıflamaktadır. Bu yüzden, hasar modu çekirdek kayması hasarından batma hasarına doğru değişmektedir ve sandviçler batma şeklindeki hasara uğramaya meyilli olmaktadır. Hasar modunu ve çökme kuvvetlerini tahmin etmek için literatürde mevcut bulunan teorik modellerden de faydalanılmıştır. Sonuçlar, hem analitik hesapların hem de deneysel bulguların birbirleriyle uyumlu olduğunu göstermiştir.

**Anahtar Kelimeler:** Batma, Çekirdek kayması, Hasar modu, Sandviç yapılar, Üç nokta eğilme

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## 1. INTRODUCTION

Conventional industrial materials such as metals and their alloys have been replaced with stiff, strong and lightweight hybrid materials with growing and developing technology. A sandwich structure, belongs to hybrid material family, consists of two thinner face sheets bonded to a relatively thick core material with the aid of a matrix surrounding. The face sheets can be made of metallic sheets, fiber reinforced composites whereas the core can be made of metal or polymer foams, honeycomb, balsa wood, corrugated structures [1-2]. Fiber-metal laminates (FMLs) have also been used for face sheets [3]. Due to their high stiffness to weight ratio, good impact and fatigue resistance, sandwich composites have arisen as structural members in the fields of automotive, transportation, space and aviation, marine, sporting goods, and etc. [4].

The variations in constituent materials allow many researchers to investigate the effects of them on physical and mechanical properties of sandwich structures under different loading conditions. Therefore, the previous studies have mostly concentrated on the influences of different types of face sheets, thickness of both the face sheets and the core, type and density of the core, type of matrix material. For example high impact toughness and better insulation to heat and acoustic can be obtained by using aluminum (Al) foams [3, 5-7]. On the other hand, polymer foam cores can be used for weight critical application where high flexural rigidity is essential [2].

The sandwich constituent materials' properties, geometric dimensions and types of loading are affecting factors for the initiation and growing of failure modes. The failure of the sandwich structures may occur mainly due to the face yield, core shear, indentation, face sheet debonding, and face sheet wrinkling [8,9]. For instance, as the thickness ratio of face sheet to core ( $t/c$ ) decreases, the failure mode changes from core shearing to indentation due to the weakness of face sheet and the sandwiches have tendency to fail based on the indentation. On the other hand, the thicker cores provide more rigidity to a sandwich structure, and

it resist higher bending loads due to the increased moment of inertia. Therefore, there is a transition between the failure modes and the type of failure mode should be investigated [10].

Styles et al. [11] investigated the effect of core thickness (5 mm, 10 mm, and 20 mm) on deformation behavior of an Al foam core ( $230 \text{ kg/m}^3$ ) sandwich structure having thermoplastic composite face sheets under four-point bending. It was found out that the thinner specimens exhibited skin wrinkling and fracture, and some core cracking, and core crushing was seen in thinner foam cores while the thicker specimens failed due to core indentation. But it was concluded that the incidence of core indentation was eliminated by increasing the face sheet thickness. In addition, it was reported that increasing core thickness drastically improved the structural rigidity. Kabir et al. [12] investigated effect of three-point bending behavior of very thin (0,32 mm) Al face sheets that were constructed with 6 mm and 12 mm Al foam cores, respectively. Although very thin face sheets primarily yielded indentation failure, core shear failure was occurred in the case of using high strength face sheets. Jiang et al. [13] established an analytical model to predict the failure modes in terms of face yield, core shear and indentation. In order to verify the model, they used several sandwich designs with 10-20-30-40-50 mm thick Al foam core having 0.17 relative density and 0.5-3-6 mm thick Al face sheets, and subjected the sandwich specimens to the three-point bending tests. Although the proposed failure models were in a good agreement with experimental results for the sandwich structures having thick face sheets, the determination of the load carrying capacity and the analysis of the indentation failure mode required further improvements. Similar conclusions for polymer foam core/fiber reinforced face sheet sandwiches are existed in the literature. Lim et al. [14] fabricated sandwich panels with woven plain glass fiber epoxy prepregs and 10 mm thick PVC foam core. While face sheet thickness varied from 0.58 mm to 1.02 mm, core density changed from  $54 \text{ kg/m}^3$  to  $117 \text{ kg/m}^3$ . The increase in thickness of the face sheets caused a change in failure mode. Thinner facings tended to fail by face fracture, but as the thickness increased, it tended to core compression or shear yielding. On the other hand, due to the change of core density, an obvious change in failure modes was not observed.

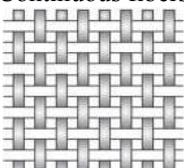
Sandwich design principles are based on the failure modes, and the collapse force that predicts the maximum load carried by the structure before failure. Therefore, examination of the failure behavior under a particular loading condition is essential to diagnose the type of failure. It also helps to designer to select more suitable constituent materials and geometry for the further sandwich constructions. In this study, three-point bending behavior of low-density polymer foam core carbon/epoxy sandwich beams were experimentally investigated considering the effects of core thickness and support span length. The findings were also compared with the analytical approaches available in the literature, and the primary failure modes of the sandwich beams were addressed.

## 2. MATERIALS AND METHOD

### 2.1. Materials

Sandwich specimens were constructed with woven carbon fiber fabrics and PVC foam core materials. Three different core thickness values (10 mm, 20 mm and 30 mm) were considered in the study. The fiber face sheets were bonded to the foam core by using polymer matrix. Table 1-3 provide physical and mechanical properties of sandwich constituents.

**Table 1.** The properties of carbon fiber fabric [15]

Property	Value
Fabric sketch and description	Plain weave, Woven, Continuous fibers 
Areal density	200 g/m <sup>2</sup>
Thickness	0.20 mm
Density	1790 kg/m <sup>3</sup>
Tensile strength	3800 MPa
Tensile modulus	240 GPa
Tensile strain	1.6 %

**Table 2.** Physical and mechanical properties of PVC foam core material [16]

Physical and Mechanical Properties	Value
Commercial name	Airex C70.48
Density	48 kg/m <sup>3</sup>
Thickness (mm)	10, 20, 30
Compressive strength	0.60 MPa
Compressive modulus	48 MPa
Tensile strength	0.95 MPa
Tensile modulus	35 MPa
Shear strength	0.55 MPa
Shear modulus	16 MPa

**Table 3.** Physical and mechanical properties of the matrix system [17]

Physical and Mechanical Properties	Epoxy resin	Hardener
Density (kg/m <sup>3</sup> )	1.13-1.17	0.96-1.00
Viscosity (mPa.s)	700-900	10-50
<b>The Matrix Properties</b>		
Density	1,18-1,20 kg/m <sup>3</sup>	
Flexural strength	110-140 MPa	
Modulus of elasticity	3.2-3.5 GPa	
Tensile strength	70-80 MPa	
Compressive strength	80-100 MPa	

### 2.2. Manufacturing of Sandwich Specimens

Sandwich composites were manufactured by using vacuum bag method. At the start of process, the amount of matrix material was determined based on the total amount of fiber fabrics. Epoxy resin was used together with suitable hardener to prepare the matrix. Ratio of the hardener in the mixture was 25 wt. %. The mixture was stirred carefully to minimize voids which weaken the final product. Then, manufacturing of the sandwich panels were performed over an open mold by stacking the face sheets and the core with hand lay-up. For each face sheets, four plies of carbon fiber fabrics were stacked symmetrically with respect to sandwich neutral axis. During the hand lay-up, the structure was performed with care to prevent the formation of air bubbles. Because the shear forces transmitted between the face sheet and the core mostly depend on chemical bonding

of the layers. Figure 1 illustrates the schematic view of the sandwich manufacturing. As seen, the sandwich panel was enclosed by a sealant tape within a vacuum bag. The perforated release film and breather were used over the sandwich panel. The former allows passing of air bubbles from the structure, draining of excessive resin and ease of handling whereas the latter collects the excessive resin.

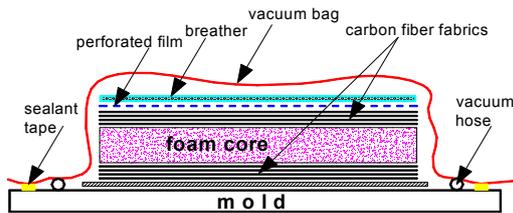


Figure 1. Schematic view of sandwich manufacturing

Lastly, sandwich panels were cured for 24 hours under vacuum atmosphere at room temperature.

The fabrications were made considering three different core thickness values and two different lengths. Designation of the sandwich samples were based on the considerations, and given in Table 4. For instance, a sandwich configuration of S1.T10.L20 has 10 mm thick foam core (T10), a length of 200 mm (L20) and named as sample one (S1). All sandwich configurations have identical face sheets and have 0.82 mm skin thickness.

After the sandwiches produced, their fiber volume fraction ( $V_f$ ) values were determined with burn off tests. As provided by McDonough et al. [18], the specimens taken from sandwich panels were burned in a muffle furnace at 600 °C for an hour. Then, according to weight differences of fiber and matrix of face sheets before and after the burn off tests, %  $V_f$  values were calculated and given in Table 4. The findings are consistent since the results slightly change from 49.2% to 51.8%.

### 2.3. Experimental Study

Sandwich specimens were tested under three-point bending loading. As given in Table 4, long and short length (L) specimens are available and the

tests were performed with two different support span lengths. Figure 2 demonstrates the schematic views of the three-point bending loading according to support span lengths (S). In this figure, t, c, and d are the thickness of face sheets, core and sandwich, respectively [19,20].

Table 4. Sandwich configurations and  $V_f$  values

Sandwich Configurations	Core Thickness (mm)	Length (mm)	$V_f$ (%)
S1.T10.L20	10	200	51,8
S2.T10.S25	10	250	51,8
S3.T20.S20	20	200	49,2
S4.T20.S25	20	250	49,2
S5.T30.S20	30	200	50,7
S6.T30.S25	30	250	50,7

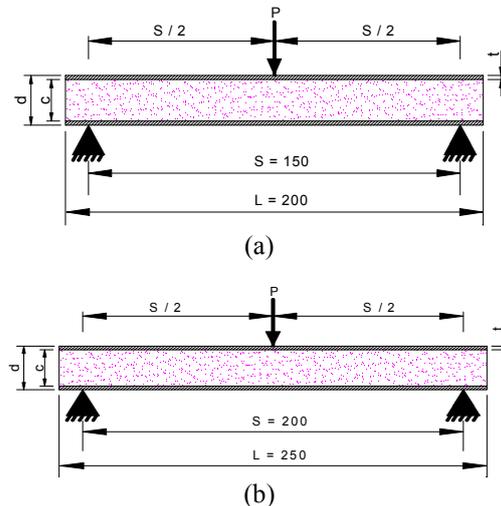


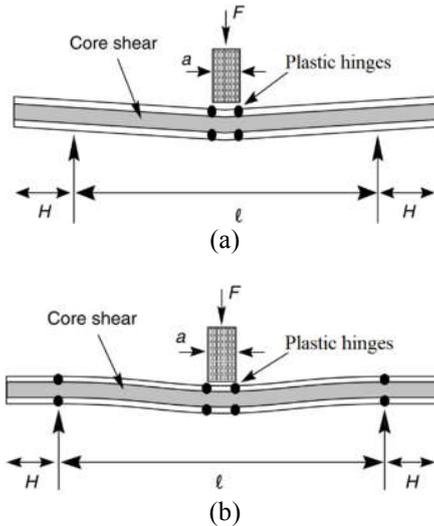
Figure 2. Schematic views of bending tests under a span length of; a) 150 mm, b) 200 mm (dimensions are in mm)

ASTM C393 [19] and ASTM D7249 [20] standards were utilized for bending tests and Instron universal testing machine was used. The testing speed was set to 2 mm/min.

### 2.4. Theoretical Study

Particularly two different failure mechanisms are introduced for polymer foam core carbon fiber sandwich structures since they are related to scope of the present study. These are core shear and indentation failure modes. Ashby et al. [8]

provided the basic principles of the failure modes based on the schematic representations as shown in Figure 3 and 4. In addition, core shear failure mode also has two different types called as Case I and Case II.



**Figure 3.** Failure mechanisms of core shear modes; a) Case I, b) Case II [8]

In case I, the formation of plastic hinges occurs at mid-span under the loading roller whereas in case II, the plastic hinges occur both at mid-span under loading roller and outer support rollers.

The collapse force,  $F$ , was defined by Ashby et al. [8] as the failure force by core shearing and it is calculated according to Equations 1 and 2 for the first and second cases, respectively.

$$F_I = \frac{2bt^2}{1} \sigma_y^f + 2bc\tau_y^c \left(1 + \frac{2H}{1}\right) \quad (1)$$

$$F_{II} = \frac{4bt^2}{1} \sigma_y^f + 2bc\tau_y^c \quad (2)$$

Where  $F_I$  and  $F_{II}$  are the collapse forces for case I and case II, respectively. And the notation  $b$ ,  $t$ ,  $c$ , and  $l$  denote the sandwich width, facing thickness, core thickness and span length, respectively.  $\sigma_y^f$  and  $\tau_y^c$  denote tensile yield and core shear yield strengths, respectively.  $\tau_y^c$  was obtained from manufacturer data sheet [16] whereas  $\sigma_y^f$  is

calculated based on the following analytical Equations 3-6 provided by Kaw [21];

$$\sigma_2^f = E_2 \cdot \epsilon_2^{ult} \quad (3)$$

Where,  $\sigma_2^f$  is transverse tensile strength of the facing material,  $E_2$  and  $\epsilon_2^{ult}$  are transverse modulus and transverse ultimate strain of the facing, respectively. Both of them are obtained in Equations 4 and 5. Here, facing yield strength ( $\sigma_y^f$ ) is taken equal to transverse tensile strength ( $\sigma_2^f$ ) since its value is smaller than the longitudinal tensile strength as expected and taken as the critical one.

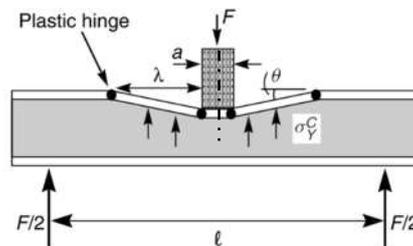
$$E_2 = \frac{E_f E_m}{V_f E_m + E_f (1 - V_f)} \quad (4)$$

$$\epsilon_2^{ult} = \left[ \frac{d}{s} \cdot \frac{E_m}{E_f} + \left(1 - \frac{d}{s}\right) \cdot \epsilon_m^{ult} \right] \quad (5)$$

Where,  $E_m$  and  $E_f$  are modulus of matrix and fiber elements, respectively,  $\epsilon_m^{ult}$  is ultimate strain of the matrix.  $d/s$  which is the fiber diameter to fiber spacing dependent upon  $V_f$  and it was defined by Kaw [21] for circular cross-sectional fiber with square array orientation as follow (Equation 6);

$$\frac{d}{s} = \left(\frac{4V_f}{\pi}\right)^{1/2} \quad (6)$$

Figure 4 presents the schematic view of the indentation failure mode. In this kind of failure mode, the formation of plastic hinges occurs on top facing of the sandwich structures at both under the loading roller and adjacent to it. In this figure,  $a$  denotes loading roller diameter,  $\lambda$  is the wavelength. The collapse load,  $F$ , for indentation failure was defined by Equations 7 and 8 [8].



**Figure 4.** Indentation failure mode [8]

$$F=(2\lambda+a)b\sigma_y^c+\frac{4.M_P}{\lambda} \quad (7)$$

$$M_P = (b.t_f)/4 \quad (8)$$

However, the analytical model for the indentation provided by Ashby et al. [8] did not consider the span length during finding the collapse failure force of the sandwich panels. Therefore, a different model provided by Steeves and Fleck [22] was also used (Equation 9) for evaluation of the indentation failure load,  $P_i$ . The model given by Steeves and Fleck [22] also considers the span length.

$$P_i=bt_f\left(\frac{\pi^2\sigma_c^2E_frd}{3L}\right)^{1/3} \quad (9)$$

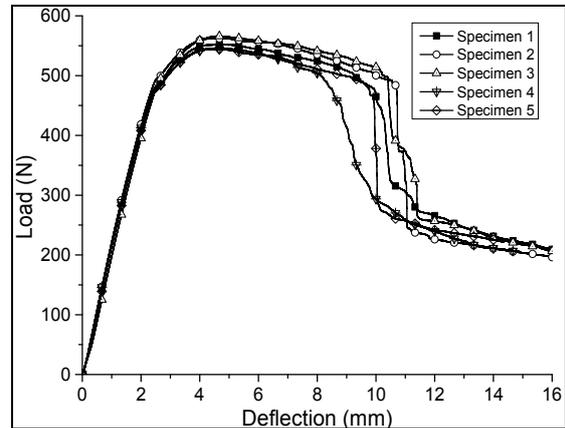
### 3. RESULTS AND DISCUSSION

#### 3.1. Three-point Bending Test Results

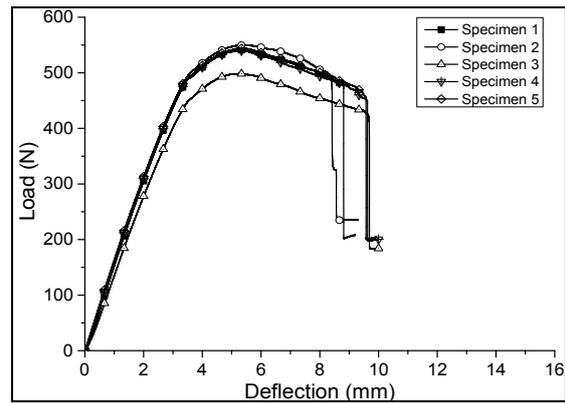
The sandwich samples given in Table 4 were subjected to quasi-static three-point bending loading. Each sample was tested with five replications to verify consistence of the results. The raw data in terms of load and deflection were obtained from the testing machine software and then plotted for each configuration. In Figures 5-7, the load-deflection curves of the sandwich specimens were presented based on sandwich length and the core thickness, respectively. The maximum bending load values of sandwich beams carried before failure are given in Table 5. Standard deviations are also given in the last column of the table.

As seen from the figures, the sandwich specimens showed a linear increase in the slope of bending force/deflection, and then a nonlinear and gradual increase of the slope was continued up to a maximum point of the force. The sandwiches apart from S1.T10.L20 and S2.T10.L25 configurations were failed with a sudden drop after the bending force value was reached to the maximum. However, for the sandwiches having 10 mm thick core, a downward slope, which starts at the maximum point up to sudden drop of the force, was observed.

In Figure 5(a), the bending load was carried with a small decreasing slope between the approximate deflection values of 4 mm and 10 mm. At this interval, fibers and matrix failures were initiated. But, the load was carried by the upper face sheet, and there was core crushing between the facings. Lastly, a sudden drop in force was observed due to upper face sheet compressive failure at a deflection of ~10 mm. In the case of long-length specimens, presented in Figure 5(b), similar behavior was observed but the decreasing slope between the maximum point and initiation of sudden drop of the force is higher compared to that of short length specimens. This is due to the long support span length of the specimens.



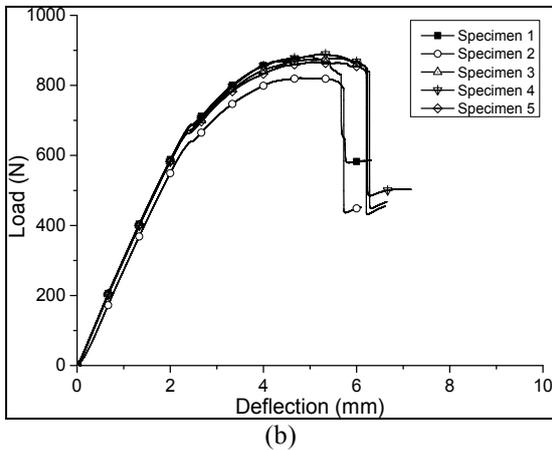
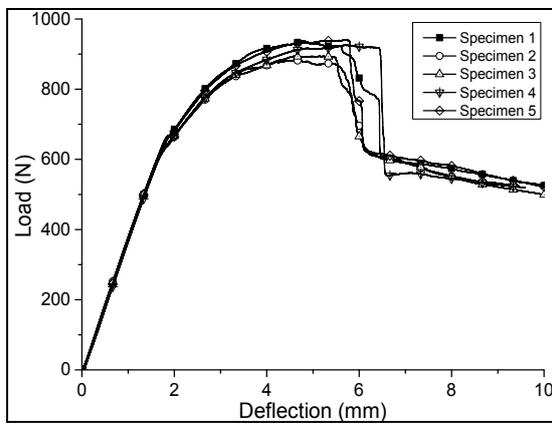
(a)



(b)

**Figure 5.** Load-deflection curves of 10 mm thick core sandwich specimens having a length of; a) 200 mm, b) 250 mm

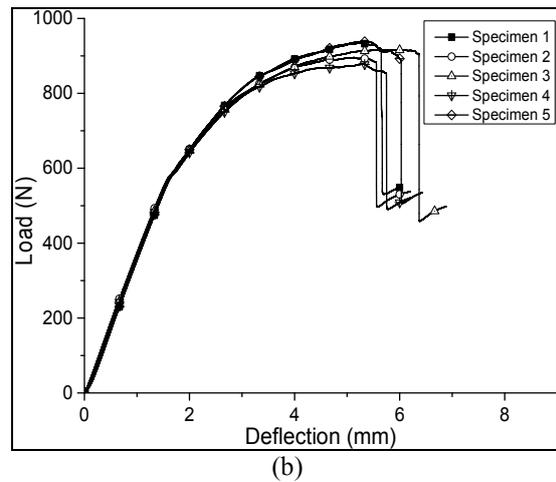
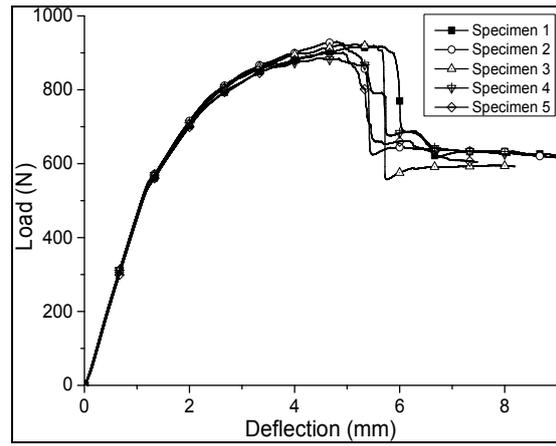
Although the deflection between the end of linear increase of the slope and the maximum point of the bending force was small, in the case of 20 mm thick core sandwich panels, the amount of specimens' deflection was found higher as shown in Figure 6. And drop of the bending force occurred suddenly after the force was reached to the maximum. Initiation of the sudden failure was approximately 6.29 mm (Figure 6a) and 6.22 mm (Figure 6b) for short and long specimens, respectively.



**Figure 6.** Load-deflection curves of 20 mm thick core sandwich specimens having a length of; a) 200 mm, b) 250 mm

As seen in Figure 7 the sandwiches' deflections between the end of the linear point and the maximum point are larger than both 10 mm and 20

mm thick core sandwich specimens. And the sudden drop in bending force occurred approximately at 5.59 mm deflection for short specimens (Figure 7a) whereas it was 5.75 mm for long specimens (Figure 7b).



**Figure 7.** Load-deflection curves of 30 mm thick core sandwich specimens having a length of; a) 200 mm, b) 250 mm

In all figures above, the initial stiffness of the short specimens are obtained higher than that of longer specimens. In addition to that as presented in Table 5, load carrying capacities of the long-length specimens decreased due to the increased support span length under three-point bending tests as expected [23].

**Table 5.** The maximum bending loads of sandwich configurations before loading

Sandwich Configurations	Max. Bending Load (N)	Std. Dev.
S1.T10.L20	554,36	8,76
S2.T10.S25	535,07	18,38
S3.T20.S20	916,15	23,56
S4.T20.S25	867,73	24,31
S5.T30.S20	911,99	15,59
S6.T30.S25	912,95	23,04

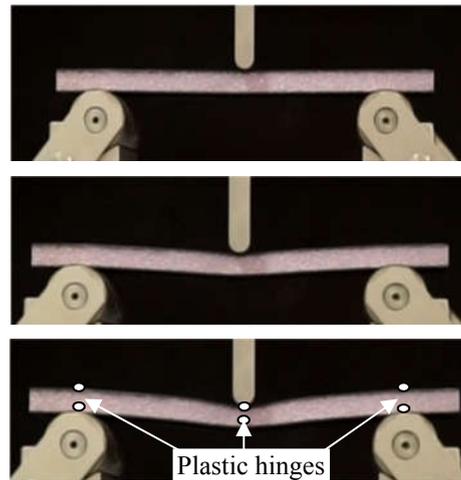
**3.2. Examination of Failure Behaviors**

Although all sandwich configurations initially show a linear increase in bending force up to a certain point, the non-linear portion of the force increment strongly associated with the change of failure behavior due to the increase of core thickness. Because Bezazi et al. [24] stated that the nonlinear behavior depends upon the foam core properties under the effect of core shearing forces and/or indentation.

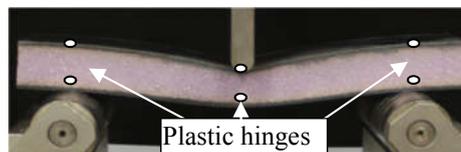
In order to decide the failure modes of the sandwiches, images of the bending behavior of the specimens were captured periodically by a camera during three-point bending tests. For instance, as presented in Figure 8, the time-dependent bending behavior of S1.T10.L20 was monitored progressively. This provided very similar behavior to core shear mechanism of case II as given previously in Figure 3. A similar behavior was also observed for S2.T10.S25 sandwich beams. As discussed in the literature [8], the failure was developed due to core shear since the most portion of the collapse force was carried by the core material as the sandwich specimens were exposed to transverse shear forces. Figure 9 shows the failure of S3.T20.L20 sandwich configuration that looks like as core shear followed by the indentation whereas Figure 10 shows the indentation failure of S5.T30.L20 sandwich configuration.

The collapse forces of the sandwich configurations were predicted with the aid of theoretical equations mentioned in the Section 2.4, in Materials and Method. The calculated results (Theo. Load) are given in Tables 6-8 comparatively together with

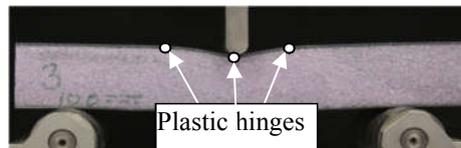
experimentally (Exp. Load) obtained results. In the case of 10 mm thick core sandwiches the differences are 1.79% and 3.51% for the short and long length specimens, respectively. For 20 thick core sandwiches, indentation failure models were applied and according to Ashby [8] model, 4.31% and 10.13% difference are found for short and long length specimens, respectively. However, according to Steeve and Fleck [22] model, when the effect of span length is considered, the differences are obtained 9.96% and 13.63% for short and long specimens, respectively. In the case of 30 mm thick core sandwiches, the differences are obtained as 4.47% and 4.36% for Ashby [8] model as this is 3.63% and 5.94% for Steeve and Fleck [22] model for short and long specimens, respectively.



**Figure 8.** Progressive representation of failure behavior of S1.T10.S20



**Figure 9.** Failure behavior of S3.T20.L20



**Figure 10.** Failure behavior of S5.T30.L20

**Table 6.** The collapse forces of 10 mm thick core sandwiches

Sandwiches	Exp. Load (N)	Theo. Load (N)
S1.T10.L20	554.36	564.31
S2.T10.S25	535.07	553.85

**Table 7.** The collapse forces of 20 mm thick core sandwiches

Sandwiches	Exp. Load (N)	Theo. Load (N)	
		Ashby [8]	Steeve and Fleck [22]
S3.T20.L20	916.15	955.67	824.83
S4.T20.S25	867.73	955.67	749.41

**Table 8.** The collapse forces of 30 mm thick core sandwiches

Sandwiches	Exp. Load (N)	Theo. Load (N)	
		Ashby [8]	Steeve and Fleck [22]
S5.T30.L20	911.99	952.76	945.13
S6.T30.S25	912.95	952.76	858.71

#### 4. CONCLUSION

In this study the bending behavior of very low-density polymer foam core carbon/epoxy sandwich beams were investigated and their failure analysis were made. The experimental results are in a good agreement with theoretically obtained results. The following conclusions can be drawn from the study;

- While 10 mm thick core sandwich beams failed due to core shearing, failure mode of thick core sandwiches changed from core shearing to indentation.
- As the face sheet-core thickness ratio ( $t/c$ ) decreases, the sandwich structures highly resist bending but fail based on the indentation failure mode.
- Especially, 30 mm thick core sandwich specimens approximately carried the same bending load compared to that of 20 mm thick core due to indentation. Because face sheets, load carrying members of a sandwich, become

weaker. In addition, the transferring of shear stress throughout the core decreases.

- As stated by Daniel et al. [9] indentation creates concentrated loads on the structure which is a serious problem for sandwich design. Therefore, there should be a thickness limit of the core in order to avoid indentation.

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