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Finite-element analysis of EPP foam core/self-reinforced PP sandwich structures

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In this study, fully recyclable and elastic–plastic deformable sandwich panels were developed by considering the mass production requirements, as well as the lightweighting needs of the automotive industry. Expanded polypropylene (EPP) foam core and self-reinforced polypropylene (PP) thermoplastic composite face sheets were selected to produce sandwich panels. Three-point bending experiments were performed to obtain the flexural behavior of the sandwich panels. Finite-element analysis (FEA) of the sandwich beams was carried out and confirmed by experimental results. Three different EPP foam cores with densities of 65.7, 36.5 and 27.0 kg/m^3 were used. The FEA models were built in the Abaqus commercial software in three-dimensional (3D) space, and analyses were performed using 3D elements. The crushable foam material model was selected for FEA from the Abaqus material model database to obtain the best correlation with the foam compression test results. The force–displacement results of the three-point bending FEA results excellently correlated with the experiments. In three-point bending experiments of the sandwich panels, elastic–plastic deformation of the core with indentation failure was observed. The lowest-density foam core sandwich beam showed the highest deformation and energy absorption performance. Also, deflection recovery was observed after load removal for all sandwiches.

Notation

D_1 density (65.7 kg/m^3)
D_2 density (36.5 kg/m^3)
D_3 density (27 kg/m^3)
R^2 Pearson's correlation coefficient
S von Mises stress (MPa)

1. Introduction

Foam materials with a cellular structure are capable of being highly deformed under a constant load. This feature gives these cellular structures the ability to absorb shock and impact energy.[1,2] Thanks to this ability and their low density, they are widely used in crashworthy passive safety parts, particularly in the automotive, aerospace, naval and construction industries.[3] Due to carbon dioxide (CO_2) emission regulations, automotive manufacturers accelerated their vehicle weight-reduction efforts in recent years. In addition to these regulations, manufacturers should not neglect to ensure the safety of passengers and drivers in the event of accidents and crash due to increased passenger and pedestrian safety criteria. Therefore, foam material with a cellular structure, particularly expanded polypropylene (EPP) foam material, which has low production cost and density, has been the most preferred material of automotive manufacturers in the production of crash-resistant structures.[4–6] Another superior advantage of EPP foams is that they are fully recyclable materials. EPP foam material is often used as padding material in the interior front body area, front and rear bumper beam systems and side door panels. Due to their superior properties of having high specific flexural stiffness, high buckling resistance and high natural frequencies, the use of sandwich structures is rapidly becoming popular in the automotive industry. These structures are produced by placing a thick and lightweight core material between two thin and stiff sheets. The role of the thin face sheets is carrying the in-plane and bending loads, while the thick core part carries the shear loads.[7–10] Compatibly with the EPP foam material used in the core, the facial sheets should also have shock resistance. Therefore, self-reinforced polypropylene (SRPP) composite plates, which have been introduced in recent years, provide a significant advantage with their high toughness, 15–20% failure strain and low price, compared with those traditional fiber-reinforced composite plates.[11–14] Both the reinforcement and matrix phase of the self-reinforced materials consist of the same material. Thus, these structures are also called as homocomposites.[15] In addition to these properties, SRPP materials, just the same as EPP foam materials, are fully recyclable materials.

It would be appropriate to examine the mechanical behavior of polymeric foam materials subjected to a compression load in three main parts. This typical stress–strain behavior under compression loading of polymeric foams is shown in Figure 1. The first part of the curve is the linear elastic region, the second is the plateau region and the third is the densification region, where the density and the carried loads increase. The linear elastic region is the part in which the cells within the structure exhibit impermanent bending and buckling deformations. The plateau region is the part in which the strain is significantly increased despite the slight increase in load. The use of foam materials as very favorable

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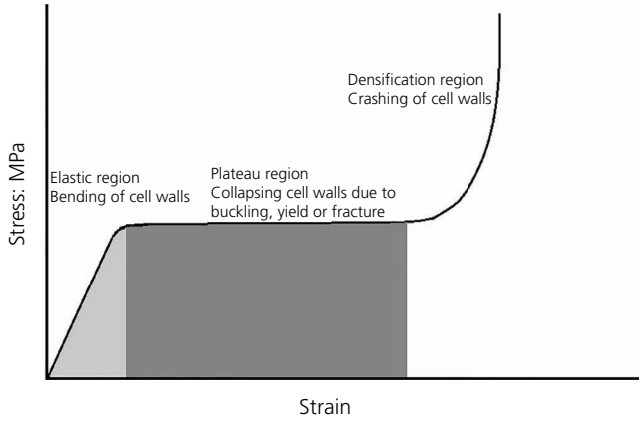


Figure 1. Typical polymer foam compression stress–compression strain behavior

energy-absorbing structures is caused by the deformation behavior in this region. In this region, the foam materials perform large deformations under an almost constant load. After large deformations, there are not enough spaces inside the cells, and deformed cell walls lap on each other, and the foam material behaves the same as a solid material.[16–18]

This mechanical behavior, together with the low density of the foam material, has been a critical study object that has attracted the intense attention of researchers. In particular, significant studies have been carried out on EPP foam in recent years. Sopher and Granthen[19] presented in their research on foams used in automotive interior parts that EPP foam has many advantages over other competing foams. Sadighi and Salami[20] investigated the mechanical behavior of EPP foam material under a low-impact compression load experimentally and numerically using the Abaqus software. In their study in which two different foams were examined together with EPP foam, they experimentally tested the thickness effect on the energy absorption capability of structures, and they carried out finite-element analyses (FEAs) by using the Abaqus software and examined the concordance of experiment–analysis results. Reyes and Børvik[21] studied the quasi-static behavior of the crash part, where extruded polystyrene (PS) and EPP foams with different densities were used as cores. They experimentally tested the performance characteristics of foam materials placed between two thin steel plates under quasi-static compression test and compared the results of the structures. As a result of their research, they showed the advantages of two foams compared with each other for different purposes such as energy absorption, reduction of load and back-plate displacement. Reyes and Børvik[22] also studied the same structures to investigate their energy absorption capabilities with their low weight under low-velocity impact. Andena *et al.*[23] experimentally investigated the compression behavior of varying densities of PS and polypropylene (PP) foams. They compared the experimental data with the material models in the literature and examined the microstructures of foams, considering the correlation with the measured mechanical properties.

In this study, lightweight, fully recyclable sandwich panels suitable for automotive industry mass production requirements were developed by using three different densities of EPP foam cores and nine-ply layered SRPP thermoplastic composite face sheets joined with ethylene/vinyl acetate copolymer (EVA) hot-melt adhesive. EPP foam cores with three different densities were subjected to compression tests. Three-point bending tests of sandwich panels were conducted according to the ASTM D 7250 standard.[24] Numerical models were created on the Abaqus/CAE software program to validate the material parameters. The crushable foam material model was selected for the EPP foam core, and material parameters were verified.

2. Materials and method

In this section of the paper, experimental and numerical steps are introduced in detail. In the experiment part, compression tests of EPP foams with three different densities were given. Then, three-point bending tests of EPP foam core with SRPP thermoplastic composite sandwich structures were explained. The crushable foam material model that was used for numerical simulations that define the EPP foam is described first. A numerical simulation model for the three-point bending test is shown in the last part.

2.1 Experiments

EPP foam specimens were extracted from the EPP foam block to obtain homogeneous density and avoid foam cell defects. Three different foams with variable densities were used for quasi-static compression tests. In this study, the used EPP foams had 65.7, 36.5 and 27.0 kg/m^3 densities, named D_1, D_2 and D_3, respectively. For compression tests, a cubic sample volume of 25 × 25 × 25 mm was chosen. Each EPP foam bead size was between 1 and 3 mm, and the bead shapes varied between spherical and ellipsoidal. Quasi-static compression tests were conducted using a Zwick Proline Z010 TH tensile–compression device, which has a 10 kN maximum load capacity and 0.01 N load sensitivity, 0.038 µm drive system travel resolution and ±2 µm positioning repetition accuracy. In this tensile–compression device, five compression tests for each foam type were performed at a 0.01 s^{-1} strain rate. Figure 2 shows the quasi-static test device and EPP foam specimens.

The quasi-static compression responses of D_1, D_2 and D_3 foams are given in Figure 3. A classical cellular material behavior (linear elastic behavior, plateau stress region and foam densification) was observed according to compression test results. Obtained results show that elastic region stress and plateau region stress increased with the density of foams. These test results were used to determine the correct parameters of the crushable foam material model for finite-element simulation. Sandwich panels were prepared by using EPP foam cores and two SRPP face sheets (Lankhorst Pure). The EPP foam cores with three different densities and SRPP (nine-ply thermoplastic layered composite) face sheets were joined by using hot-melt EVA adhesive (Bosch glue stick Black 2607001178). The three-point bending test specimen dimensions were 200 × 50 × 25 mm according to the ASTM D 7250 standard. The sandwich

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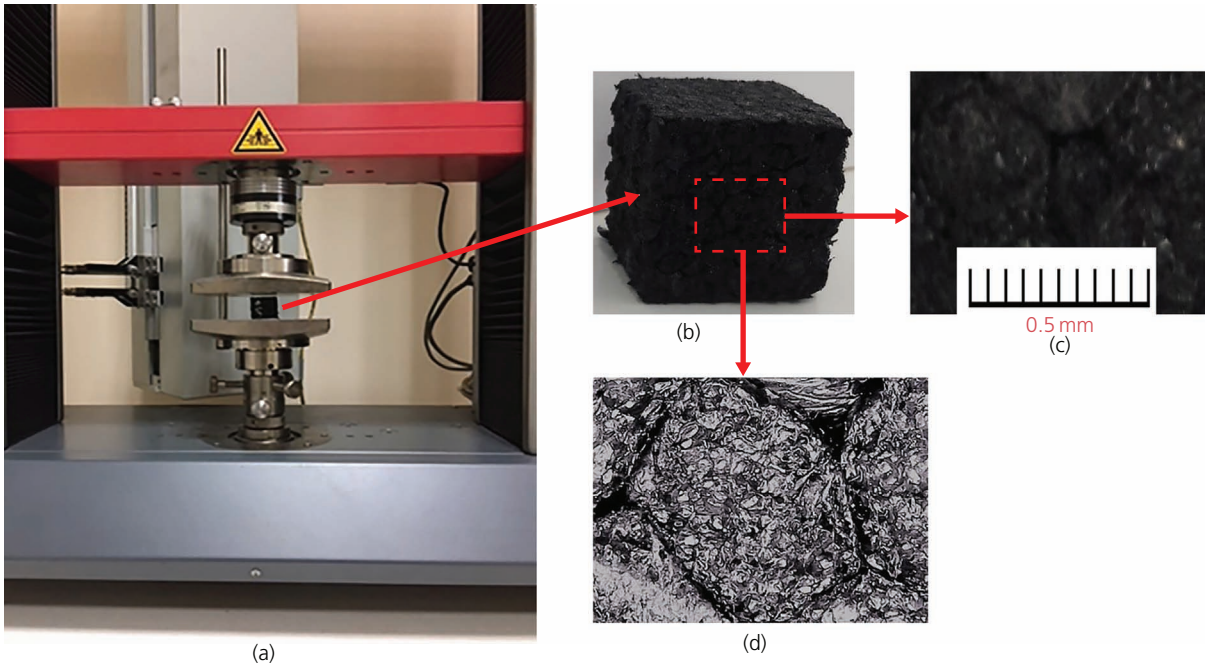


Figure 2. (a) Quasi-static compression test in a Zwick Proline Z010 TH tensile–compression device; (b, c) EPP foam specimen; (d) beat structure of the EPP foam

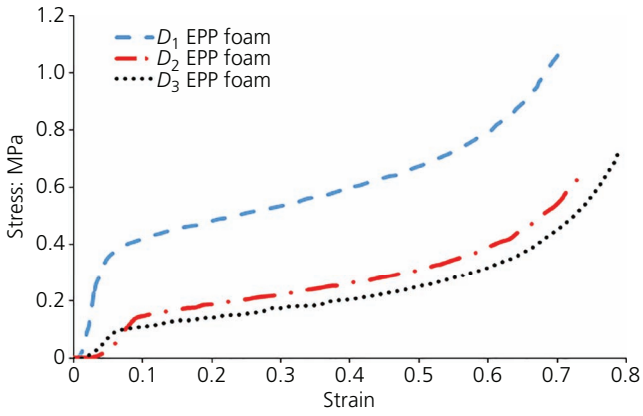


Figure 3. Compression responses of D_1, D_2 and D_3 EPP foams

material elements and preparation of the sandwich beam by application of hot melt adhesive on the surface of SRPP composite face sheet shown in Figure 4. Three-point bending experiments were conducted at a 20 mm/min cross-head speed and bending test fixture.

Figure 5(a) shows sandwich panel deformation during a three-point bending experiment. Figure 5(b) shows the developed sandwich panel deformation after the three-point bending experiments were performed. It was observed from the three-point experiments that even with large deflection of the specimen, the sandwich materials did not show any adhesive failure and debonding of core and face sheets. This indicates that the interface between the core and face sheets can be accepted as a perfect bonding.

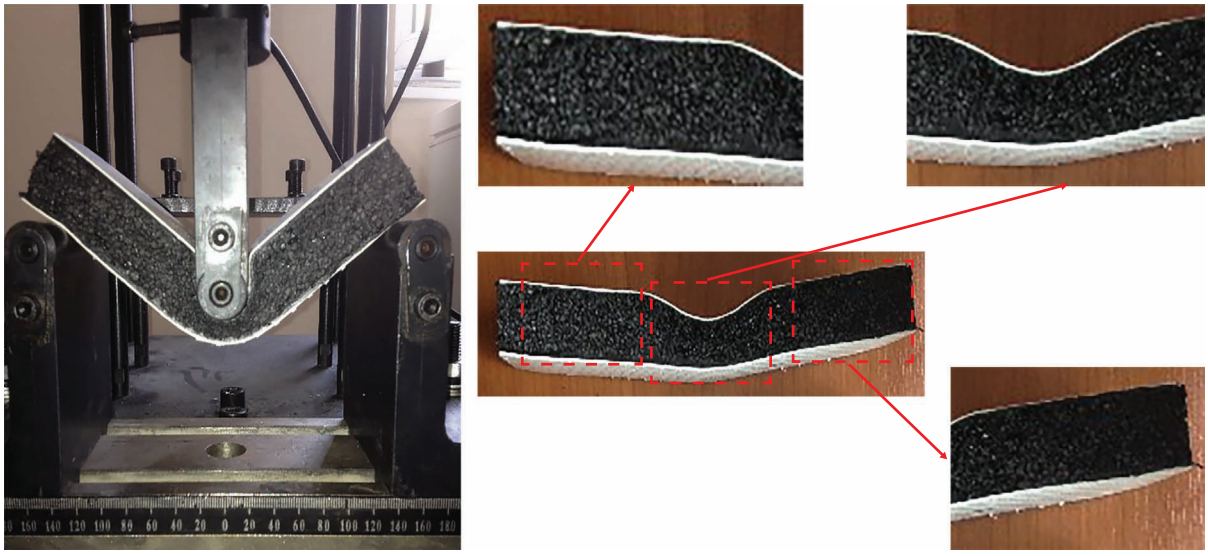
2.2 Numerical procedure

The Abaqus/CAE commercial finite-element program was used for three-point bending simulations. The Abaqus/Explicit solver was run for three-bending simulation of the sandwich specimens under the same conditions with the three-point bending experiments. The core material in the model was described using EPP foam properties, and the face sheet was described by using SRPP thermoplastic composite properties. The solid and shell geometries and finite-element meshes are created in the Abaqus/CAE software program. Three different finite-element models were obtained for each EPP foam (D_1, D_2 and D_3). The EPP foam core and SRPP face sheets were modeled as a deformable body with the pure Lagrangian domain. The three-point bending test fixture tip and supports were modeled as a rigid body. The interface between the EPP foam core and SRPP face sheets was described as a tie constraint. This means that the EVA adhesive between the core and face sheets was not included in the FEA. The reason for this assumption is based on the observation of test specimens, which did not show any debonding between the face sheets and the core or adhesive failure in all three-point bending experiments. The Abaqus/Explicit step time was chosen as 0.08 s. The general contact algorithm was selected for explicit analysis. Reaction forces and displacements were chosen with the history output request procedure. A 20 mm/min constant velocity was applied to the rigid tip. The finite elements used for the simulation model are given as follows for each component: for the EPP foam

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Figure 4. Components of EPP foam core SRPP sandwich beam and application of EVA hot melt adhesive on the SRPP face sheet for the production of the sandwich beam specimen



(a) (b)

Figure 5. Three-point bending experiments: (a) sandwich specimen deflection during an experiment; (b) sandwich specimens after tests

core, 3900 linear hexahedral elements of type C3D8R (C3D8R: an eight-node linear brick, reduced integration, hourglass control); for the SRPP face sheets, 1300 linear quadrilateral elements of type S4R (a four-node doubly curved thin or thick shell, reduced integration, hourglass control, finite membrane strains); and for rigid bodies, 608 linear quadrilateral elements of type R3D4 (a four-node three-dimensional bilinear rigid quadrilateral). Figure 6 shows the finite-element model of the three-point bending experiment of the sandwich panel.

A crushable foam model with isotropic hardening was selected as a material model for the EPP foam core. This material model is used for energy absorption structures. The material model consists of two parts: elastic and plastic parts. The elastic part of the response is only a linear isotropic elastic behavior. The plastic part of the model is the function of the von Mises circle in the deviatoric stress plane and an ellipse in the meridional stress plane. Readers can refer to the Abaqus material documentation for more details about the crushable foam model.[25] For this study, the isotropic hardening model was chosen. The uniaxial compression test results of each EPP foam were used to define the evolution of the yield surface (isotropic hardening). The linear elastic and plastic part coefficients of the model are given in Table 1 for each EPP foam. The linear elastic definition was used for SRPP face sheets according to material data sheets that were taken from the Lankhorst Pure company web site.[26]

3. Results and discussion

Three-point bending test and simulation results for EPP foam core SRPP thermoplastic sandwich structures are given in Figure 7.

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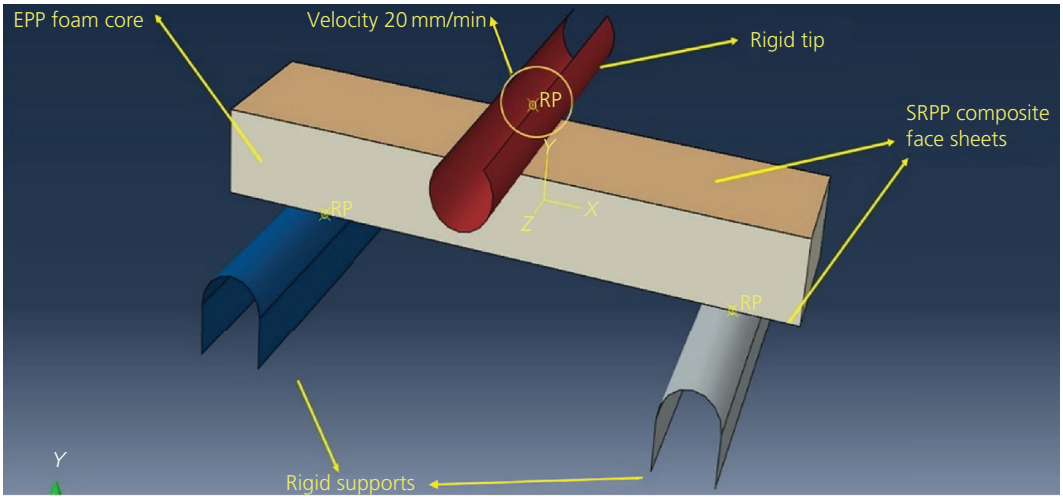


Figure 6. Finite-element model of the three-point bending EPP foam core sandwich panel

Table 1. Crushable foam material model parameters with isotropic hardening depending on variable densities

	Young's modulus: MPa	Poisson's ratio	Compression yield stress ratio	Plastic Poisson's ratio
D_1 foam (0.0657 g/cm^3)	15.0	0.4	2.1	0.375
D_2 foam (0.0365 g/cm^3)	12.5	0.4	2.5	0.350
D_3 foam (0.0270 g/cm^3)	7.5	0.4	2.4	0.380

In this figure, it can be seen that all deflection and deformation shapes are the same. These deformations contain both elastic and plastic deformations.

The force–displacement curves are given in Figure 8. In this figure, experimental and finite-element simulation results are compared with each other for all types of developed sandwiches. The force–displacement curves showed that the EPP foam core SRPP sandwiches' energy absorption was increased due to the rising foam density each foam density (D_1, D_2 and D_3). Figure 8 also shows that the FEA results perfectly matched with the experiments for all foam densities when implemented the crushable foam constitutive model for EPP foam core. Pearson's correlation coefficient R^2 was calculated to be higher than the 0.95 value for all finite-element simulation and experimental results. This means that an excellent correlation between three-point bending tests and FEA was obtained.

The self-reinforced, nine-layered PP face sheets did not show any damage, and deflected sandwiches sprang back and released elastic deformations after the load removal. Figure 9 shows the final shapes of the sandwiches after the three-point bending experiments. It was observed that the developed sandwich panels recovered most of the deformations after load removal.

The sandwich deformations occurred due to the indentation of the test fixture loading tip. The deformation levels are dependent on the core density. This means that a lighter core has more space for deformation. The three-point bending tip is indented to the surface and deforms the core. The obtained permanent deflections of the sandwich specimen at the midpoint of the front face were measured as 6.30, 3.58 and 2.20 mm for the D_1, D_2 and D_3 core densities, respectively.

The plastically deformable face sheets did not show any damage on the surface or the nine-ply face sheet sections. Figure 10 also shows that no core crack, debonding of face sheets or adhesive failure occurred in the developed sandwich panels. This behavior is based on the high tensile strength and considerable deformation ability of the expanded thermoplastic PP foam core material. Even with these large deformations, the sandwich panels remained monolithic. This behavior showed that the EVA adhesive interface was deformed together with the surface plates and core without any rupture or separation.

4. Conclusion

In this study, lightweight and fully recyclable sandwich panels were developed. Compression tests of EPP foams were conducted to determine the material behavior depending on the variable densities. Sandwich panels that consisted of SRPP face sheets and an EPP foam core were produced. In the sandwich, design and applied production techniques were selected to develop suitable sandwich material for mass production requirements of the automotive industry. The obtained observations and conclusions are summarized as follows.

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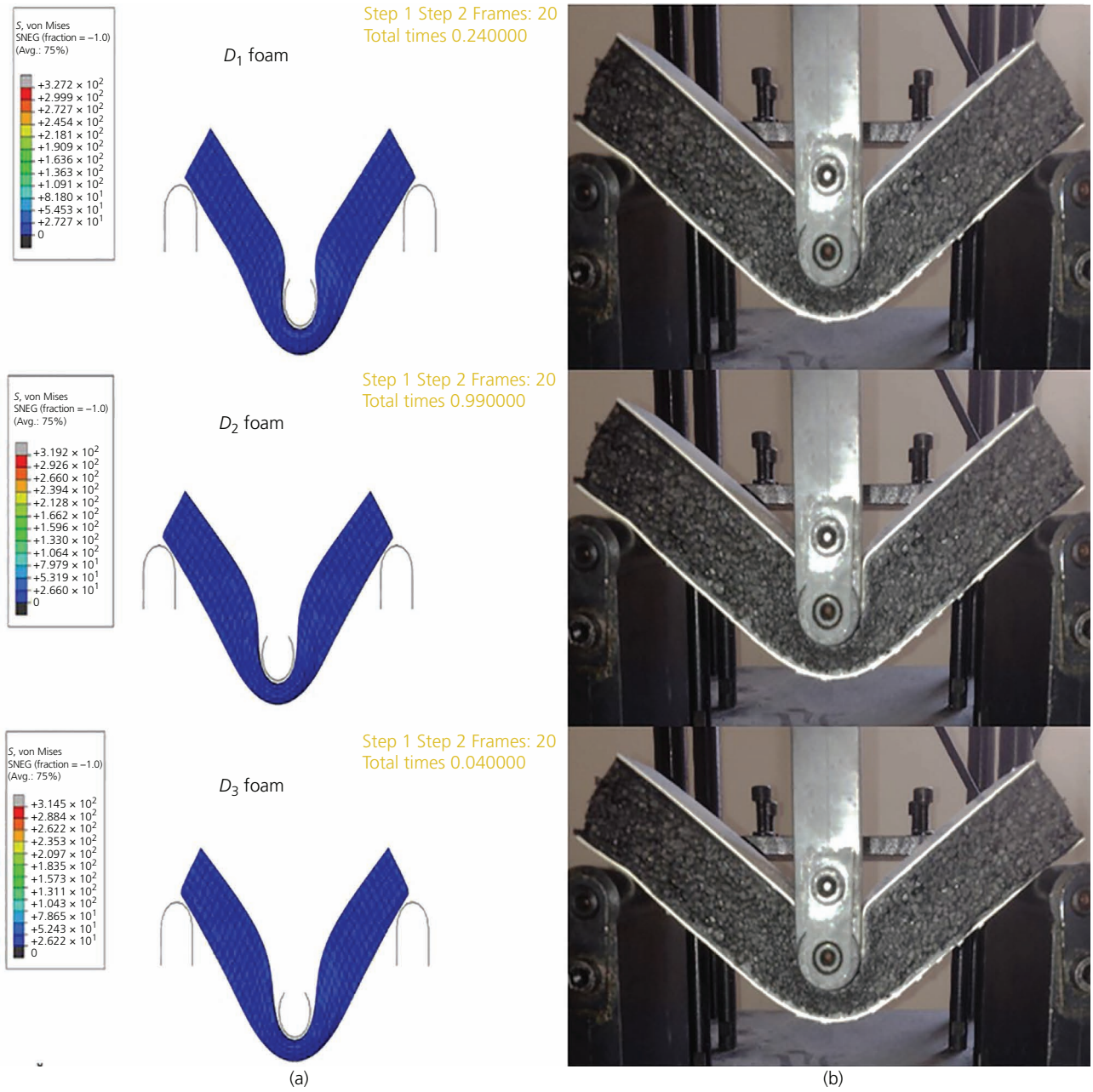


Figure 7. Three-point bending test and simulation results for each foam core sandwich panel: (a) deflected specimen shapes under maximum load in three-point bending finite-element simulations; (b) deflected specimen shapes under maximum loads in three-point bending experiments. SNEG, reference surface of the shell

- The EPP foam material model was selected as the crushable foam model. The material constants were also calculated by correlation of the model with the compression test results of the EPP foam core. The excellent agreement between the experimental and FEA load–deflection curves validates the crushable foam material model and calculated material parameters.
- The SRPP face sheets and EPP foam core sandwich panels showed plastically deformable damage behaviors. Neither debonding between the face sheets and foam core nor adhesive failure was observed during the large deflection of the sandwich beam.
- Indentation failures were obtained for all types of sandwiches. The amount of the indentation decreased in the sandwich beams with reducing EPP foam core density.
- No face sheet damage, crack or ply failure was obtained in the SRPP thermoplastic composite face sheets.

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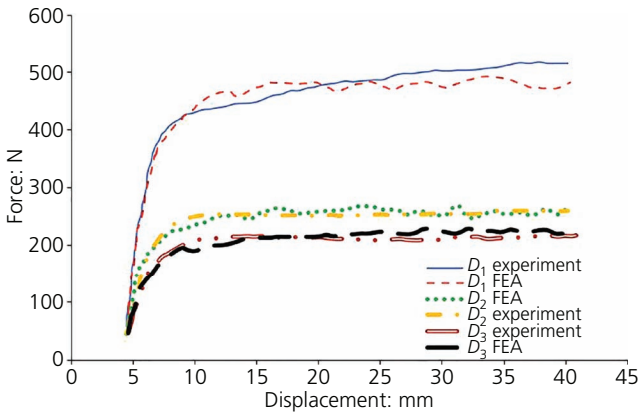


Figure 8. Force–displacement curves of three-point bending test and simulation



Figure 10. Permanent deformations of the sandwich beams after three-point bending experiments

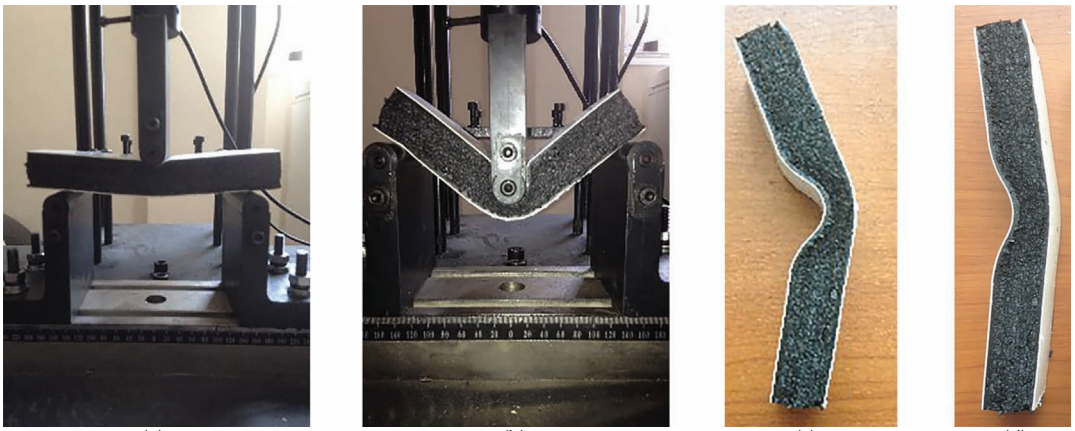


Figure 9. Elastic and plastic deformations of the developed sandwich panel: (a) starting loading for three-point bending; (b) deformation of the sandwich beam in the maximum loading condition; (c) tested sandwich shape right after the experiment at the freestanding condition; (d) recovering sandwich beam after 5 min later from the experiment at the freestanding condition

- No core crack or fracture was obtained. The only core failure was a foam cell crash.
- All developed sandwich panels demonstrated deflection recovery after load removal.

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