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Indentation of Foam-Based Polymer Composite Sandwich Beams and Panels Under Static Loading

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Foam core composite sandwich structures are highly susceptible to damage when subjected to localized loading. Therefore, thorough study of the role of factors such as face sheet thickness, indentor diameter value, and crosshead displacement rate in indentation events is important. The objective of the present work is to investigate experimentally and numerically the influence of these factors on the nonlinear static indentation behavior of sandwich beams and panels consisting of glass fiber/resin face sheets and PVC (polyvinylchloride) foam core. Static indentation tests are carried out on sandwich composite beam and panel specimens using steel cylindrical and spherical indentors, respectively. Numerical models are developed for simulating the mechanical response of sandwich structures subjected to localized indentation beyond the limit of elastic deformation in the foam core. In this relation, the *CRUSHABLE FOAM and the *CRUSHABLE FOAM HARDENING options in the ABAQUS finite element program system are used. The numerical analysis results demonstrate good agreement with experimental data. It is found that increasing the face sheet thickness and indentor diameter value leads to increase in the load (for a given displacement). It is shown also that the indentation behavior does not exhibit sensitivity to crosshead displacement rate over the conditions considered in the present work.

Keywords elastic-plastic behavior, finite element analysis, foam core sandwich composite structures, indentation, mechanical testing

1. Introduction

Due to the their high strength and low weight, sandwich structures based on strong composite face sheets bonded to a low density foam core are finding increasing use in the transportation industry and civil engineering (Ref 1). The basic advantage of the sandwich structures is that the overall bending stiffness can be increased considerably almost without increasing the weight of the structures. According to the sandwich concept, the face sheets form stress couple countering the external bending moments (i.e., the faces are loaded in a membrane state of stress), while the core works in shear and supports the faces against bucking or wrinkling. However, this state of stress of sandwich constituents can be completely destroyed when highly localized external lateral loads are applied. The localized loads usually lead to formation of a complex multiaxial state of stress in the vicinity of the load application area. Due to the low transversal stiffness, the local bending of the face sheet under localized loads induces a significant damage in the foam core which may result in a premature failure of the entire sandwich construction (Ref 2-6). Thus, much research efforts have been given to the problems associated with the mechanical response of foam core sandwich structures subjected to local loading.

The analytical solutions based on the elastic foundation analogy (Ref 7-14) can be divided into two groups:

(1) Solutions that use the Winkler foundation model. These are the simplest possible solutions and treat the core material (supporting the loaded face) as continuously distributed linear tension-compression springs. The stiffness of the springs is defined by the transversal foundation modulus. The most serious drawback of this group of solutions is that they do not account for the shear stresses at the face-core interface.
(2) Solutions account for both normal and shear stresses at the face-core interface give more adequate results for the local bending of the face sheet (Ref 12-14). These solutions are based on a two-parameter elastic foundation model (i.e., the shearing and transverse foundation moduli are used for characterization of the core material).

However, due to the fact that all of the above solutions are based on the assumption of linear elastic behavior of the constituent materials, not one gives a clear description of the onset and development of plastic (irreversible) strains in the sandwich structures. Therefore, the practical applicability of the results obtained using the Winkler approach is rather limited. A much more realistic approach is based on applying nonlinear continuum models. Using nonlinear models gives an explicit description of the irreversible failure of sandwich structures. However, the application of nonlinear models usually is related to use of finite element computer programs. Research work on constitutive modeling of foam plasticity is currently under active development. The latest achievements and results in this

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field are promptly included in the ABAQUS finite element code. Therefore, this code is particularly suitable for treating the problems associated with the foam core crushing in the vicinity of the area of external localized load application. It is not surprising that the ABAQUS code is frequently used for simulating the crushing behavior of structural foams (Ref 15-17).

Although much research already exists in the field of static indentation response of sandwich structures, new configurations are continually being introduced and need to be analyzed and certified.

The main purpose of this work is to investigate the nonlinear mechanical behavior of foam core polymer composite sandwich beams and panels subjected to static localized loading (indentation). Special attention is given to the influence of composite face sheet thickness, indentor diameter value, and loading rate on the indentation response. For this purpose, static indentation tests are carried out on various sandwich beam and panel configurations using cylindrical and spherical indentors, respectively. The indentation response of sandwich beams and panels is simulated by a nonlinear model developed on the basis of the ABAQUS program system. The foam model is calibrated using a stress-strain curve obtained by testing foam cylindrical specimens in uniaxial static compression. The predicted results are compared with the indentation test data to prove the accuracy of the finite element model.

In a perspective view, the results obtained from the present study can be used as a basis for further optimization of foam core sandwich structures with respect to their indentation performance at an early stage of the design process.

2. Static Indentation Tests of Sandwich Beams and Panels

Three sandwich configurations with thickness of the composite face sheets of 2.4, 4.8, and 7.2 mm were evaluated during the course of this research program. The sandwich configurations considered were fabricated with quasi-isotropic glass fiber reinforced plastic (GFRP) face sheets comprising Chomrat 19S3 (0°/90°) E-glass weaves impregnated with Jotun Vinylester 8550 resin. The quasi-isotropic configuration was chosen in order to avoid the introduction of the plies orientation as a further parameter in the numerical modeling procedure.

Closed cell PVC foam manufactured by Divinycell International (Lahom, Sweden) was used as a core material for the sandwich configuration investigated. The nominal density of this foam is 100 kg/m^3. In this article, this foam is referred to by its trade name, H100. The foam considered has a cell size of approximately 0.4 mm. The manufacturing process of the H100 foam consists of the mixing of the chemical polymer components together and the thermal expansion of the polymer mass in hot water. The H100 foam was supplied in the form of large plates with a thickness of 50 mm.

The sandwich panels were manufactured by means of vacuum infusion method. The E-glass fiber weave and the H100 foam core were assembled in a mold and sealed by a vacuum bag. The resin was infused by a pressure difference outside and inside the mold. Sandwich beam and panel specimens were cut out of the panels using a diamond blade saw. Any dust generated during the cutting procedure was removed using a compressed air supply. The in-plane dimensions of the specimens were 250 × 50 mm for beams and 250 × 250 mm for panels.

The static indentation tests were carried out in an INSTRON universal testing machine at room temperature (23 °C) as shown in Fig. 1 and 2. The sandwich specimens were supported by a stiff substrate to avoid the global bending during the indentation. The load was applied through steel cylindrical indentors for beams and steel spherical indentors for panels. To determine the indentor diameter effect on the indentation behavior, three indentor diameter values were used: 25, 50, and 75 mm.

The indentation tests were conducted at crosshead displacement rates of 2, 20, 20, 40, 60, 80, and 100 mm/min in order to investigate the rate sensitivity of the sandwich configurations considered. The sandwich beam and panel specimens were loaded centrally up to an indentation of 8 mm. The unloading was conducted in displacement control at a constant crosshead speed of 20 mm/min. Static indentation test setup is illustrated in Fig. 3.

The load-displacement response was recorded for both loading and unloading phases of the indentation testing. The instant value of the residual dent was measured during the unloading phase by monitoring the load. The displacement when the load dropped to zero was taken as the instant residual

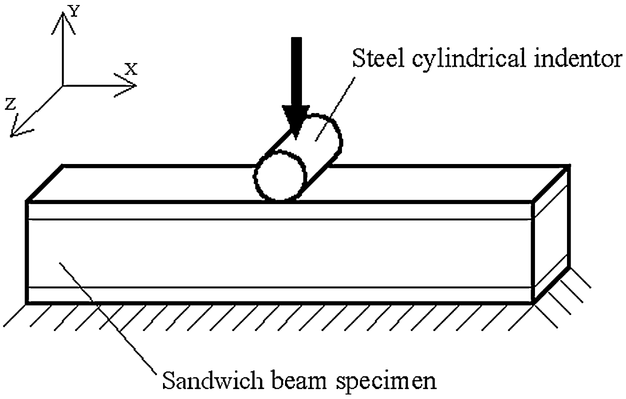

Fig. 1 Sandwich beam indentation test scheme

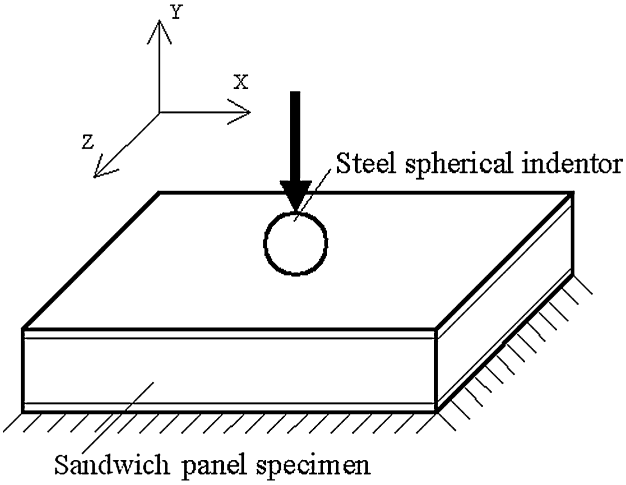

Fig. 2 Sandwich panel indentation test scheme

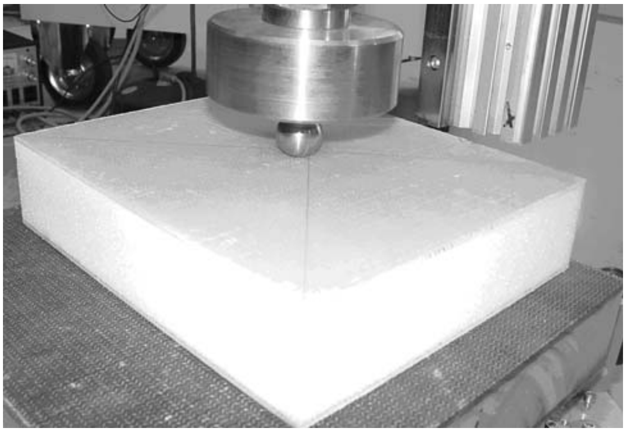

Fig. 3 Indentation test setup

dent magnitude. It should be noted that residual dent measurements were also conducted also immediately after the test by sliding a dial gage over the contact area between the face sheet surface and the indentor. The residual dent magnitudes measured in this way were slightly lower than those obtained during the unloading phase of the test. This finding was attributed to the relaxation effects in the crushed foam in the postindentation period.

Five sandwich specimens were tested for each experimental situation. A very good repeatability of the test results was obtained.

Experimentally obtained load-displacement diagrams for sandwich beam and panel specimens with the three different face sheet thicknesses using indentors with different diameters are reported in Fig. 4-9. As one can see, all the specimens tested exhibit generally nonlinear load-displacement responses. The linear elastic behavior is limited to relatively low values of the indentation. However, there are some substantial differences in the indentation behavior of beams and panels. For instance, following the initial linear elastic phase, the slope of the load-indentation traces of beam systems decreases with increasing indentation suggesting the occurrence of continuous degradation of the specimen stiffness (Fig. 4-6). In contrast, the load-indentation response of panel systems has three distinct ranges where different factors play the major role (Fig. 7-9). In range *OA*, the load-indentation diagram follows a practically linear elastic relationship. The second range *AB* is dominated by a decreasing overall stiffness of the panel system due to the crushing of the foam core. The slope of the load-displacement traces decreases with increasing indentation. However, at larger displacements (range *BC*), the slope increases indicating an overall panel specimen stiffness increase.

It can also be observed (Fig. 4-9) that increase in face sheet thickness leads to increasing the load (for a given indentation). The critical load (which corresponds to the beginning of the nonlinear section of the load-indentation) also increases on increasing the face sheet thickness. This peculiarity can be attributed directly to the increased local bending stiffness when using a thicker composite face sheet.

It should be specified that in the present study the critical load was determined as the load at which the initial linear elastic range of the load-displacement diagram ends. The gradual decrease in specimen stiffness seen in Fig. 4-9 makes this a slightly difficult task, especially for panel systems. The determination of the critical load is easier for beam systems where the foam core is visible throughout the indentation test. During the testing, by simultaneous observations of the lateral surface of the beam specimens and load-indentation response, it was found that the onset of foam crushing corresponded to the end of the initial linear elastic range of load-indentation response. Therefore, the load at the end of the linear elastic

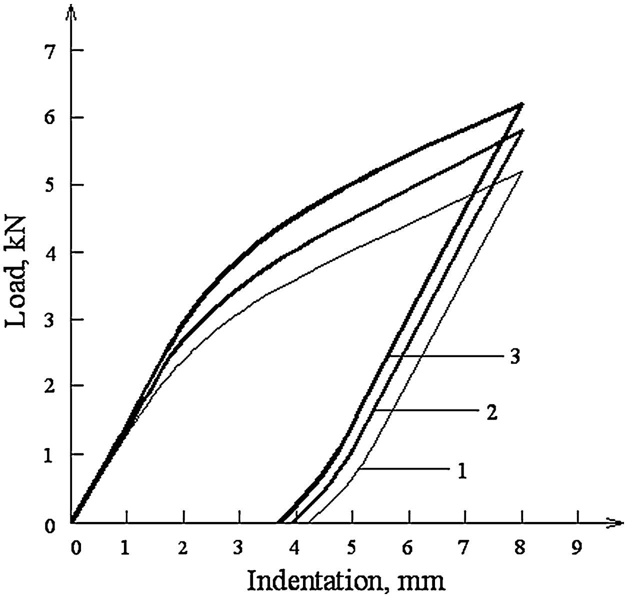

Fig. 4 Load-displacement responses derived from indentation test performed on sandwich beam specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 2.4 mm

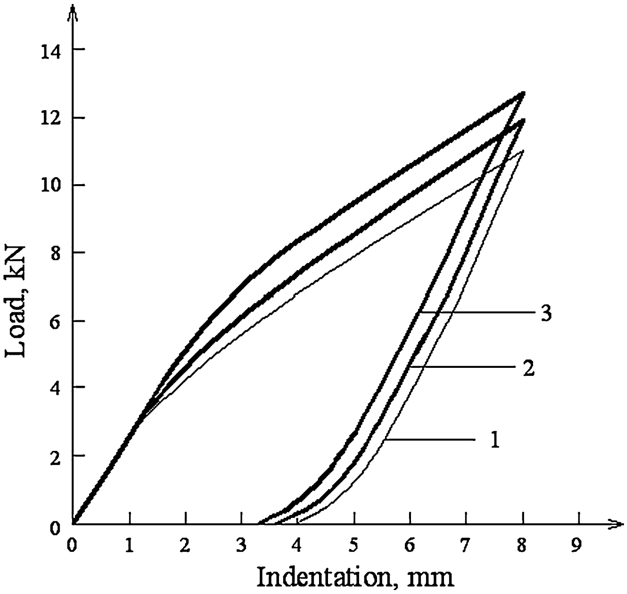

Fig. 5 Load-displacement responses derived from indentation test performed on sandwich beam specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 4.8 mm

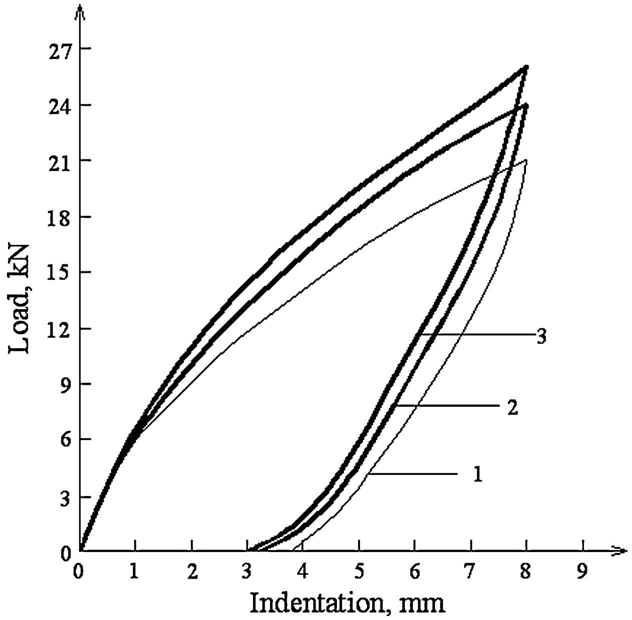

Fig. 6 Load-displacement responses derived from indentation test performed on sandwich beam specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 7.2 mm

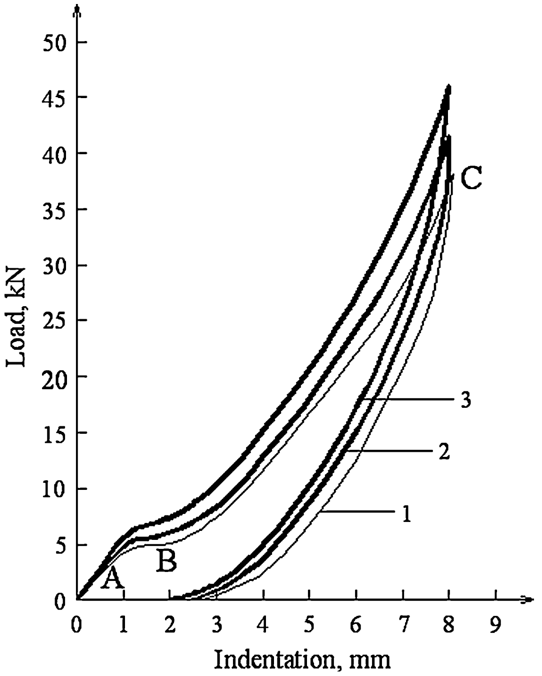

Fig. 8 Load-displacement responses derived from indentation tests preformed on sandwich panel specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 4.8 mm

range was regarded as the critical one. At small indentation magnitudes, it was observed on the lateral surface of beam specimens that foam crushing initiated in the zone immediately under the indentor. With increasing the indentation magnitude, the crushed zone first increased its size lengthwise (along the x-axis), due to the ability of the face sheet to distribute the load. At the final indentation magnitude of 8 mm, the length of the crushed zone along the x-axis was about three times greater than the indentor diameter.

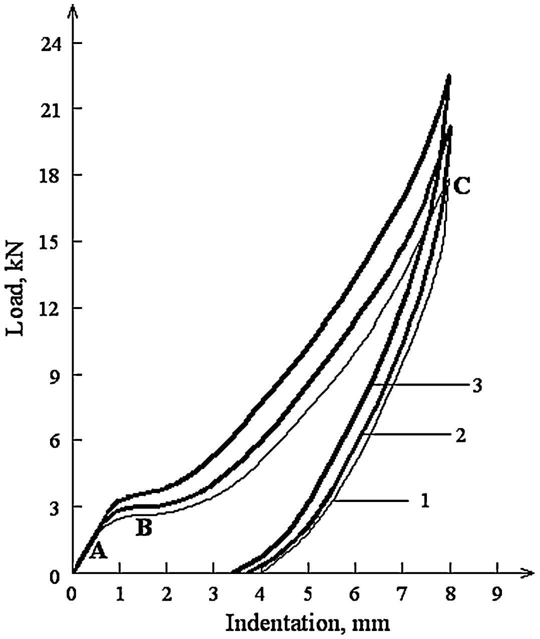

Fig. 7 Load-displacement responses derived from indentation tests preformed on sandwich panel specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 2.4 mm

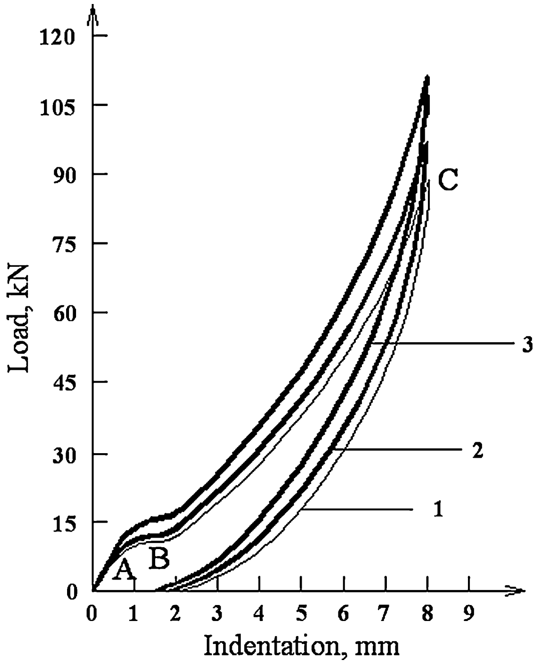

Fig. 9 Load-displacement responses derived from indentation tests preformed on sandwich panel specimens at a crosshead displacement rate of 2 mm/min using indentor diameters of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face sheet thickness is 7.2 mm

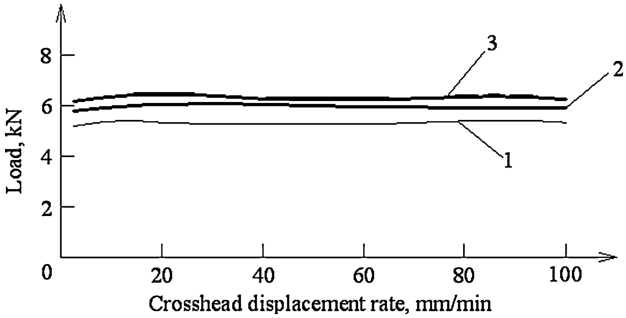

Fig. 10 The variation of the maximum load with crosshead displacement rate. The results are derived from indentation tests performed on sandwich beam specimens with indentor diameter of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face thickness is 2.4 mm

It was also observed that when using a thicker face sheet the length (along the *x*-axis) of the crushed zone increases due to the increased ability of the face to distribute the load. This effect was more pronounced for higher displacement magnitudes.

Sandwich specimens were subjected to postindentation visual inspection. No visible damage in the face sheet and face/core interface was observed. Therefore, in the finite element modeling, the face sheet was regarded as a linear elastic material and no face/core debonding was assumed. It should be mentioned that several indentation tests were carried out at indentation magnitudes higher than 8 mm. In this case damage in the face sheet in the contact area with the indentor was seen as "whitening" on the surface due to localized delamination and matrix cracking. However, such indentation magnitudes were not considered in this study.

The indented zone of the foam core was subjected to inspection after testing using a microscope. It was found that the structure of the foam in this zone is characterized by densification due to foam cell buckling and crushing. It was also found that the thickness of the skin in the indented area is not changed by the indentation.

Figures 4-9 indicate the fact that increasing the face sheet thickness leads to decrease in the instant residual dent magnitude. This finding can be explained in the following way. During the unloading phase of the indentation test the indented face sheet flexes back and pulls up the crushed and densified foam in the damaged zone under the indentor. Obviously, when the face is stiffer, the pulling effect is stronger which leads to decrease in the residual dent magnitude. Figures 4-9 also show that the decrease in the residual dent magnitude (when using a thicker face sheet) is more pronounced for panels compared to beams. This peculiarity can be attributed to the spatial work of panes, while the beams work in 2-D conditions. In this relation, it should be remembered that the influence of membrane stresses is more significant on the indentation behavior of panels compared to that of beams.

Figures 4-9 give information about the influence of indentor diameter magnitude on the indentation behavior of sandwich systems considered. As can be seen, the load increases on increasing the indentor diameter (for a given displacement). This can be explained by the fact that using a larger indentor diameter leads to formation of a larger contact area between the indentor and the face sheet.

Figures 10 and 11 show the rate sensitivity of the value of the maximum load (which corresponds to the maximum indentation value of 8 mm) for two of the sandwich systems investigated. It is clear that the maximum load values do not appear to exhibit any sensitivity to crosshead displacement rate. Similar observations were made when the rate sensitivity of the load-displacement responses of the sandwich configurations with face sheet thickness of 4.8 and 7.2 mm was evaluated, leading to the conclusion that the indentation behavior of sandwich systems investigated was generally rate-insensitive for the testing conditions considered here.

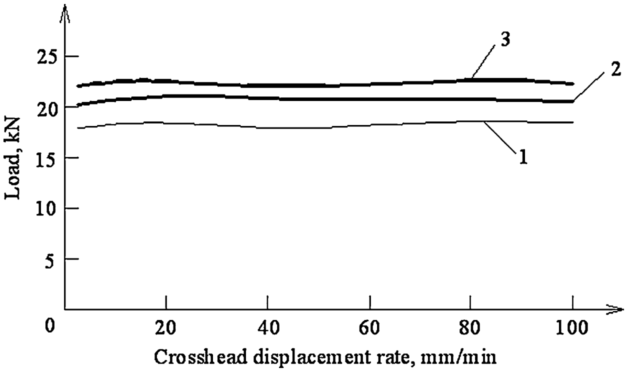

Fig. 11 The variation of the maximum load with crosshead displacement rate. The results are derived from indentation tests performed on sandwich panel specimens with indentor diameter of 25 mm (*curve 1*), 50 mm (*curve 2*), and 75 mm (*curve 3*). The face thickness is 2.4 mm

3. Finite Element Modeling of Static Indentation Response

A finite element modeling procedure was developed in order to simulate the nonlinear mechanical response of foam core sandwich panel and beam systems subjected to static localized loading. For this purpose, the ABAQUS finite element commercial software was used.

Both plane and axisymmetric conditions were considered in the modeling. The numerical models were based on the dimensions and geometry of specimens used in the indentation tests. Owing to the symmetry, only a half of the length of the beam and panel specimens was modeled. The model was meshed using 4-node bilinear plane strain (CPE4) and axisymmetric (CAX4) finite elements in the plane and axisymmetric formulations, respectively. It should be specified that the indentation of a sandwich panel specimen by a spherical indentor can be considered as an axisymmetric problem in view of the fact that deformations are localized in the zone immediately under the indentor (the panel undergoes no strains in the area away from the indentor). The 2-D mesh, composed of 1200 elements, was condensed toward the contact area between the indentor and the face sheet due to the expected stress concentration in this zone. Before carrying out further simulations, a mesh sensitivity study was conducted with respect to the number of elements and the bias ratio to ensure that the mesh was fine enough to give reliable results. At the lower boundary of the model all degrees of freedom were constrained. The nodes on the vertical axis of symmetry were restricted in horizontal direction. Figure 12 gives an example of meshing used to carry out the simulation.

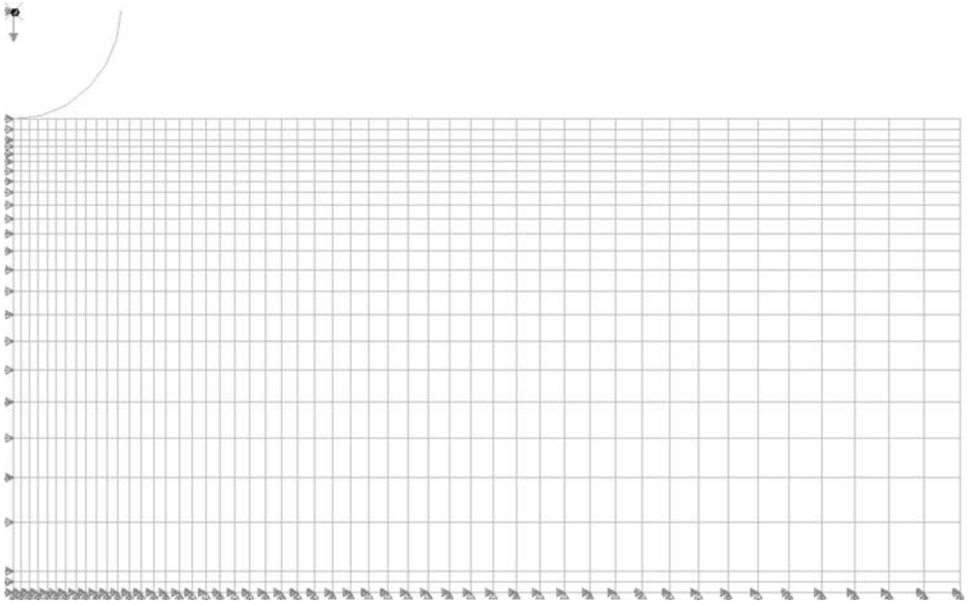

Fig. 12 Example of finite element meshing used for modeling the indentation response of sandwich specimens

Table 1 Elastic properties of the sandwich constituents

	E_{xx}, MPa	E_{yy}, MPa	E_{zz}, MPa	G_{xy}, MPa	G_{yz}, MPa	G_{zx}, MPa	ν_{xy}	ν_{yz}	ν_{zx}
Core	125	125	125	48	48	48	0.31	0.31	0.31
Face	19300	3480	19300	1650	1650	7700	0.05	0.25	0.25

The indentor was modeled as a rigid body owing to the fact that it has a much grater stiffness compared to the sandwich systems considered. In this relation, the *RIGID BODY option in the ABAQUS code was used. All degrees of freedom of the indentor were constrained except the translation in vertical direction. The loading was imposed as a prescribed vertical displacement of the indentor. The interface between the indentor and the face sheet was modeled automatically. For this purpose, the *SURFACE INTERACTION option in the ABAQUS package was used.

The face sheet was modeled as a linear elastic material. For this purpose, the *ELASTIC option in the ABAUS software was used.

The elastic properties of the sandwich constituents are presented in Table 1. The in-plane moduli of the composite face sheets were measured according to ASTM methods. Other elastic properties were estimated by laminate theory or taken from the Divinycell Technical Manual.

The H100 foam core was modeled as an elastic-plastic material with hardening. In this relation, the *CRUSHABLE FOAM and the *CRUSHABLE FOAM HARDENING options in the ABAQUS program system were used. The hardening behavior was defined on the basis of stress-strain curve obtained from uniaxial compression test. For this purpose, foam cylindrical specimens with a radius of 25 mm and height of 50 mm were tested. These specimens were prepared in the following way. As mentioned before, the foam core material was delivered in the form of large plates. The cells on the top and bottom surfaces of the plates were open. To reduce the influence of these open cells, the plate surfaces were primed with a thin layer of polyester. In this way, the open cells were reinforced (this is justified in view of the fact that in practice the foam is usually sandwiched between two stiff face sheets).

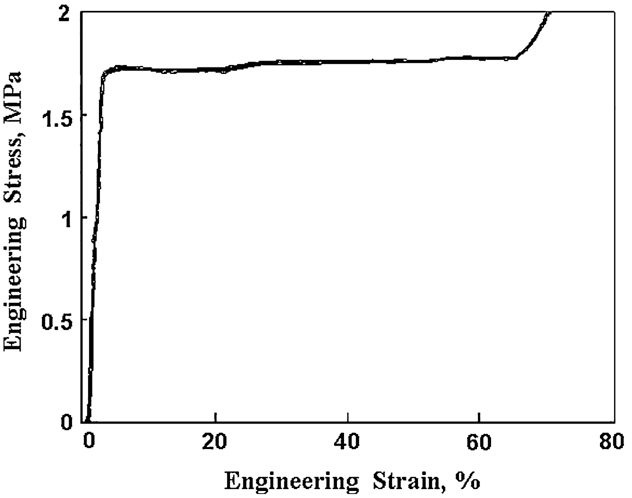

Fig. 13 Uniaxial compressive stress-strain behavior of the H100 foam

Cylindrical specimens were subsequently drilled out. The top and bottom surfaces of the specimens were subjected to visual inspection to ensure that the cells were completely reinforced with polyester. The specimens were tested in uniaxial compression at a constant crosshead speed of 2 mm/min.

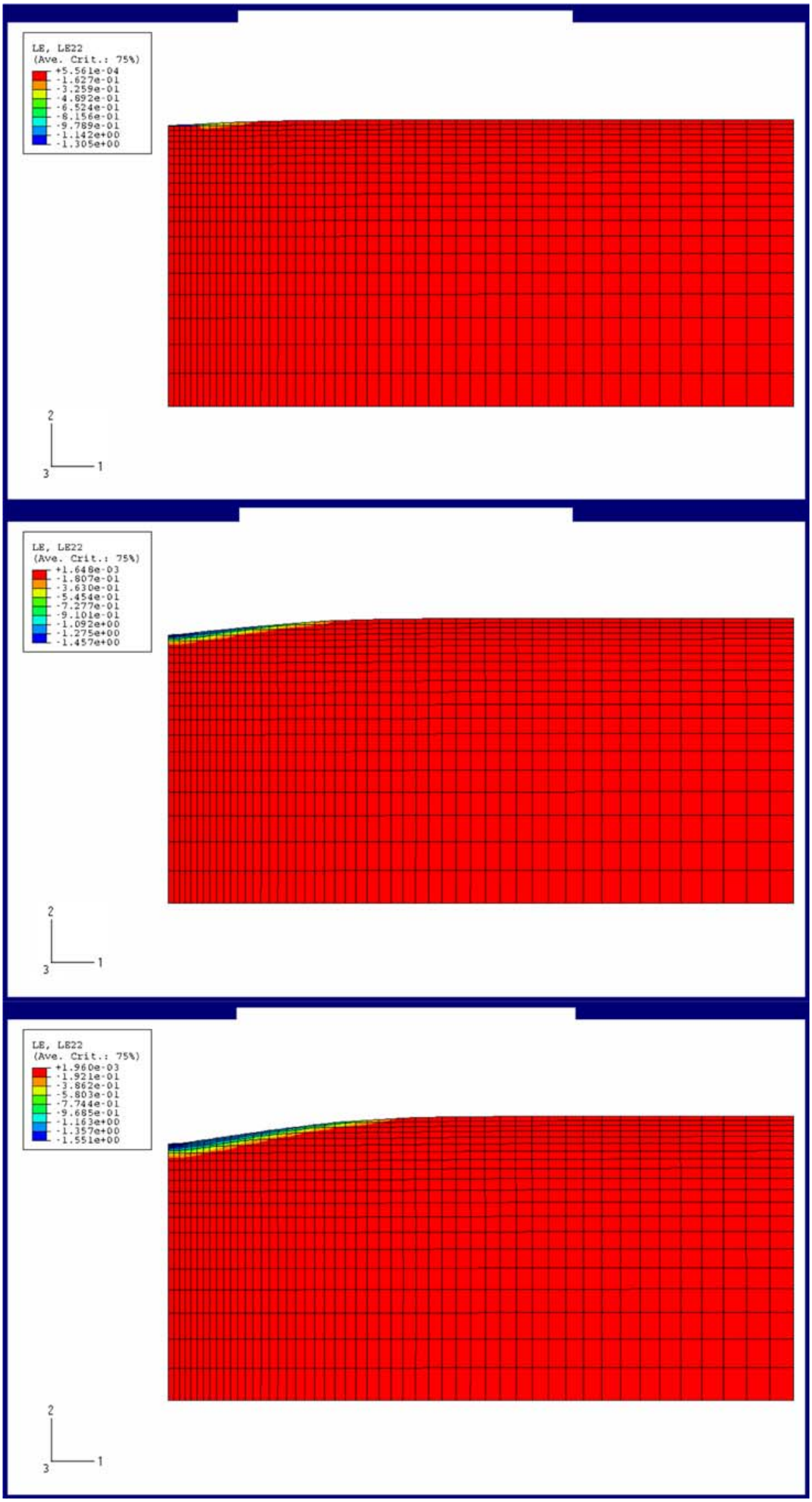

Fig. 14 Evolution of the vertical strain field, ε_{22}, in a panel specimen with increase of the indentation

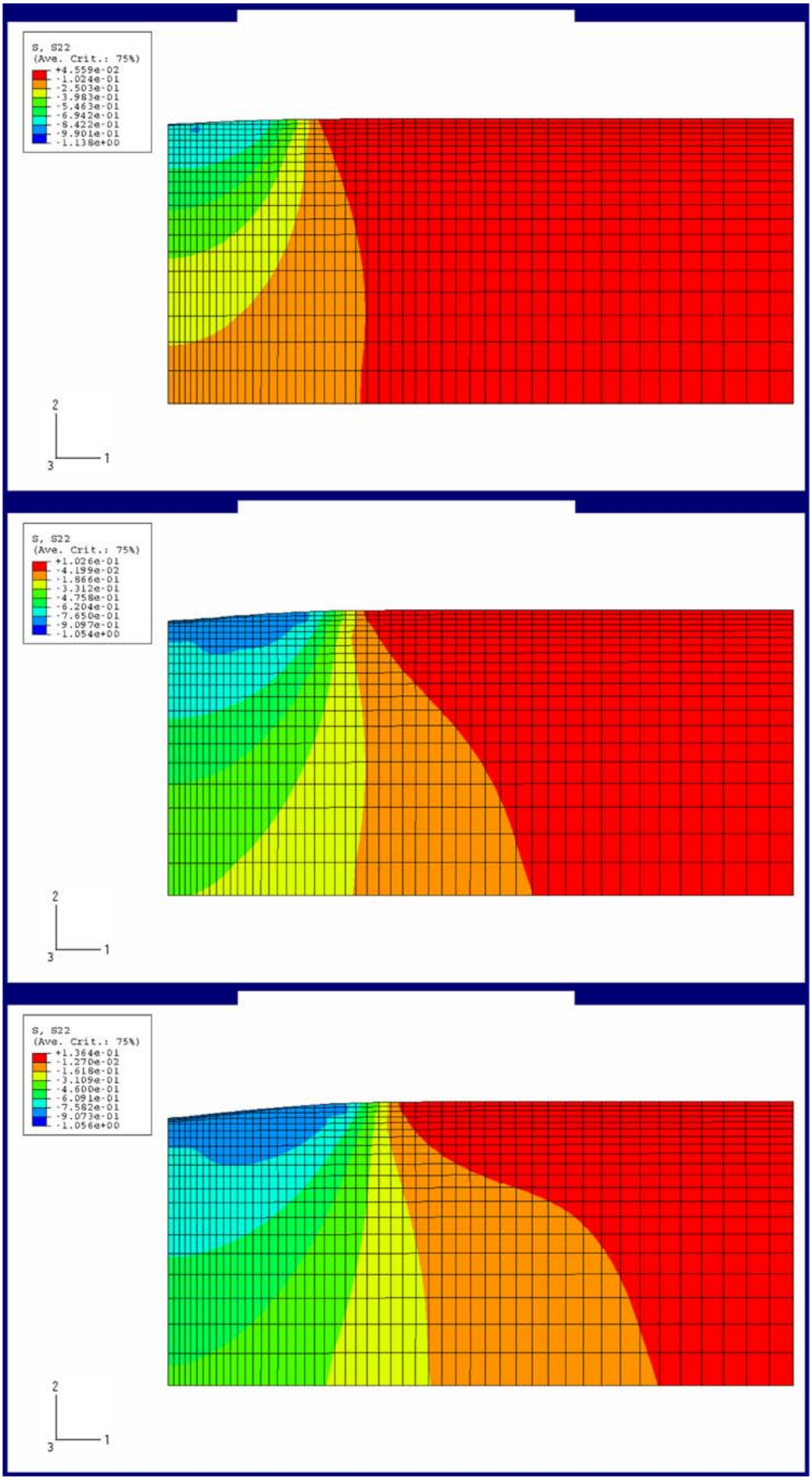

Fig. 15 Evolution of the vertical stress field, σ_{22}, in a bean specimen with increase of the indentation

The engineering stress-strain curve was recorded during the test (Fig. 13). As one can see, the stress-strain curve has three distinct ranges. The initial linear elastic range is followed by a protracted plastic plateau at which the stress level almost does not change. Following the end of the plastic plateau, hardening takes place and the stress level increases rapidly.

The engineering stress-strain curve (Fig. 13) was used to calibrate the *CRUSHABLE FOAM HARDENING material model. For this purpose, characteristic points were selected along the curve. Their "coordinates" in terms of engineering (nominal) stress $\sigma_{\rm nom}$ and strain $\varepsilon_{\rm nom}$ were transformed into true (Cauchy) stress $\sigma_{\rm true}$ and volumetric logarithmic plastic strain $\varepsilon_{\rm V}$ by the equations

$$\sigma_{\rm true} = \sigma_{\rm nom}(1 + \varepsilon_{\rm nom}), \qquad \text{(Eq 1)}$$

$$\varepsilon_{\rm true} = \ln(1 + \varepsilon_{\rm nom}), \qquad \text{(Eq 2)}$$

$$\varepsilon_{\rm pl} = \varepsilon_{\rm true} - \frac{\sigma_{\rm y}}{\rm E}, \qquad \text{(Eq 3)}$$

$$\varepsilon_{\rm V} = \ln\left(1 + \varepsilon_{\rm pl}\right), \qquad \text{(Eq 4)}$$

where $\sigma_{\rm y} = 1.70$ MPa is the uniaxial yield stress $E = 125$ MPa is Young's modulus. The nominal stress and strain in uniaxial compression are defined as

$$\sigma_{\rm nom} = \frac{F}{A}, \qquad \text{(Eq 5)}$$

$$\sigma_{\rm nom} = \frac{u}{h}, \qquad \text{(Eq 6)}$$

where F is the compressive force, A is the cross section of the cylindrical foam specimen, u is the axial displacement, and h is the height of the undeformed specimen.

The large deformations in the indentation test were taken into account via the *NLGEOM option in the ABAQUS code.

Both loading and unloading phases of the indentation test were modeled. For this purpose, the *STEP option in the ABAQUS program was used. The unloading was modeled applying a reversed prescribed displacement of the indentor. The instant residual dent magnitude was determined during the second (unloading) step of the modeling. The displacement, when the load dropped to zero, was assumed to be the residual dent.

The numerical model developed was used to simulate the indentation behavior of different sandwich systems. The evolution of the vertical strain, ε_{22}, in a sandwich panel specimen during indentation is illustrated in Fig 14. Due to the ability of the face sheet to distribute load, the zone of high ε_{22} is more developed in the radial direction without considerable expansion down the core. The evolution of the vertical stress, σ_{22}, during the indentation process is shown in Fig. 15. One can see that the σ_{22} field is characterized with high compressive stresses concentration in the zone near the indentor. The basic purpose of the finite element modeling was to predict the load-displacement response and to compare it with the measured one. Such comparisons are presented in Fig. 16 and 17. As can be seen, the finite element results are in good agreement with the experimental data for both loading and unloading phases. It should be mentioned that the numerical results for indentation behavior of sandwich systems with face sheet thickness of 4.8 and 7.2 mm were also in good agreement with the test data.

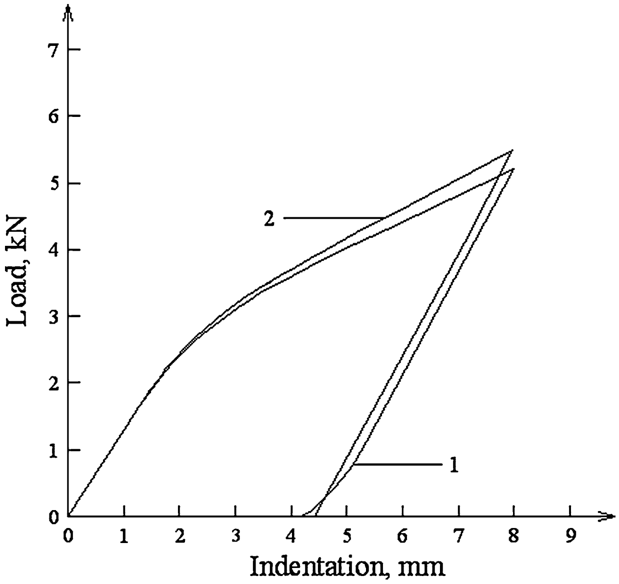

Fig. 16 Comparison between experimental results (*curve 1*) obtained in the case of sandwich beam specimen indented at a cross-head displacement rate of 2 mm/min with an indentor diameter of 25 mm and results deducted from numerical modeling (*curve2*). The face sheet thickness is 2.4 mm

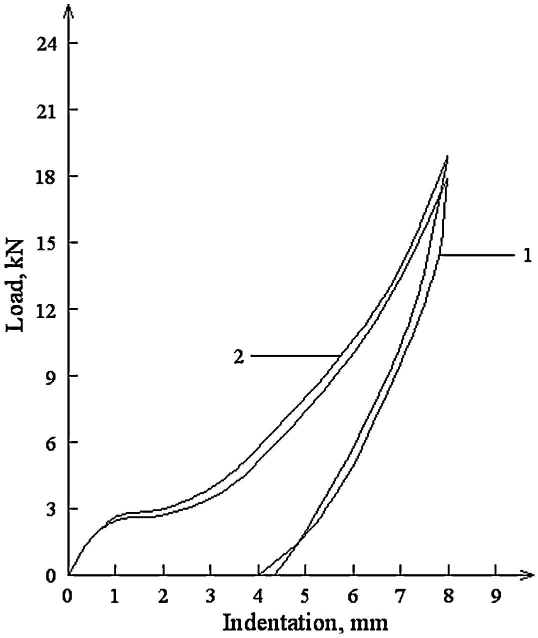

Fig. 17 Comparison between experimental results (*curve 1*) obtained in the case of sandwich panel specimen indented at a cross-head displacement rate of 2 mm/min with an indentor diameter of 25 mm and results deducted from numerical modeling (*curve 2*). The face sheet thickness is 2.4 mm

4. Conclusions

A thorough investigation was undertaken of the mechanical behavior of foam core polymer composite sandwich beam and panel systems subjected to local static loading. Indentation tests were conducted on sandwich beams and panels with thicknesses of the face sheet of 2.4, 4.8, and 7.2 mm using indentors with diameter values of 25, 59, and 75 mm. To investigate the rate sensitivity of the indentation behavior, the tests were carried out at seven different crosshead displacement rates. A nonlinear finite element model was developed for simulating the indentation response. The validity of the model was examined through comparisons with experimental data.

The main results of the present research may be summarized as follows:

(1) The sandwich systems investigated exhibit generally nonlinear indentation behavior due to the local foam core crushing in the zone underneath the indentor. The foam crushing is caused by the high stress concentration induced during the indentation process.
(2) The static indentation response is qualitatively different between the beam and panel systems. In panels, the indentation response has three sections. In the initial section, the response follows a practically linear relationship. In the second section, the response is dominated by decrease in overall stiffness due to foam crushing. The third section is characterized by gradual increase of the overall stiffness. In the indentation response of sandwich beam specimens, the third section is missing, i.e., there is initial linear section followed by a section of decreasing stiffness alone.
(3) As expected, increasing the face sheet thickness leads to increase in the load (for a given displacement). The critical load (at which the nonlinear section of the load-indentation response begins) increases as well. This finding can be attributed to the increased ability of the thicker face sheet to distribute the load over larger area. The residual dent magnitude decreases on increasing the face sheet thickness. This is related to the increased bending stiffness of the face sheet and consequent increase of the pulling effect during the unloading phase of the indentation test.
(4) Using indentors with larger diameters leads to increase in the load (for a given displacement). The critical load also increases. This is due to the fact that the load is distributed over a larger contact area.
(5) The indentation experiments carried out at different crosshead displacement rates show that the indentation behavior of the sandwich systems investigated is rate-insensitive over the range of testing conditions considered in the present study.

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