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NUMERICAL STUDIES OF THE DYNAMIC BEHAVIOUR OF SANDWICH PLATES INITIALLY WEAKENED BY THE IMPACT DAMAGE

Vyacheslav N. Burlayenko, Tomasz Sadowski

Abstract: Free vibrations of impact-damaged sandwich plates with honeycomb and foam cores are studied. It is assumed that damages caused by impact events are to exist before the vibration start and to be constant during oscillations. The influence of the impact damage modes involving the core crushing (planar damage), face sheets fracture (indentation) and the core to face sheets interface degradation (debonding) on the natural frequencies and associated mode shapes of the sandwich plates is investigated using commercially available finite element code ABAQUS^{TM}.

1. Introduction

A major concern of sandwich materials, which are widely used in a structural design, is their proneness to impact-induced damage. Such localized damage can be attributable to either fabrication or in-service life of sandwich structures. Depending on the shape and size of impact objects, their mass and velocity as well as material properties and geometry of target sandwich structures a number of damage modes can be identified. Damage states associated with low velocity impacts in sandwich panels are usually confined to the impacted face sheet, the core and the interface between them [1]. Nevertheless, this impact-induced barely visible damage level (BVDL) greatly affects the load capacity of the structural components, causing them to fail at lower loads than expected [2]. Therefore, inspection procedures and structural analysis are to be used to detect and predict the impact damage extension within the sandwich structures. One of known non-destructive testing techniques for diagnosing and detection the location and severity of damage in sandwich structures is based on the data of structural vibration responses such as natural frequencies, mode shapes, modal damping, response functions and so on [3]. By an alternative of complex and expensive experiments required for finding dynamic responses of damaged structures may be numerical approaches, for instance, the finite element method (FEM). In this case, the reliability and practicality of FE predictions depend on the accuracy of used models.

Therefore, elaborating accurate and efficient dynamic models of sandwich structures containing defects caused by impact events is an important precondition in the context of the health monitoring and damage detection problem and it is the main aim of this study. Moreover, the sensitivity of natural frequencies and associated mode shapes of sandwich plates with respect to the post-impact state including local geometry perturbations and stiffness degradation due to the core crushing and the core-to-face sheet debonding is also evaluated.

2. Impact region properties

In general, a low-velocity impact with a blunt object produce permanent indentation in a face sheet accompanied with substantial core crushing damage beneath and around the impacted site and core-to-face sheet debonding (cavity) within this region [4]. In some cases of low velocity impact the face sheet remains a little damaged and may mask the core crushing and interface degradation from visual inspection co-called as barely visual impact damage (BVID). The key geometrical parameters of representative cross-section of a sandwich specimen impacted are shown on the Fig. 1 and include the peak depth of the residual face sheet indentation δ_i, the peak depth associated with core fracture δ_c and planar dimension of damaged face sheet radius R_i, and planar dimension of the crushed core R_c.

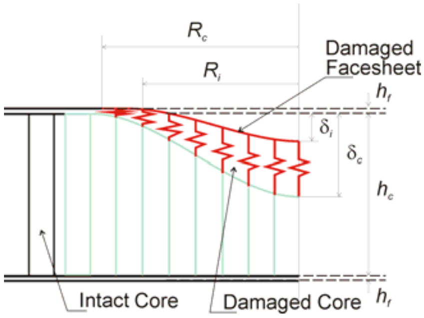


Figure 1. Impact-damaged region.

However, it results from the work [5] that models of sandwich panels accounted for only the impact-based geometrical perturbations are not accurate. The actual damage state of the supporting core, core-to-face sheet interface as well as possible changes in the local stiffness of the face sheet due to impact-induced damage should be taken into account.

Thus, it is obviously that the dynamic behavior of impacted sandwich panels depends on the wide range of parameters associated with their post-impact state involving the core crushing (planar damage), face sheets damage (indentation) and the core-to-face sheet interface degradation (debonding). Consequently, due to difficulty to obtain an analytical solution for this problem, the finite element (FE) modeling method can provide a powerful tool for investigations.

3. Finite element modeling

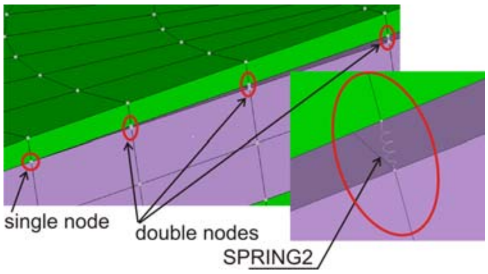
The simulation of free vibration of sandwich plates were carried out by using the commercial software ABAQUS/Standard version 6.6 [6]. A parametric input file was developed to enable representation of various post-impact configurations, thus results of dynamic analysis over a wide range of the size and form of impacted regions were obtained. A number of assumptions were adopted in this study to analyze the influence of impact-induced damages on oscillating sandwich plates. Firstly, the impact damage is assumed to be predetermined before the vibrations start and to be constant during oscillations. Secondly, the linear free vibrations are considered. Thirdly, the complicated impact-induced damage geometry is idealized by a regular spherical form in a depth and circle within a plane of plates. Fourthly, the cellular honeycomb core is treated as an orthotropic homogeneous material, whereas an isotropic material presents the foam core.

A three-dimensional (3D) FE model has been developed by combining general-purpose continuum shell SC8R elements for representing the face sheets with solid C3D8I elements for modeling the core. Because the required FE model should closely reproduce local geometry perturbations induced by the impact, the general mesh was subdivided into three different zones: the fine meshed impacted region including a hemispherical profile of the dented face sheet and crushed core as well as interfacial debonding between them, the next zone surrounding the impacted region with gradually decreased mesh density, and the coarse meshed fully bonded. It needs to notice that debonding was simulated as a small gap between the core and the face sheet.

Multi-point constrains (MPC) were imposed in all nodes of elements between the face sheet and the core of the sandwich plate nodes, these nodes are denoted as single nodes. Detaching between the elements of the crushed core and impacted face sheet in the damaged region was modeled by removing of those MPC and, as a consequence, the double nodes appear in this zone, Fig. 2 (a). In order to prevent the debonded face sheet from overlapping with the core and to model opening and closing of the interfacial damage during vibrations, 3D spring SPRING2 elements were introduced between nodes of the debonded region. This element had zero stiffness in tension and very big stiffness in compression, if relative displacement goes to zero, Fig. 2 (b). The part of the core crushed due to the impact was simulated by reducing gradually the stiffness of elements along the damaged area. Then, a circular region of the damaged core, including a subset of elements, is surrounded by the undamaged core. The properties of the damaged core as the respective subset of elements were calculated by multiplying their initial undamaged properties by a reduction factor, Fig. 2 (c).

4. Numerical results

Effects of the impact damage on vibration responses of sandwich plates were assessed by comparing numerical results of free vibration analysis between intact and damaged plates. Results from non-des a)



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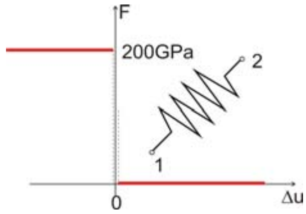

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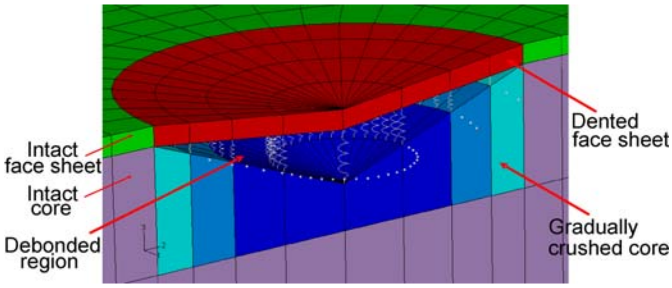


Figure 2. Detailed view of the FE model: (a) the debonded region, (b) the spring behavior, (c) the stiffness reductions.

tructive inspection and destructive sectioning of damaged plates, observed in works [7], were used as initial conditions for post-impact damage states (residual face sheet dent, core cavity depth, debonding size, etc.) in numerical calculations presented further.

Convergence studies to obtain values of natural frequencies as accurately as possible at the minimum number of elements required with the view to optimize computational time were carried out first. A sandwich beam cored by foam with rectangular cross-section containing damage at the middle span was considered, Fig. 3 and its material properties are shown in Table 1.

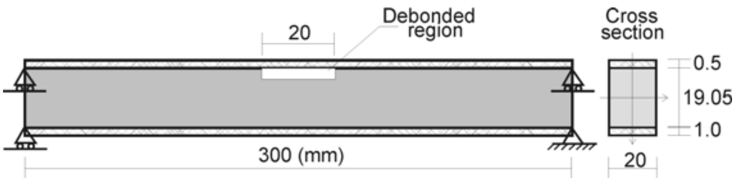


Figure 3. Model of the damage sandwich beam with foam core.

The experimental data for the first five modes of the beam were obtained in [8] and were compared with the present numerical calculations performed using ABAQUS's model discussed above. The close results can be seen, Table 2.

Components	Material constants
Core	E_c = 50, MPa G_c = 21, MPa ρ_c = 52, kgm^{-3}
Face sheets	E_f = 36000, MPa ρ_f = 4400, kgm^{-3} ν = 0.3

Table 1. Material properties of the damaged sandwich beam with foam core.

Mode No.	1	2	3	4	5	6
Analysis [9]	288.98	388.32	1093.2	1146.9	1771.3	1842.2
Present FEA	293.07	433.67	1093.1	1132.0	1769.9	2080.2

Table 2. Mode frequencies of the damaged sandwich beam with foam core (Hz).

The influence of the indentation region size (internal damage diameter of the impact site) on natural frequencies and mode shapes of a sandwich plate subjected to a low velocity impact was further studied. For this purpose, simply supported rectangular honeycomb sandwich plate with in-plane dimensions 180×135 mm^2 containing impacted zone at the center was considered. The material properties of the plate are shown in Table 3. The size of the debonding was taken as 1% of h_f. The stiffness coefficients in the corresponding elements of the crushed core zone were gradually reduced in steps of 20% from 0 to 60%, such approximation corresponds to the experimental results in [9].

Components	Material constants
Aluminum honeycomb core, h_c = 5 mm	E_{11} = 0.461, MPa E_{22} = 0.461, MPa E_{33} = 1494, MPa G_{12} = 0.194, MPa G_{13} = 341.7, MPa G_{23} = 192.1, MPa ρ_c = 57.17, kgm^{-3}
CFRP face sheet, h_f = 1 mm	E_{11} = 140, GPa E_{22} = E_{33} = 10, Gpa G_{12} = G_{13} = 4.6, GPa G_{23} = 3.8, GPa ρ_f = 1650, kgm^{-3}

Table 3. Material properties of the honeycomb sandwich plate.

The size of the prescribed indentation region was defined by a planar damage parameter $D_{\%}$, denoting the ratio the area of circular face sheet indentation zone A_D to the total area of the rectangular plate A.

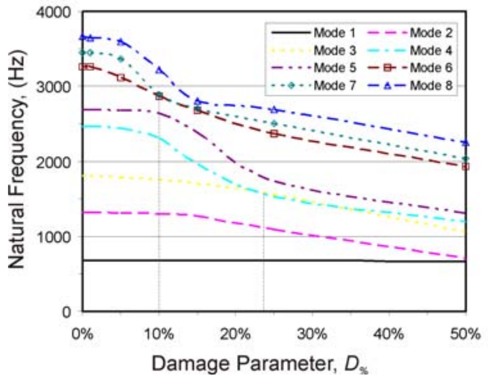


Figure 4. Eigenfrequencies as a function of the indentation region size.

The calculations showed that the natural frequencies as well as some mode shapes of sandwich plates subjected to the impact are shifted from corresponding intact plates and this effect on the higher modes is greater than the lower ones. Also, it does not exhibit monotonous trends as mode number increases. Fig. 4 shows the effect of indentation region size, varied from 9 mm to 63 mm that corresponded to a variation of the damage parameter from 1% to 50%, on the first eight natural frequencies. It can be seen that the natural frequencies generally decrease with the increase of the damage parameter, while the first torsional mode is practically insensitive to the presence of the impact planar damage. From Fig. 4 one can also see that the presence of the relatively small planar damage ($D_{\%}$ is less than 5%) does not almost change the lower natural frequencies, and decreases the higher natural frequencies only. However, the influence of indentation region size becomes more visible with the increasing of the diameter of the damage zone. In these cases even the first bending frequency is diminished up to 30%.

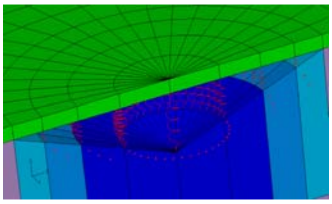
Parametric studies over a wide range of sizes of various damage parameters produced by impact events were further carried out. Only one sandwich configuration was considered consisting of h_f = 2.4 mm GFRP faces and h_c = 50 mm PVC H100 foam core. The mechanical properties of the constituent materials are shown in Table 4. In-plane dimensions of the plate was 270×180 mm^2. It was assumed that the plate is impacted an object with a hemispherical tip and the diameter of the impact damage is known and equal to 72 mm ($D_{\%}\approx$10%). This magnitude of the planar damage was taken for all parametric calculations.

Components	Material constants
Foam core	E_c = 135, MPa G_c = 45, MPa G_{13} = 341.7 ρ_c = 100, kgm^{-3}
GFRP face sheet	E_{11} = E_{33} = 16500, Mpa E_{22} = 3800, MPa G_{12} = G_{23} = 1800, MPa G_{13} = 6600, Mpa ν_{12} = 0.05 ν_{13} = ν_{23} = 0.25 ρ_f = 1650, kgm^{-3}

Table 4. Material properties of the sandwich plate with foam core.

An interfacial debonding (cavity) is especially detrimental, since the face sheet and core would then act separately, and by that the sandwich concept will locally lose. The influence of a depth of the debonded zone on free vibration responses of the damaged sandwich plates was firstly investigated. It was found that natural frequencies of the impacted plates slightly decrease with increasing of the cavity depth up to the magnitude approximately equal to half of the face sheet thickness and after that they practically do not change, Fig. 5. Simultaneously, curvatures of local mode shapes at the impact site slightly increase when the cavity depth increases. The mentioned effect of the insignificant changing of the lower natural frequencies remains for higher ones as well. Thereby, numerical results obtained allow concluding that free vibration responses are not suitable for detecting through-the-thickness damage as a residual indentation of the core. The same conclusions regarding the unnoticeable influence of the residual face sheet indentation depth on the natural frequencies can be drawn from the Fig. 6. And again the curvatures of the local mode shapes were more changeable with the residual face sheet indentation increasing. Thus, non-sensitivity such damage detection method to the defects exerted in the transverse direction is confirmed. Finally, the influence of face sheet property degradation due to the impact on dynamic characteristics of damaged sandwich plates was examined. Six separate cases of face sheet properties were considered. Each of them was assumed as an inclusion at the impacted region of a material with degraded material properties corresponding to

100%, 80%, 60%, 40%, 20% and 0 of the virgin face sheet properties. The last case simulates the



Details for debonded region meshing.

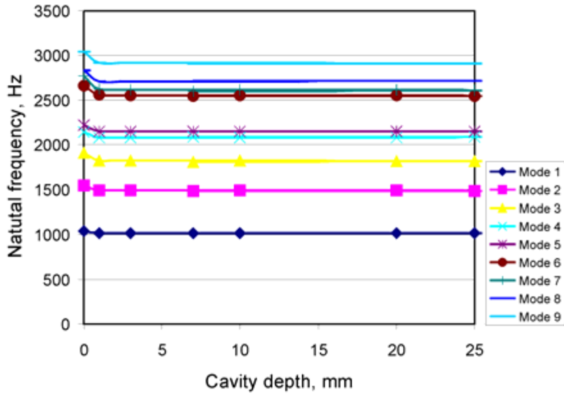
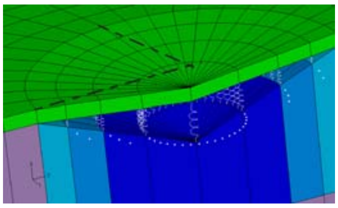


Figure 5. Changes in natural frequencies with cavity depth increasing.



Details for face sheet residual indentation meshing.

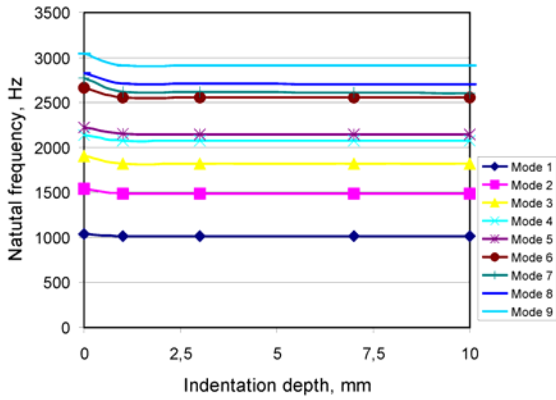
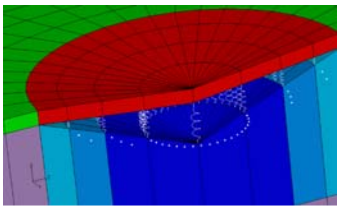


Figure 6. Changes in natural frequencies with face sheet residual indentation increasing.



Details for damaged face sheet meshing.

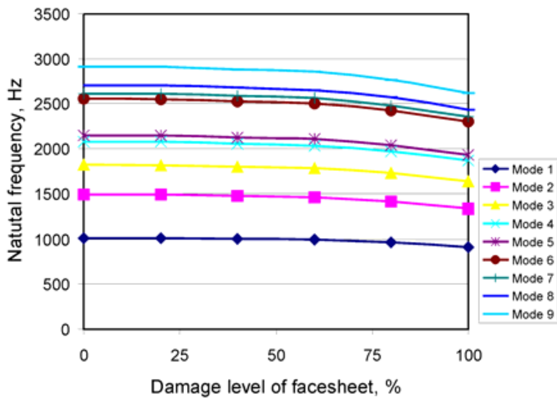


Figure 7. Changes in natural frequencies with face sheet damage increasing.

damaged face sheet with an open hole. One can be seen from Fig. 7 that appreciable decreasing of natural frequencies with increasing the face sheet degradation level takes place. In doing so, this effect is more remarkable for the higher frequencies. The behavior of the impact-damaged sandwich plate shows that the presence of the damaged region substantially reducing the local stiffness only slightly alters the overall bending stiffness of the plate. Consequently, the reliability of such approach to identify the low damage level of any thin structural layer as the face sheet damage due to the impact is relatively low.

5. Conclusions

The main results of this study can be summarized as follows: firstly, both natural frequencies and mode shapes of sandwich structures subjected to low velocity impact are sensitive to the presence of the impact-induced damage. In doing so, the natural frequencies usually decrease due to loss in stiffness caused by the damage. Secondly, higher natural frequencies and mode shapes are more sensitive to the impact damage presence than lower ones. Thirdly, natural frequencies and associated mode shapes are the most sensitive to the planar size of the impact domain. Fourthly, natural frequencies and associated mode shapes are poorly sensitive to the damage extended through the thickness and are moderately dependent on the face sheet damage.

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Burlayenko Vyacheslav. National Technical University 'Kharkov Polytechnic Institute', Department of Applied Mathematics, 21 Frunze Str., 61002 Kharkov, Ukraine, burlayenko@kpi.kharkov.ua.

Sadowski Tomasz. Lublin University of Technology, Department of Solid Mechanics, 40

Nadbystrzycka Str., 20-618 Lublin, Poland, t.sadowski@pollub.pl.