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Effects of local damage on vibration characteristics of composite pyramidal truss core sandwich structure

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ABSTRACT

The effects of local damage on the natural frequencies and the corresponding vibration modes of composite pyramidal truss core sandwich structures are studied in the present paper. Hot press molding method is used to fabricate intact and damaged pyramidal truss core sandwich structures, and modal testing is carried out to obtain their natural frequencies. A FEM model is also constructed to investigate their vibration characteristics numerically. It is found that the calculated natural frequencies are in relatively good agreement with the measured results. By using the experimentally validated FEM model, a series of numerical analyses are conducted to further explore the effects of damage extent, damage location, damage form on the vibration characteristics of composite pyramidal truss core sandwich structures as well as the influence of boundary conditions. The conclusion derived from this study is expected to be useful for analyzing practical problems related to structural health monitoring of composite lattice sandwich structures.

1. Introduction

A sandwich structure consists of two thin external layers of high-strength material and a thick intermediate layer of light-weight material. The former are usually called the face sheets and the latter the core [1–5]. Composite sandwich structures have many advantages over conventional structural materials, such as high bending stiffness, low specific weight, and good thermal and acoustical insulation [6–9]. Sandwich structures can be classified as honeycomb, foam, and lattice truss core sandwich structures [10–14]. Lattice truss core sandwich structures have not only the advantages of super-light porous materials, but also such features as simple processing and regular shape. Thus, it is a potential substitute for aluminum alloy, composite materials, and light metallic foam which are widely applied in the fields of transportation, machinery (such as high-speed train, aircraft, high-grade machine tool) and so on [15–21]. Nevertheless, the current applications of lattice truss core sandwich structures are mainly limited to secondary components. Such "exploitation with caution" is caused by a proneness of lattice truss core sandwich structures to a variety of defects and damages because of their own structural complexity as well as the high influence of manufacturing process on the product quality. It is, therefore, important to explore the effects of local damage on their mechanical properties such as vibration characteristics.

Hu and Hwu [22] developed a one-dimensional model considering transverse shear effect and rotary inertia of the core for free vibration analysis of a honeycomb sandwich beam with an across-the-width delamination located at the interface between the top face and the core. With this model, the natural frequencies and vibration modes of the delaminated composite sandwich beam were obtained by solving the eigenvalues and eigenvectors of 12 simultaneous homogeneous algebraic equations. Based upon the general solution, the effects of the faces, the core, and the delamination of the beam on its free vibration behavior were studied thoroughly. Kim and Hwang [23] conducted a vibration test on a honeycomb sandwich beam composed of carbon/epoxy laminated composite faces and Nomex-aramid honeycomb core to investigate the effects of debonding on its natural frequencies and flexural rigidity. Burlayenko and Sadowski [24] studied the dynamic behavior of a sandwich plate with flexible core partially delaminated at the face/core interface numerically. The influences of debonding size, debonding location, and debonding type on the modal parameters of the damaged sandwich plate with various boundary conditions were also investigated. Baba and Thoppul [25] investigated the influence of face/core debonding on the vibration behavior of a composite sandwich beam made up of carbon/epoxy laminated

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faces and polyurethane foam core experimentally, and found that the face/core debonding causes reduction of the natural frequencies, whereas the damping loss factor increases due to the presence of debonding. Sokolinsky et al. [26] investigated the free vibration behavior of sandwich beam with locally damaged transversely flexible (soft) core. The results demonstrated that a local damage of small length, which is located in the span of a soft-core sandwich beam, leads to a significant reduction in the natural frequencies.

The above studies could provide foundation for the development of vibration-based nondestructive evaluation techniques and health monitoring approaches. However, up to now, the effects of local damage on the natural frequencies and vibration modes of composite lattice truss core sandwich structures have been rarely studied. In the present paper, the effects of local damage, in the form of missing part of the truss members, on the natural frequencies and the corresponding vibration modes of composite pyramidal truss core sandwich structures are studied both experimentally and numerically. The paper is organized as follows. In Section 2, the experimental specimens and the modal testing system are briefly described. The experimental outcomes are compared with the corresponding numerical results predicted by a FEM (finite element method) model in Section 3, and it is found that they are in good agreement with each other. By using the experimentally validated FEM model, a series of numerical analyses are carried out in Section 4 to further investigate the effects of damage extent, damage location, damage form on the natural frequencies

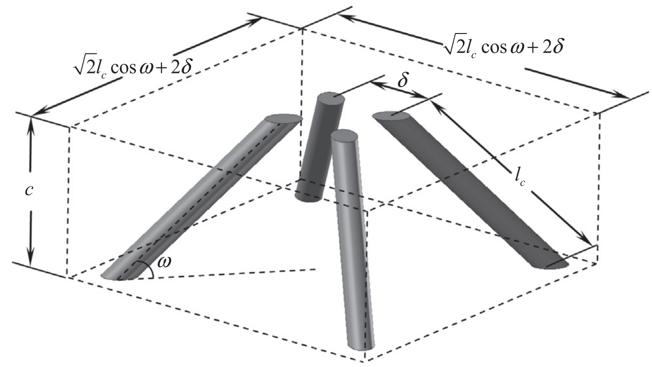

Fig. 2. Sketch of the unit cell of the pyramidal truss core.

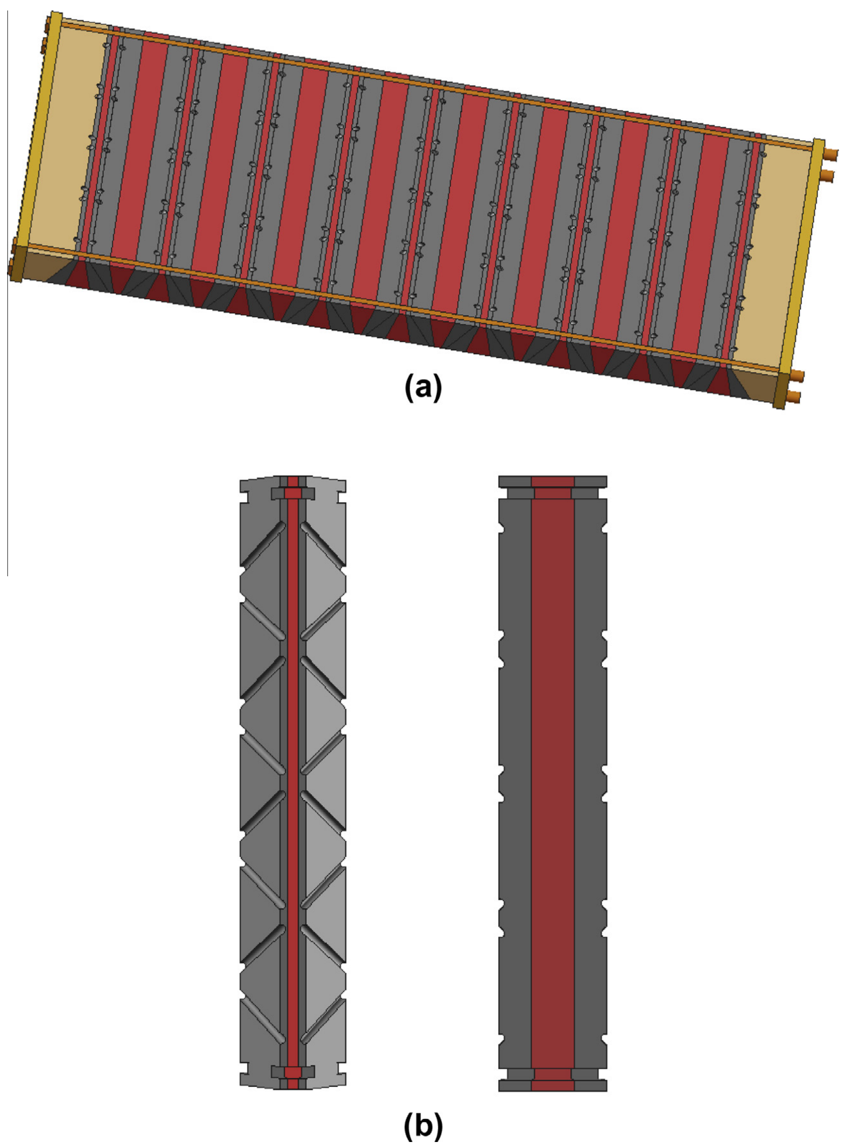

Fig. 1. Schematic diagram of the mold: (a) assembly drawing of the mold; (b) schematic diagram of single unit cell.

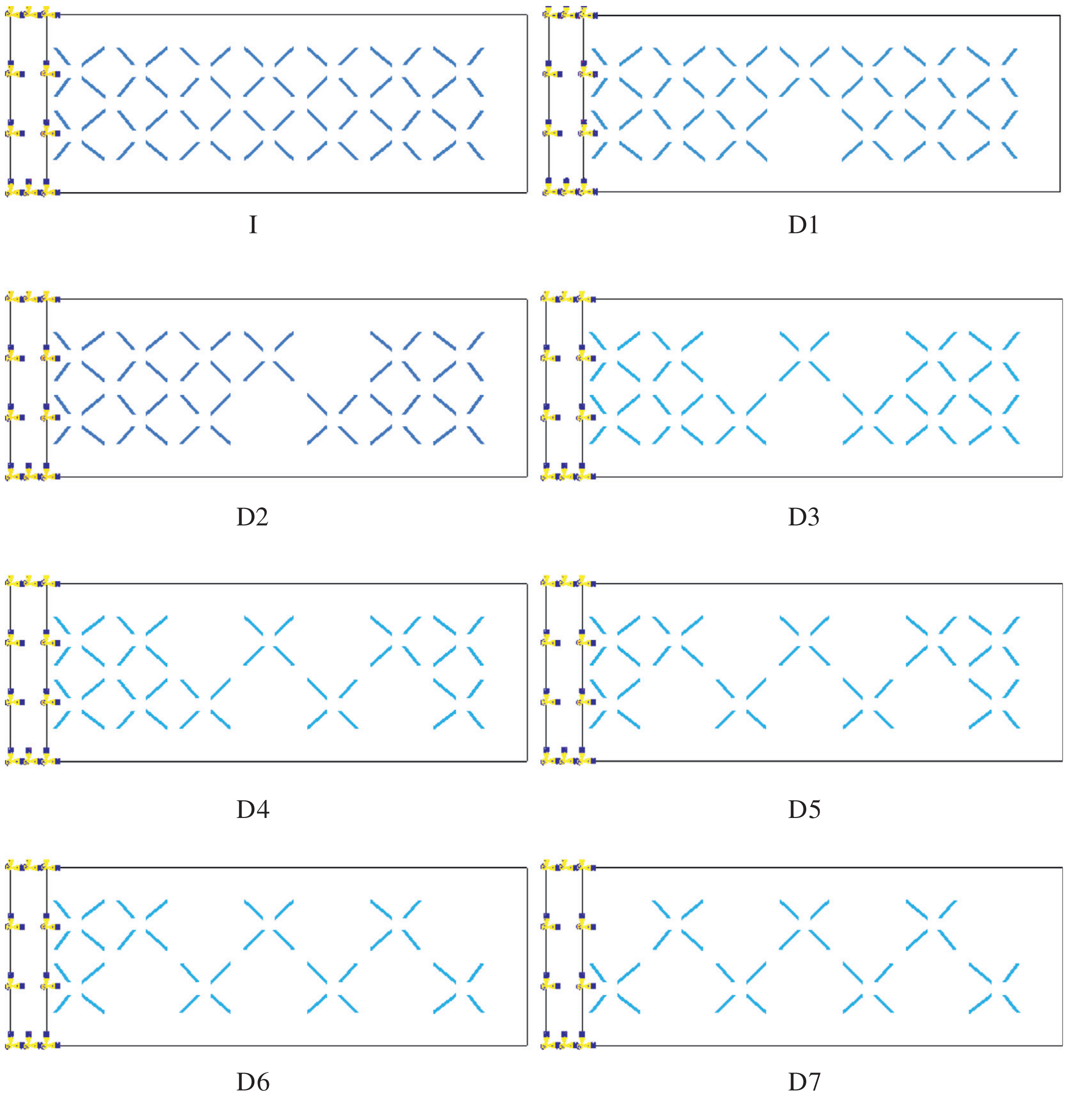

Fig. 3. Sketch of the experimental specimens with different damage extents.

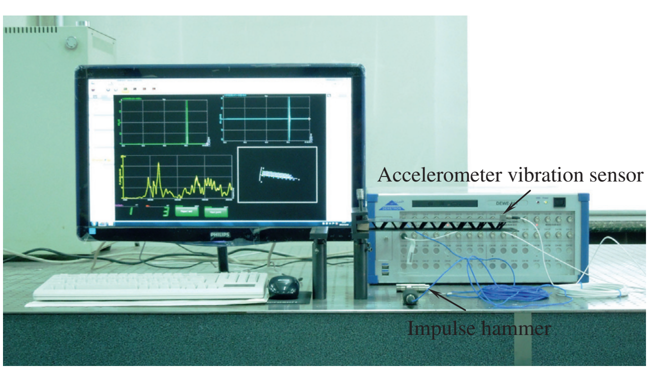

Fig. 4. Modal testing system.

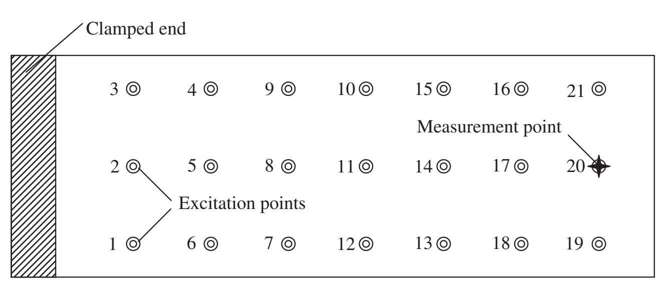

Fig. 5. Locations of excitation and measurement points of experimental specimens.

and vibration modes, as well as the influence of boundary conditions. Finally, Section 5 collects some concluding remarks of the present study.

2. Experiments

In this section, experiments are carried out to investigate the effects of local damage on the vibration characteristics of composite pyramidal truss core sandwich structures. In what follows, the experimental specimens and the testing system are briefly introduced, respectively.

2.1. Material and specimens

Carbon fiber composite pyramidal truss core sandwich structures presented in this article are fabricated from unidirectional carbon/epoxy prepregs using the mold shown in Fig. 1 by

Table 1
The material properties of unidirectional composite laminates.

E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	v_{12}	v_{13}	v_{23}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
132	10.3	10.3	0.25	0.25	0.38	6.5	6.5	3.91

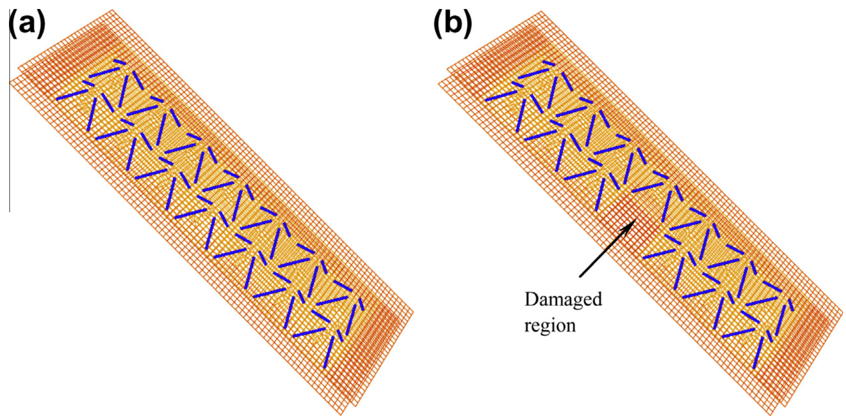

Fig. 6. Finite element models of pyramidal truss core sandwich structures: (a) the intact lattice sandwich structure; (b) the damaged lattice sandwich structure missing one unit cell.

Table 2
Convergence analysis for the intact composite pyramidal truss core sandwich structure.

Grid size(m)	Grid number	f_1 (Hz)	f_2 (Hz)	f_3 (Hz)	f_4 (Hz)	f_5 (Hz)
0.0050	2644	223.67	407.85	673.60	909.01	1048.5
0.0045	3320	218.71	392.68	656.53	870.78	1016.2
0.0040	4261	214.09	379.16	640.72	836.95	986.62
0.0035	5064	211.18	370.94	630.82	816.47	968.29
0.0030	7347	**210.48**	**368.97**	**628.43**	**811.58**	**963.86**
0.0025	10,134	210.33	368.58	627.95	810.61	962.99
0.0020	16,365	210.19	368.19	627.48	809.65	962.11

Table 3
Convergence analysis for the damaged composite pyramidal truss core sandwich structure missing one unit cell.

Grid size(m)	Grid number	f_1(Hz)	f_2(Hz)	f_3(Hz)	f_4(Hz)	f_5(Hz)
0.0050	2618	207.96	390.51	678.20	896.79	974.23
0.0045	3299	203.12	376.02	659.77	860.52	943.82
0.0040	4241	198.48	362.68	642.21	819.93	915.62
0.0035	5023	195.58	354.57	631.28	806.54	898.31
0.0030	7308	**194.87**	**352.63**	**628.64**	**801.68**	**894.15**
0.0025	10,080	194.73	352.24	628.11	800.71	893.32
0.0020	16,228	194.59	351.86	627.59	799.75	892.50

hot-pressing process. The fabrication process of the pyramidal truss core sandwich structures is given as follows. First of all, the carbon/epoxy prepregs are cut into the required dimensions. Then, they are made into composite struts as the truss members. In order to make full use of the strength of fiber reinforced composites, all the continuous fibers are aligned in the axial directions of the struts. Next, the composite struts are inserted into the holes of the mold with both ends embedding into the ten layers of the face sheets. The top and bottom face sheets are made from 10 plies of unidirectional carbon/epoxy prepregs with the stacking sequence of $[0/90/0/90/0]_s$. The face sheets and pyramidal truss core are interconnected and co-cured in one step of manufacturing process. Prior to forming the pyramidal truss core sandwich structure, a release agent is brushed on the mold surfaces in order to separate the specimen from the mold easily after curing. Finally, the preformed sandwich structure is cured at 125 °C for 1.5 h with a constant pressure of 0.5 MPa. Removing the mold after curing, the composite pyramidal truss core sandwich structure is obtained. A similar fabrication procedure has also been introduced by Wang et al. [27].

For ease of demolding, there exists a small spacing δ between the two closest truss members, as shown in Fig. 2. The geometric dimension of the specimens is $290 \times 100 \times 17$ mm^3, with the spacing $\delta = 7$ mm, the radius of the truss member $r_c = 1.25$ mm, the inclination angle of the truss member $\omega = 45°$, the thickness of the core $c = 15$ mm, and the thickness of the face sheet $t = 1$ mm. Eight groups of specimens, denoted by 'I' and 'D1'–'D7', respectively, are prepared, in which 'I' indicates the intact pyramidal truss core sandwich structure, and 'D1'–'D7' indicate the damaged pyramidal truss core sandwich structures missing 1–7 unit cells, respectively, as shown in Fig. 3. Each group includes three specimens to ensure the correctness of the experimental results.

2.2. Experimental procedure

Modal testing is a type of vibration testing on an object whereby the natural (modal) frequencies, modal masses, modal damping ratios and mode shapes of the object under test can be determined. There are several ways to do modal testing, among which impact hammer testing and shaker (vibration exciter) testing are commonplace. The weight of the specimens presented in this paper is so small that impact hammer testing is preferable.

The testing system used to obtain the vibration testing results is shown in Fig. 4, which is composed of three parts: an impulse hammer, an accelerometer vibration sensor, and a spectrum analyzer. The tests are performed on cantilevered beam specimens. The impulse hammer is used to excite the specimens, and the vibration sensor is attached to the surface of the specimen to measure the vibration responses. The specimen is excited at 21 points that are uniformly spaced in three rows along the length of the specimen, as shown in Fig. 5, which also shows the position of the measurement point. In impact hammer testing, energy is supplied to the system with a known frequency content. When structural resonance occurs, the response will be amplified. This can be clearly seen from

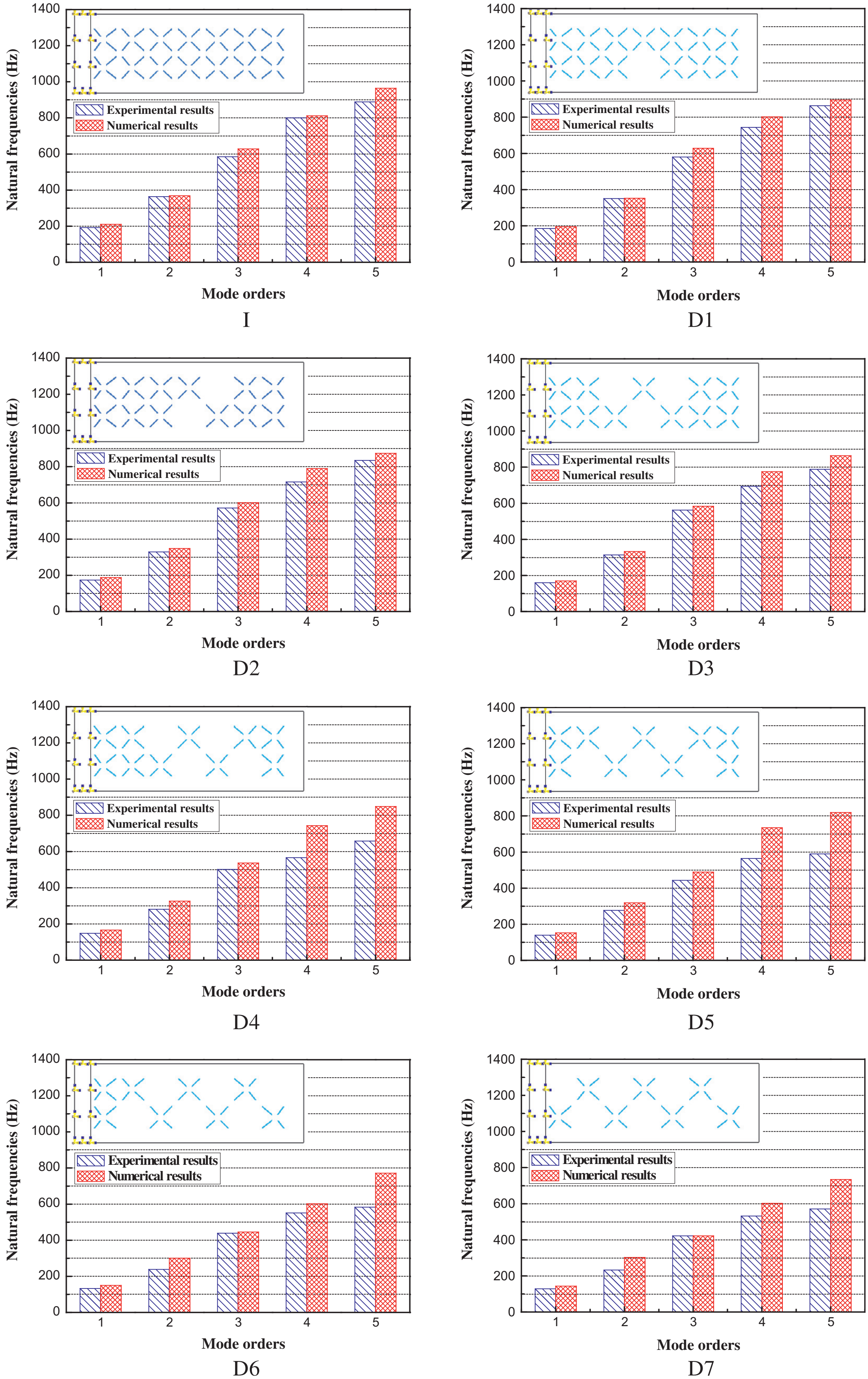

Fig. 7. Comparisons of the experimental and numerical results of the natural frequencies.

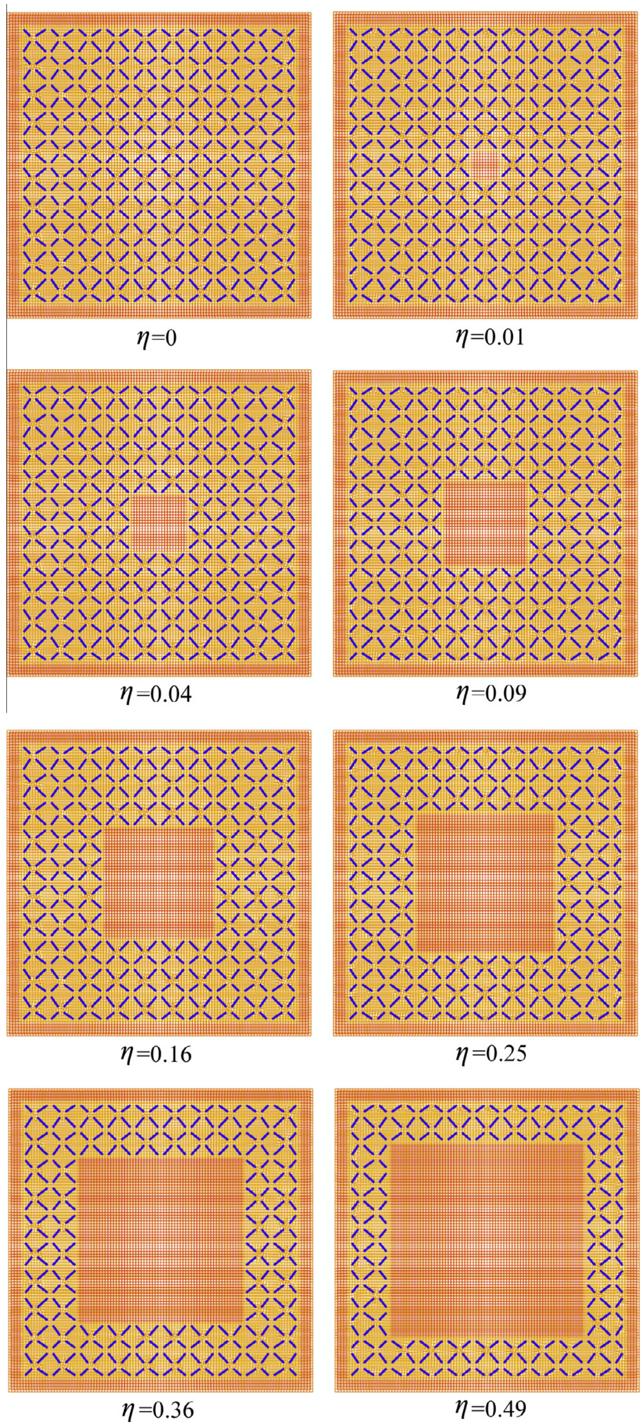

Fig. 8. Finite element models of pyramidal truss core sandwich plates with damaged regions at the center.

the response spectra. Using the force spectra and the response spectra, a transfer function, which can be used to estimate the modal parameters, is obtained. The first five natural frequencies are obtained during the testing procedure. The experimental results are discussed and compared with the corresponding numerical solutions obtained from a FEM model in the following section.

3. Numerical simulation

A FEM model is constructed in this section to simulate the vibration characteristics of the intact and damaged composite pyramidal truss core sandwich structures. Modeling of the sandwich structures and analysis of their free vibration characteristics are carried out using the commercial finite element software ABAQUS. The material properties of unidirectional composite laminates are taken from a pre-published paper of our partners [28] and shown in Table 1. 8-node doubly curved shell elements with reduced integration 'S8R' are adopted for the face sheets and 3-node quadratic beam elements 'B32' are adopted for the truss members. In comparison with adopting solid elements for both the face sheets and the truss members, the choice of the specified element types benefits for enhancing the calculation efficiency and saving the calculating time. The FEM models of the intact pyramidal truss core sandwich structure and the damaged one missing a unit cell are shown in Fig. 6. FEM models of sandwich structures with other damage extents are not given here for brevity. Clamped boundary condition is imposed at one end of the model. The free vibration analysis is performed by using a linear perturbation analysis step, and the eigenvalues, *i.e.* the natural frequencies, are extracted by the subspace iteration method.

First of all, a convergence analysis is conducted to ensure the reliability of the numerical results. The calculated first five natural frequencies of the intact composite pyramidal truss core sandwich structure and the damaged one missing a unit cell with different grid sizes and numbers are collected in Tables 2 and 3, respectively. It can be found that the results tend to be stable when the grid size is decreased to 0.0030 m, which are highlighted by bold type in the tables. Therefore, the sizes of the grids of the FEM model should be no larger than 0.0030 m.

The experimental and numerical results are compared in Fig. 7. Each experimental data is taken as the average value of three times of repetitive tests to ensure the validity. Each sub-figure shows that relatively good agreement between the experimental and numerical results is obtained, with an average relative error equaling 12.26%. The natural frequencies obtained by numerical analyses are a little higher than the corresponding values obtained by modal tests. This is mainly attributed to the following reasons. Firstly, in the preparation process of composite pyramidal truss core sandwich structures, embedding the ends of struts into the top and bottom face sheets disrupts the continuity of carbon fibers in the face sheets and results in defects, such as holes and impurities, appearing at the junctions. Secondly, the radial pressure imposed on the truss members is insufficient during the curing process, causing the modulus of the truss members to be lower than the designed value. However, the FEM models are relatively ideal, in which the effects of these manufacturing defects are not considered. Besides, comparison among different sub-figures in Fig. 7 shows that the presence of local damage leads to the decrease of the natural frequencies, and the higher order natural frequencies are more sensitive to internal damage. Thus, it can be concluded that the effects of local damage on the natural frequencies are mode dependent. This finding is informative for the development of structural damage indices using vibration techniques.

4. Fine analysis of imperfection sensitivity

By using the experimentally validated FEM model, a series of numerical analyses are carried out in this section to further investigate the effects of damage extent, damage location, damage form and boundary conditions on the vibration characteristics of composite pyramidal truss core sandwich structures.

4.1. Effects of damage extent

The effects of damage extent on the natural frequencies and the corresponding vibration modes of a clamped composite pyramidal truss core sandwich plate are investigated in this sub-section. The

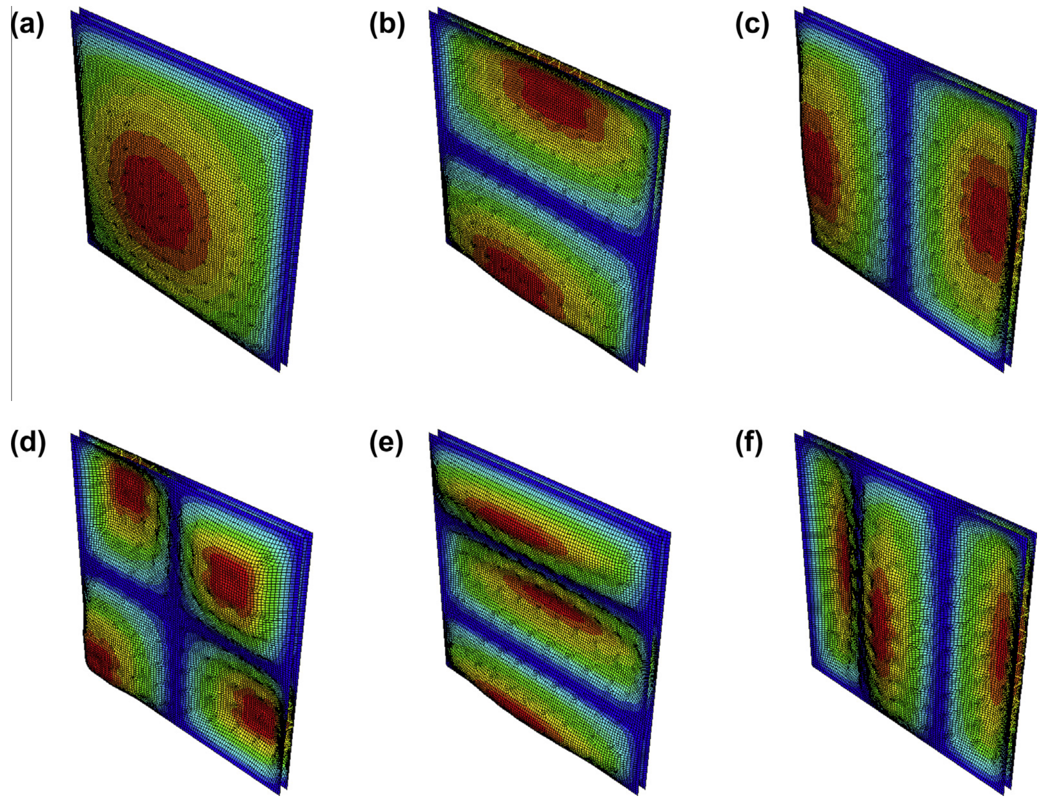

Fig. 9. The first six vibration modes of the intact pyramidal truss core sandwich plate: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

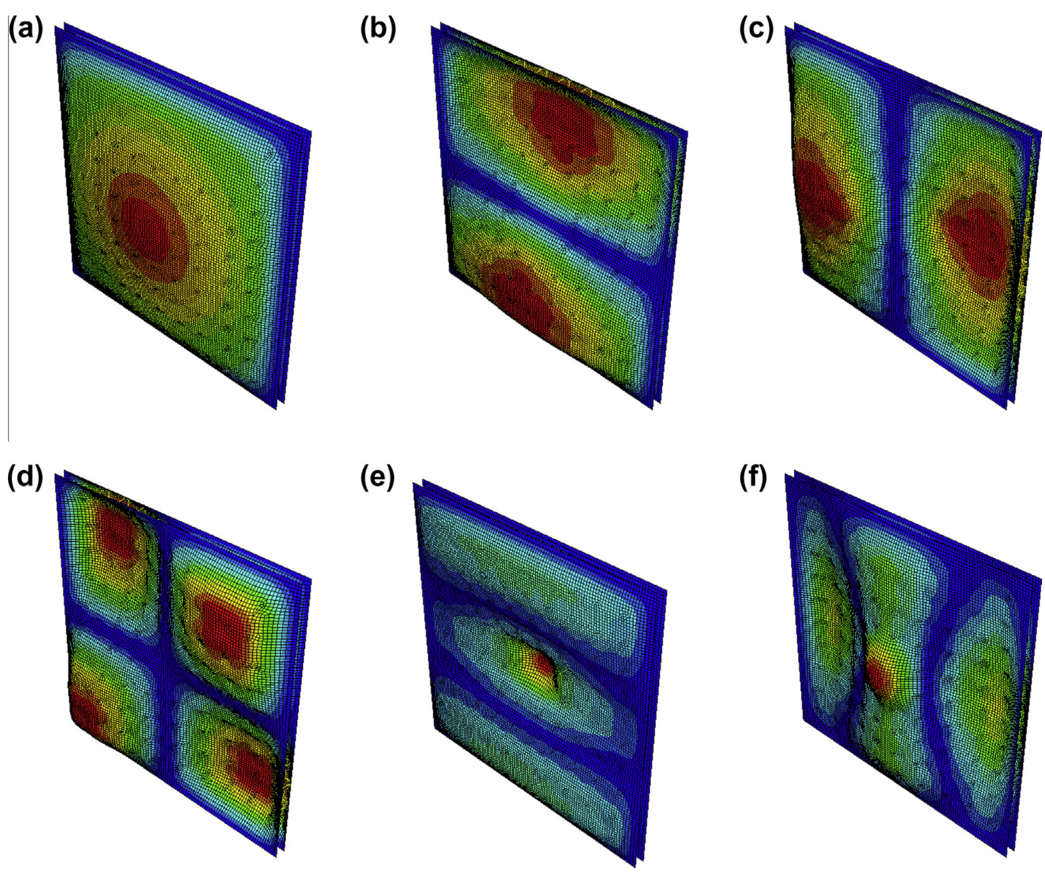

Fig. 10. The first six vibration modes of the pyramidal truss core sandwich plate with the damage parameter $\eta = 0.04$: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

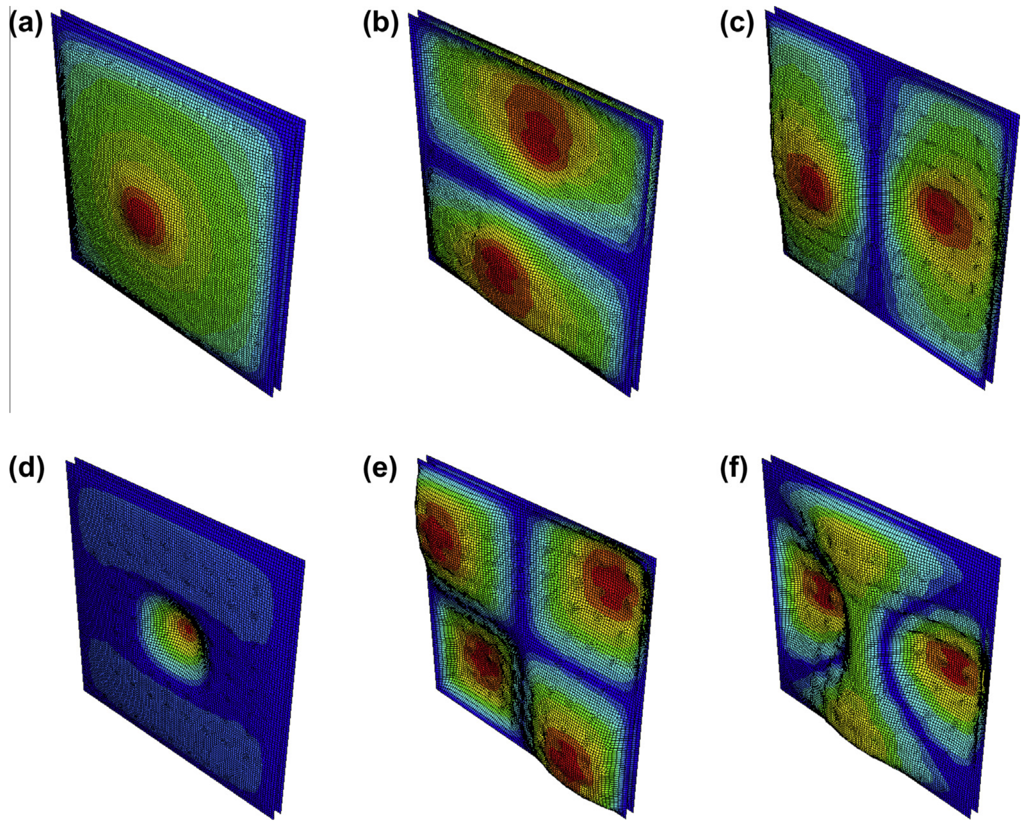

Fig. 11. The first six vibration modes of the pyramidal truss core sandwich plate with the damage parameter η = 0.09: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

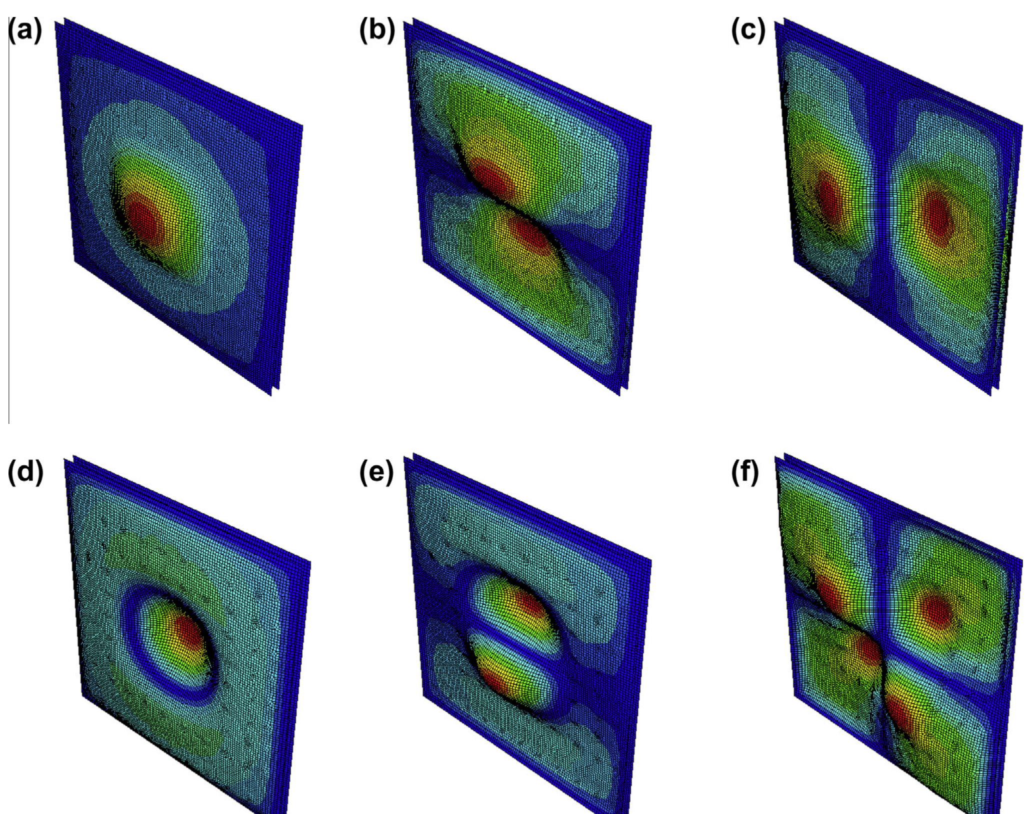

Fig. 12. The first six vibration modes of the pyramidal truss core sandwich plate with the damage parameter η = 0.25: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

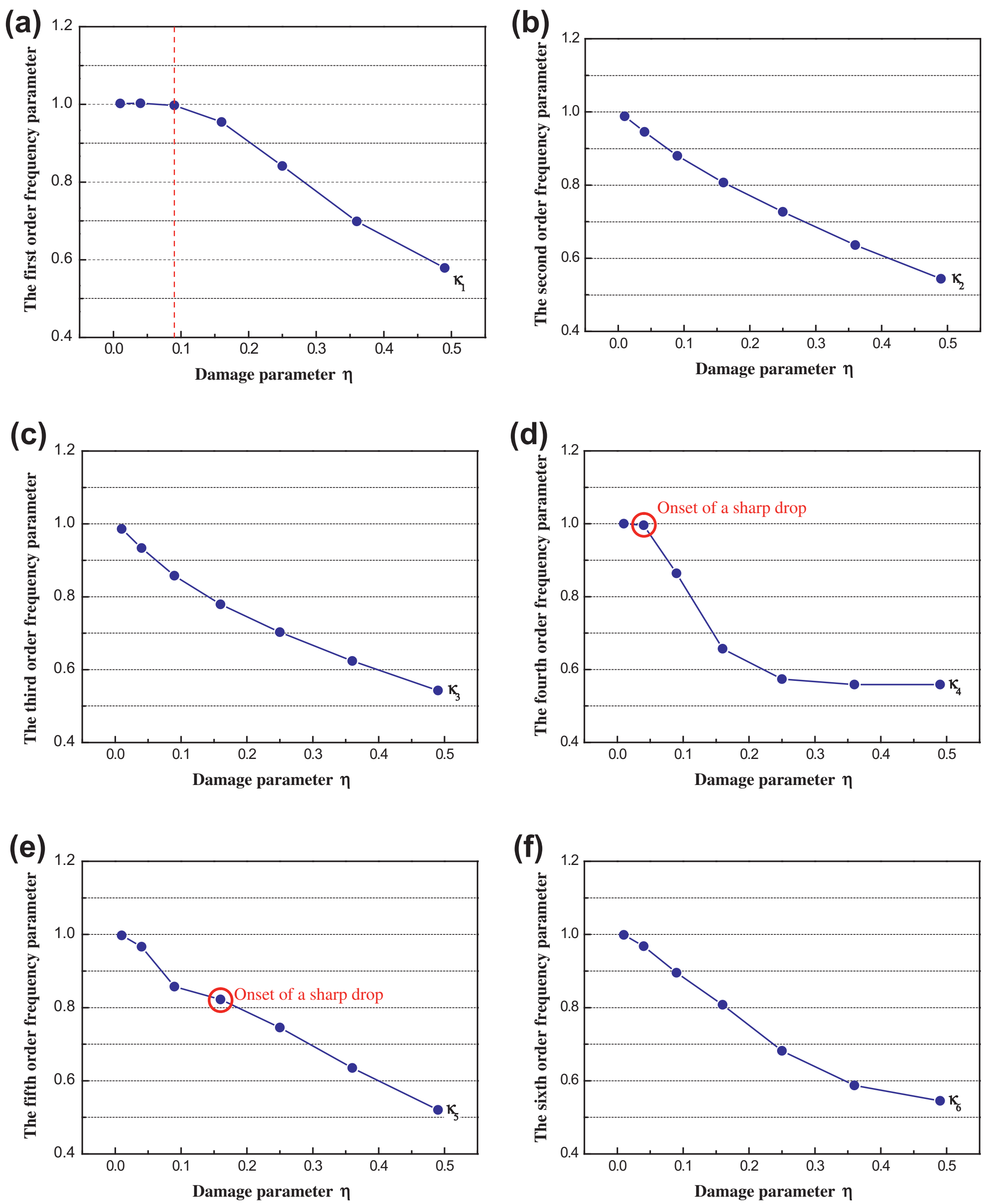

Fig. 13. Frequency parameters of pyramidal truss core sandwich plates with damaged regions at the center: (a) the first order frequency parameter, (b) the second order frequency parameter, (c) the third order frequency parameter, (d) the fourth order frequency parameter, (e) the fifth order frequency parameter, (f) the sixth order frequency parameter.

damage extent is represented by a damage parameter η denoting the ratio of the number of the missing truss members n to the number of the total truss members N within a corresponding intact pyramidal truss core sandwich plate:

$$\eta = \frac{n}{N} \tag{1}$$

Fig. 8 shows the constructed FEM models for an intact pyramidal truss core sandwich plate ($\eta = 0$) containing 10×10 unit cells and center-damaged ones with the damage parameters $\eta = 0.01$, 0.04, 0.09, 0.16, 0.25, 0.36, and 0.49, respectively. All the models have the same geometric dimension of $382 \times 382 \times 17\ \text{mm}^3$ and the same boundary conditions of clamping all the edges.

Numerical results presented in Figs. 9 and 10 respectively show the first six vibration modes of the intact composite pyramidal truss core sandwich plate and the damaged one with the damage parameter $\eta = 0.04$. The differences between the vibration modes of the intact sandwich plate (Fig. 9) and the damaged one (Fig. 10) are clearly observable in the contour plots. Fig. 10 evidently shows that the vibration modes of the damaged plate contain local deformation within its damaged region. This effect is more remarkable for higher order vibration modes, as shown in Fig. 10(e and f).

As it is mentioned above, the local deformation within the damaged region leads to the variation of the vibration modes of the damaged sandwich plate, and higher order vibration modes are

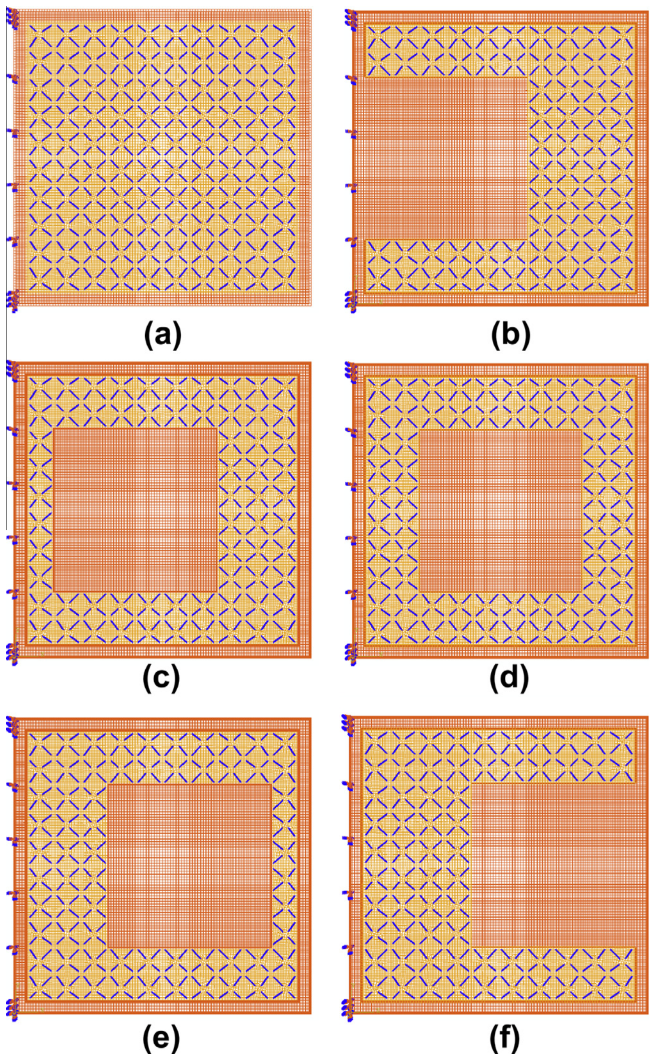

Fig. 14. Finite element models of pyramidal truss core sandwich plates with different locations of the damaged region: (a) intact pyramidal truss core sandwich plate, (b) Damage location A, (c) Damage location B, (d) Damage location C, (e) Damage location D, (f) Damage location E.

more sensitive to local damage. It is further found that with the increase of the damage parameter, the local deformations tend to dominate the vibration modes, as shown in Fig. 11(d) and Fig. 12(e). Moreover, with the emergence of such vibration modes, the corresponding natural frequencies decrease sharply. For instance, the fourth order natural frequency starts to drop sharply when the damage parameter reaches the onset of 0.04, and the fifth order natural frequency starts to drop sharply when the damage parameter is increased to 0.16.

To reflect the effects of local damage on the natural frequencies of composite pyramidal truss core sandwich structures, the following frequency parameter is defined:

$$\kappa = \frac{f_D}{f_I} \tag{2}$$

where f_D denotes the natural frequency of the damaged sandwich structure, and f_I denotes that of the intact one.

The relationship between the frequency parameters κ of composite pyramidal truss core sandwich plates and the damage parameter η is shown in Fig. 13. From this figure, one can see that the frequency parameters decrease with the increase of the damage parameter, and each order frequency parameter decreases to around 0.55 when the damage parameter increases from 0 to 0.49. Unlike other order frequency parameters, the first order frequency parameter almost identically equals to 1 when the damage parameter $\eta \leqslant 0.09$, which indicates that the first natural frequency (fundamental frequency) of pyramidal truss core sandwich structure is insensitive to local damage of the core, especially local damage of small size. Sudden changes of the vibration modes (comparing the vibration modes of the damaged sandwich plate with the intact one) lead to sharp drops of the corresponding frequency parameters, as shown in Fig. 13(d and e).

4.2. Effects of damage location

The effects of damage extent on modal parameters of composite pyramidal truss core sandwich structures are studied in the above sub-section. Different damage locations will have different influences on the vibration characteristics even if the damage extents are the same. In this sub-section, the effects of damage location on structural modal parameters are investigated.

Composite pyramidal truss core sandwich plates clamped at one edge and free at the other three edges with the same damage extents are considered. The damage parameter η is kept at 0.36, and the damaged region is set to be at the clamped edge, or at the opposite free edge, or between them, as shown in Fig. 14.

Fig. 14(a) illustrates the intact pyramidal truss core sandwich plate, Fig. 14(b) illustrates a damaged sandwich plate with the damaged region closest to the clamped edge (with a distance of 0 unit cells), which is referred as 'Damage location A', and Fig. 14(f) illustrates a damaged sandwich plate with the damaged region farthest away from the clamped edge (with a distance of 4 unit cells), which is referred as 'Damage location E'.

Numerical simulation results of the first six vibration modes of the intact cantilevered sandwich plate and the damaged one with the damage zone closest to the clamped edge (Damage location A) are given in Figs. 15 and 16, respectively. It can be clearly seen that although the first two vibration modes are hardly affected by local damage, obvious local deformation in the damaged region can be observed in higher order vibration modes due to the loss of structural stiffness. The emergence of such local deformation may lead to sharp drops of the corresponding natural frequencies.

The first six order frequency parameters of sandwich plates with the five damage locations shown in Fig. 14 are compared in Fig. 17. It can be seen from Fig. 17 that in general, the farther the damage zone is from the clamped edge, the higher the frequency parameters are, which means that the effects of local damage on structural natural frequencies become smaller as the damage zone is moved from the clamped edge to the opposite free edge. This finding indicates that the damage zone should be placed far away from the clamped edge when embedding additional components, such as fuel cell, damping materials, or wave absorbing materials, into a cantilevered lattice truss core sandwich plate through sacrificing several truss members, for in this way structural natural frequencies can be decreased by a smaller extent, so that possible resonances with the surrounding environment during serving can be effectively avoided.

4.3. Effects of damage form

To investigate the effects of damage form on the vibration characteristics, FEM models for fully clamped composite pyramidal truss core sandwich plates with the same damage parameter ($\eta = 0.36$) but different damage forms are constructed in this sub-section, as shown in Fig. 18. Fig. 18(a) illustrates a sandwich plate with its squared damaged region concentrated at the center, and Fig. 18(b–e) illustrates four sandwich plates, each with its four squared damaged regions distributed symmetrically.

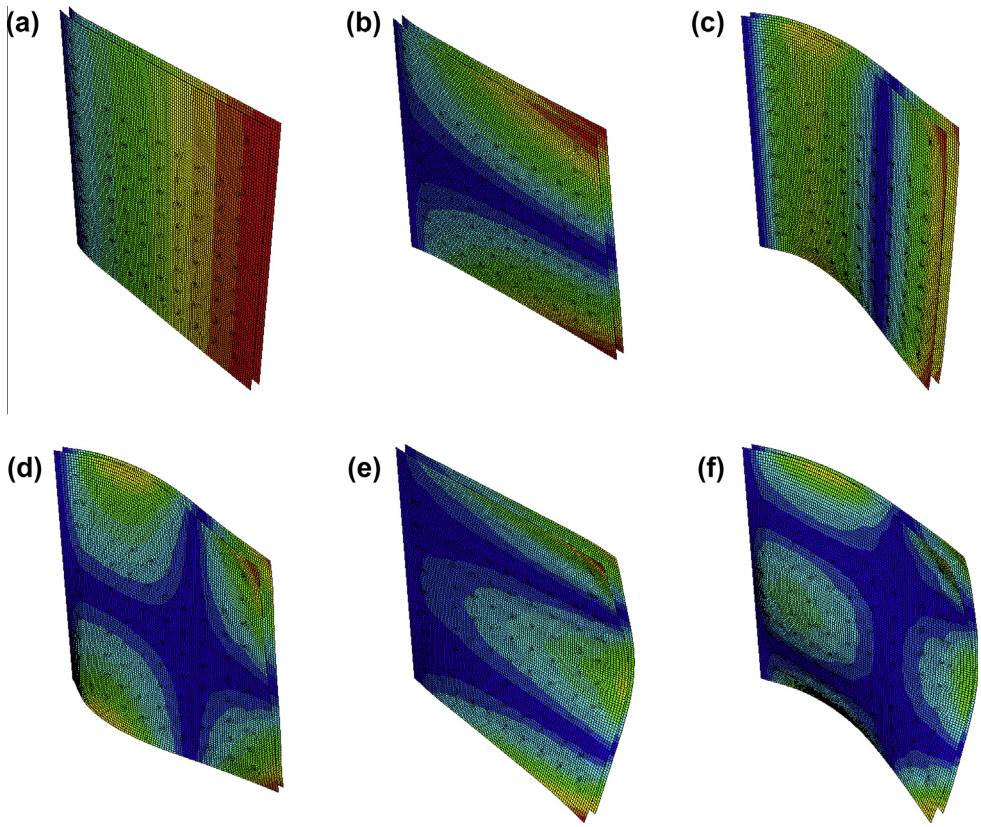

Fig. 15. The first six vibration modes of the intact cantilevered sandwich plate: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

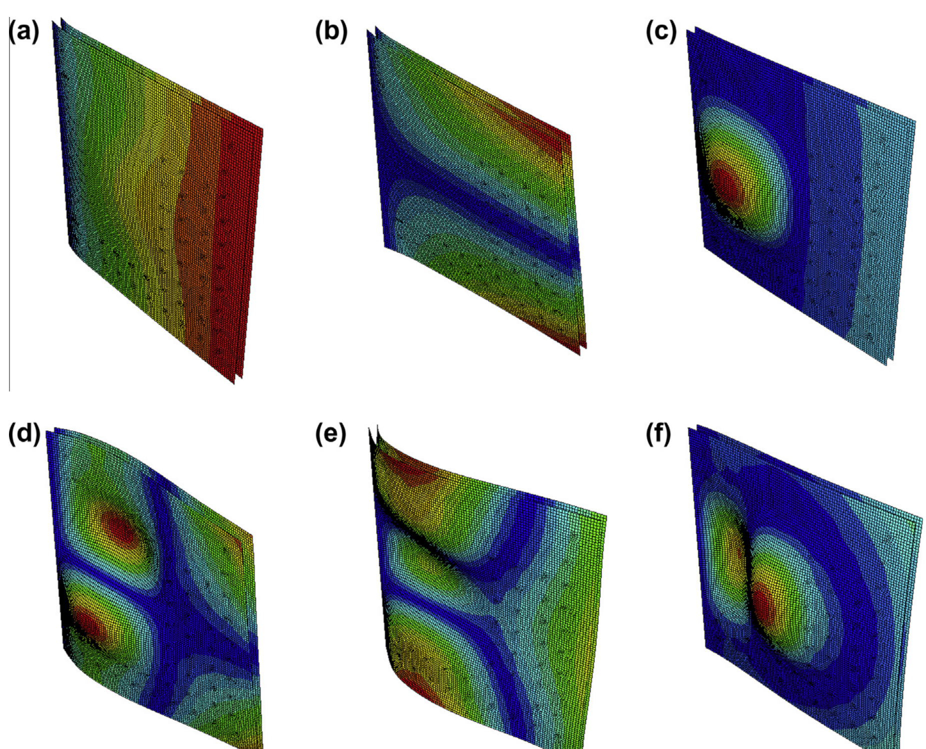

Fig. 16. The first six vibration modes of the cantilevered sandwich plate with damaged region closest to the clamped edge: (a) the first mode, (b) the second mode, (c) the third mode, (d) the fourth mode, (e) the fifth mode, (f) the sixth mode.

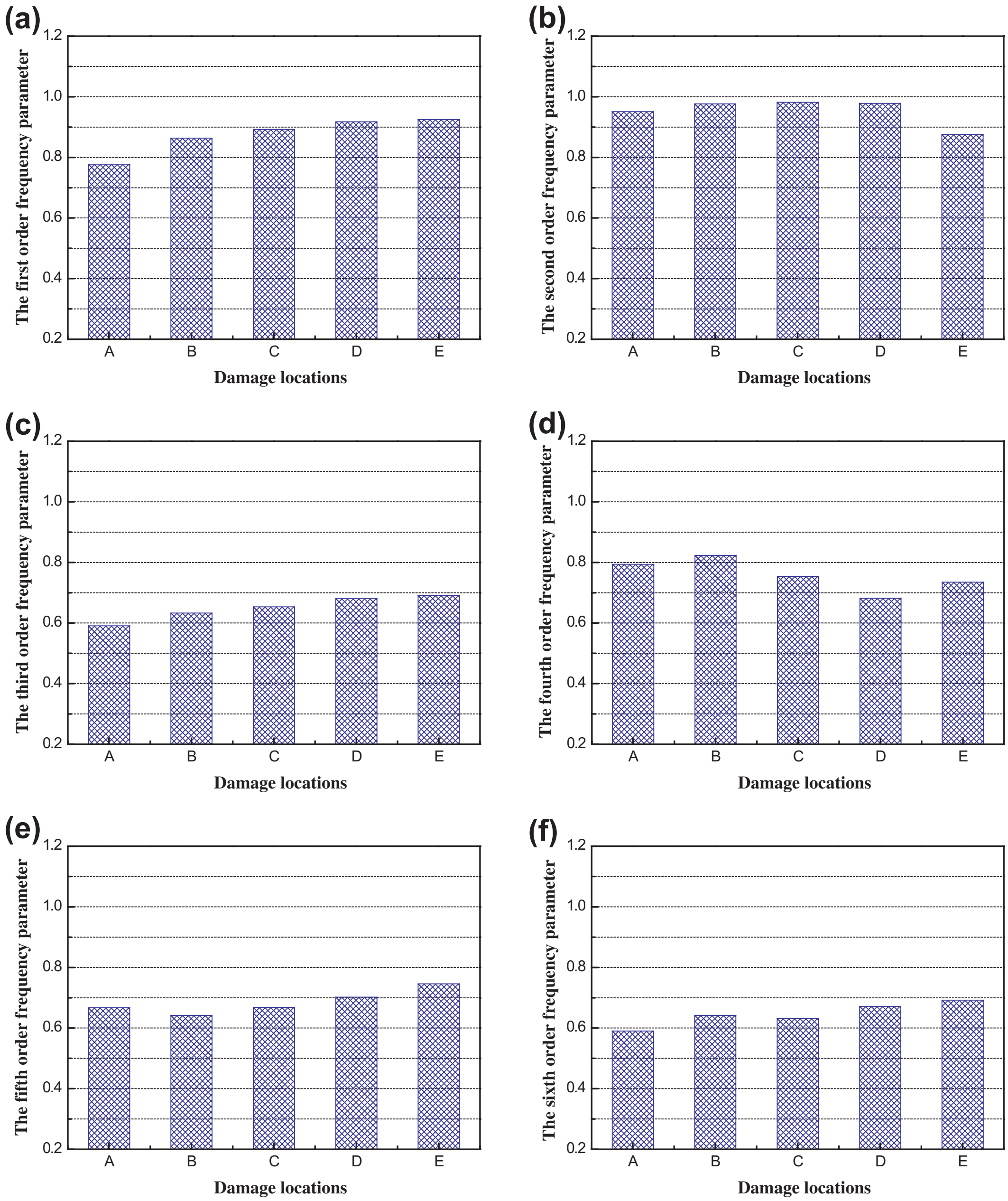

Fig. 17. Frequency parameters of pyramidal truss core sandwich plates with different locations of the damaged region: (a) the first order frequency parameter, (b) the second order frequency parameter, (c) the third order frequency parameter, (d) the fourth order frequency parameter, (e) the fifth order frequency parameter, (f) the sixth order frequency parameter.

The first four order frequency parameters of the above described five sandwich plates with five different damage forms are shown in Fig. 19. It is evident that the frequency parameters for 'Damage form A' (for which the damaged region is concentrated at the center) are the lowest, which demonstrates that this form of damage has the greatest effect on structural natural frequencies. In the case of the same damage parameter, concentrated damage causes a loss of stiffness in a large area, leading to sudden changes of the vibration modes (compared with the intact one) and sharp drops of the natural frequencies, while scattered damages have relatively smaller effects on the modal parameters. Therefore, in order to avoid concentrated damage of large areas, additional components should be placed at scattered regions when embedding them into a lattice truss core sandwich plate.

4.4. Effects of boundary conditions

It is the well-known, that boundary conditions can help to highlight the importance of localized effects in structural responses of plates. The influence of boundary conditions on the vibration characteristics of sandwich plates containing local damage at the center is studied by comparing the frequency parameters for five different types of boundary conditions, namely CCCC, CSCS, CFCF, CFFF, and SSSS, where 'F' denotes the free edge of the plate, 'S' and 'C' denote the simply supported and clamped edges, respectively. The material properties and geometric parameters are the same with those in previous calculations.

The numerical results that emphasize the effects of boundary conditions on the first six order frequency parameters of composite

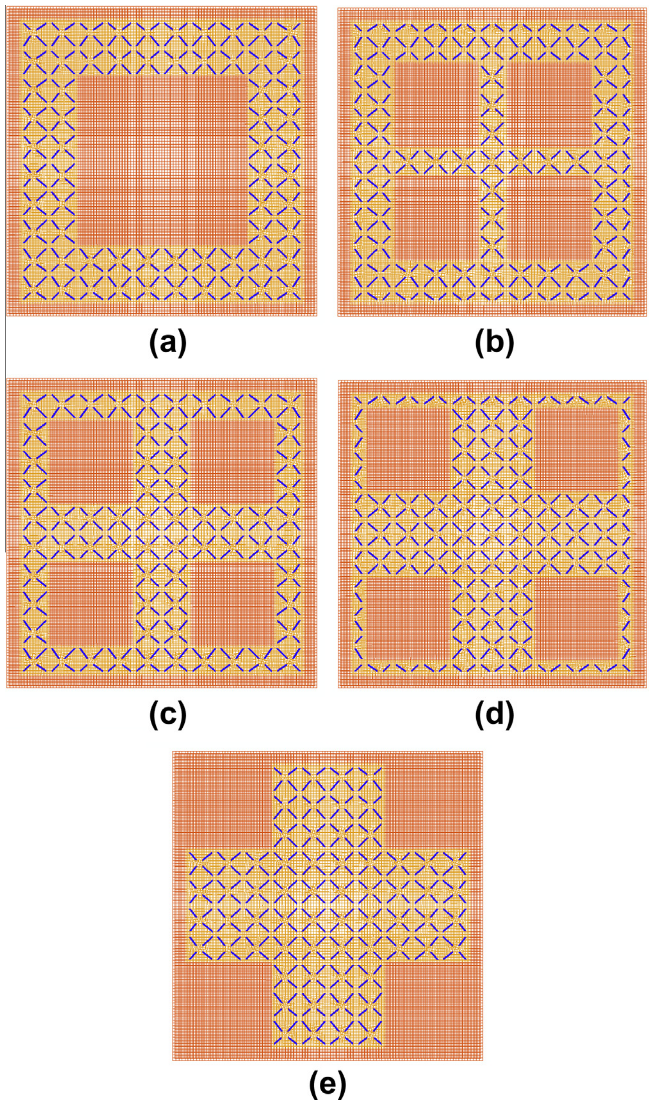

Fig. 18. Finite element models of pyramidal truss core sandwich plates with different damage forms: (a) Damage form A, (b) Damage form B, (c) Damage form C, (d) Damage form D, (e) Damage form E.

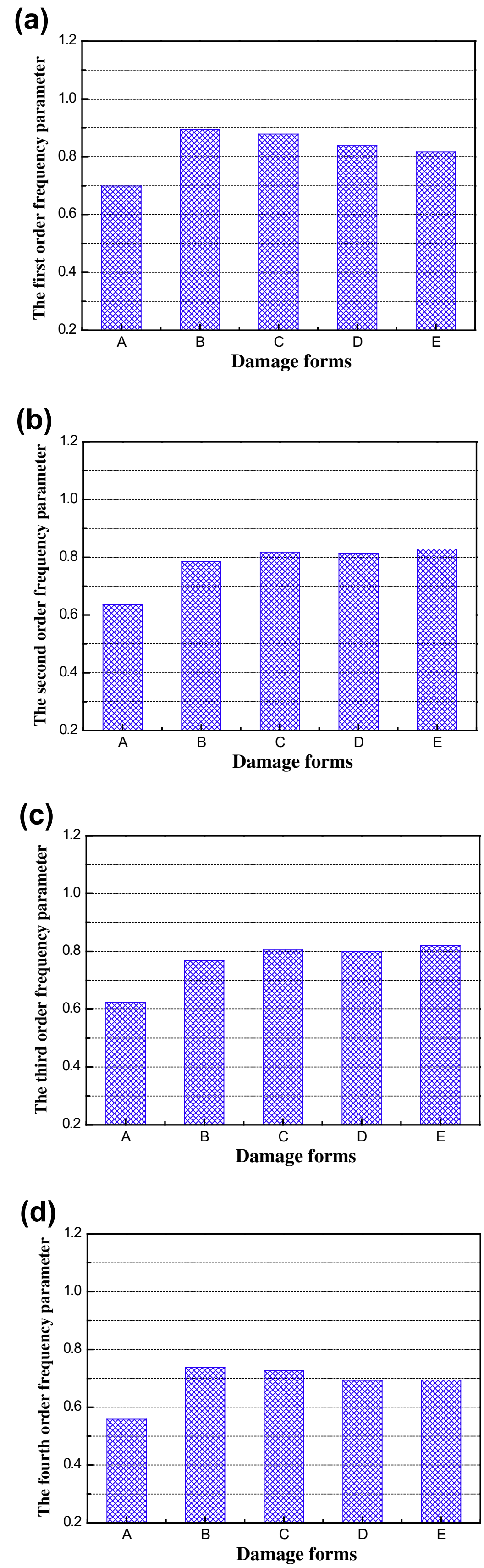

Fig. 19. Frequency parameters of pyramidal truss core sandwich plates with different damage forms: (a) the first order frequency parameter, (b) the second order frequency parameter, (c) the third order frequency parameter, (d) the fourth order frequency parameter.

pyramidal truss core sandwich plates with local damage at the center are summarized in Fig. 20. It can be observed that the frequency parameters decrease with the increase of the damage parameter, and such effect is stronger for plates under greater constraint. The greatest decrease in frequency parameters is reached for the fully clamped plate. The fundamental frequency of the fully clamped composite pyramidal truss core sandwich plate decreases by 42.10% when the damage parameter increases from 0 to 0.49, while that of the simply supported sandwich plate decreases by only 3.41%. Thereby, the presence of local damage within the sandwich plates can be detected more easily by imposing fully clamped boundary conditions.

5. Conclusions

The effects of local damage of the core on the natural frequencies and vibration modes of composite pyramidal truss core sandwich structures are studied by experimental modal analysis and numerical simulation method in the present paper. The conclusions that can be made from this study are as follows:

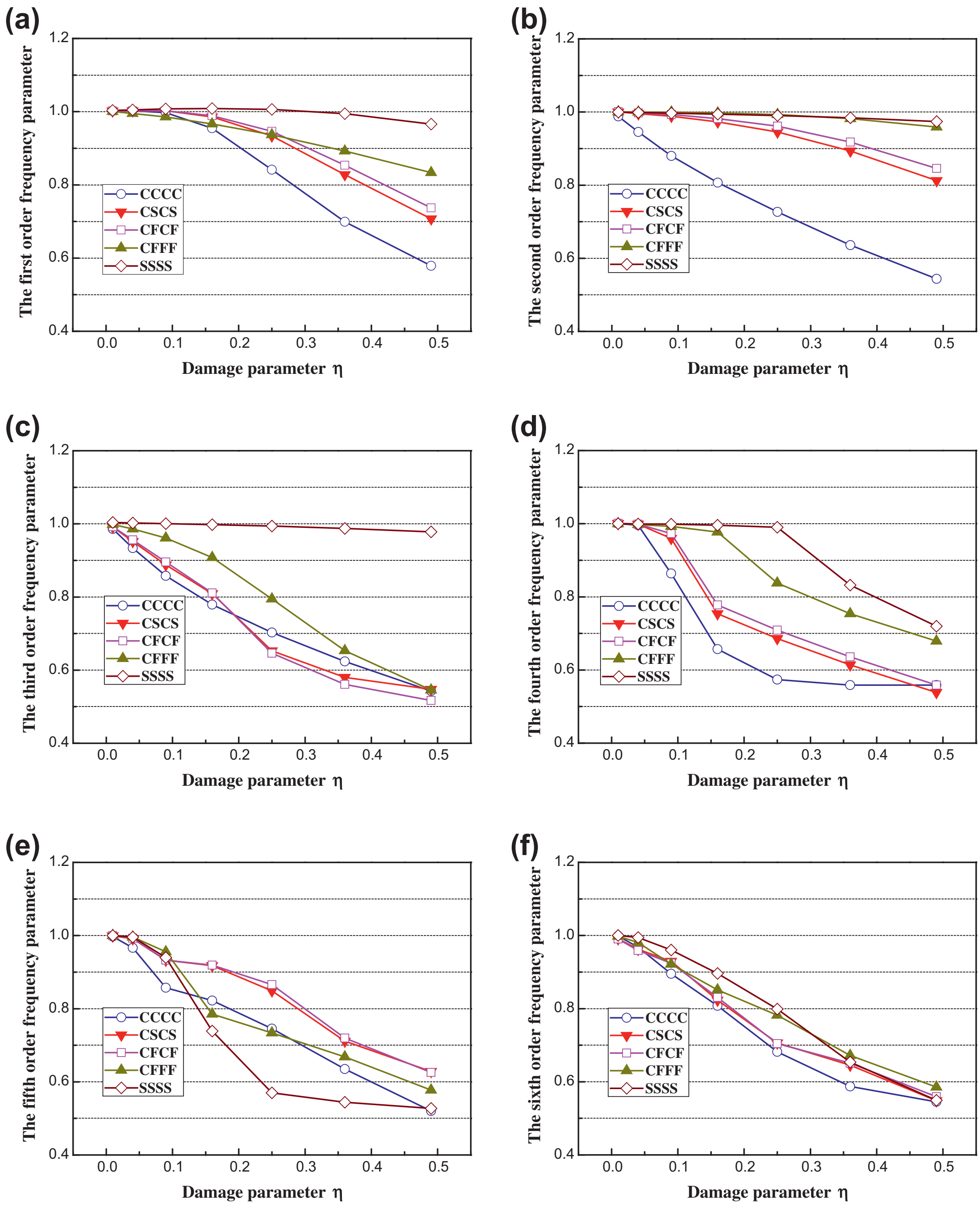

Fig. 20. Frequency parameters of pyramidal truss core sandwich plates under different boundary conditions: (a) the first order frequency parameter, (b) the second order frequency parameter, (c) the third order frequency parameter, (d) the fourth order frequency parameter, (e) the fifth order frequency parameter, (f) the sixth order frequency parameter.

(1) The structural natural frequencies decrease due to the loss of stiffness caused by the existence of local damage of the truss core. A damage parameter is defined to characterize the damage extent, and it is found that the influence of local damage becomes more significant with the increase of the damage parameter. Therefore, the damage parameter can be treated as an indicator of internal damage of lattice truss core sandwich structures.

(2) The vibration modes of the damaged composite pyramidal truss core sandwich structures show obvious local deformation in the damaged region.

(3) The vibration characteristics of cantilevered composite pyramidal truss core sandwich plates with the same damage parameter but different damage locations are compared, and the results demonstrate that the effects of local damage on structural natural frequencies get smaller as the damaged region moves from the clamped edge to the opposite free edge.

(4) Different damage forms influence structural natural frequencies in different extents. In the case of the same damage parameter, concentrated damage causes a loss of stiffness in a large area, leading to a greater decrease of natural frequencies in comparison with scattered damages.

(5) Boundary conditions imposed on the studied sandwich plate also play an important role. It is found that the fundamental frequency of a simply supported sandwich plate decreases by only 3.41% as the damage parameter increases from 0 to 0.49, while that of a fully clamped sandwich plate

decreases by 42.10%. The effects of local damage on structural natural frequencies become more significant with the enhancement of constraint at the boundaries.

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References

[1] Zenkert D. The Handbook of Sandwich Construction. London, UK: Chameleon Press Ltd.; 1997.
[2] Ahmed KM. Dynamic analysis of sandwich beams. J Sound Vib 1972;21(3):263–76.
[3] Allen HG. Analysis and Design of Structural Sandwich Panels. Oxford: Pergamon Press; 1969.
[4] Hachemane B, Zitoune R, Bezzazi B, Bouvet C. Sandwich composites impact and indentation behaviour study. Compos Part B–Eng 2013;51:1–10.
[5] Maturi DA, Ferreira AJM, Zenkour AM, Mashat DS. Analysis of sandwich plates with a new layer wise formulation. Compos Part B–Eng 2014;56:484–9.
[6] Liu T, Deng ZC, Lu TJ. Bi-functional optimization of actively cooled, pressurized hollow sandwich cylinders with prismatic cores. J Mech Phys Solids 2007;55(12):2565–602.
[7] Kim T, Hodson HP, Lu TJ. Fluid-flow and endwall heat-transfer characteristics of an ultralight lattice-frame material. Int J Heat Mass Trans 2004;47(6–7):1129–40.
[8] Tian J, Kim T, Lu TJ, Hodson HP, Queheillalt DT, Sypeckc DJ, et al. The effects of topology upon fluid-flow and heat-transfer within cellular copper structures. Int J Heat Mass Trans 2004;47(14–16):3171–86.
[9] Wang J, Lu TJ, Woodhouse J, Langley RS, Evans J. Sound transmission through lightweight double-leaf partitions: theoretical modeling. J Sound Vib 2005;286(4–5):817–47.
[10] He YZ, Tian GY, Pan MC, Chen DX. Non-destructive test of low-energy impact in CFRP laminates and interior defects in honeycomb sandwich using scanning pulsed eddy current. Compos Part B–Eng 2014;59:196–203.
[11] Jing L, Wang ZH, Zhao LM. An approximate theoretical analysis for clamped cylindrical sandwich shells with metallic foam cores subjected to impulsive loading. Compos Part B–Eng 2014;60:150–7.
[12] Xie QH, Jing L, Wang ZH, Zhao LM. Deformation and failure of clamped shallow sandwich arches with foam core subjected to projectile impact. Compos Part B–Eng 2013;44(1):330–8.
[13] Tan ZH, Luo HH, Long WG, Han X. Dynamic response of clamped sandwich beam with aluminium alloy foam core subjected to impact loading. Compos Part B–Eng 2013;46:39–45.
[14] Liu JY, Zhu X, Zhou ZG, Wu LZ, Ma L. Effects of thermal exposure on mechanical behavior of carbon fiber composite pyramidal truss core sandwich panel. Compos Part B–Eng 2014;60:82–90.
[15] Lee YH, Lee BK, Jeon I, Kang KJ. Wire-woven bulk kagome truss cores. Acta Mater 2007;55(18):6084–94.
[16] Lee BK, kang KJ. A parametric study on compressive characteristics of wire-woven bulk kagome truss cores. Compos Struct 2010;92(2):445–53.
[17] Lee BC, Lee KW, Byun JH, Kang KJ. The compressive response of new composite truss cores. Compos Part B–Eng 2012;43(2):317–24.
[18] Li M, Wu LZ, Ma L, Wang B, Guan ZX. Mechanical response of all-composite pyramidal lattice truss core sandwich panels. J Mater Sci Technol 2011;27(6):570–6.
[19] Yin S, Wu LZ, Ma L, Nutt S. Pyramidal lattice sandwich strucutres with hollow composite trusses. Compos Struct 2011;93(12):3104–11.
[20] Zhang GQ, Ma L, Wang B, Wu LZ. Mechanical behaviour of cfrp sandwich structures with tetrahedral lattice truss cores. Compos Part B–Eng 2012;43(2):471–6.
[21] Tian SX, Chen ZM, Chen LL, Zhang DL. Numerical analyses on influence of damage configuration on vibration parameters for lattice sandwich plate. Int J Appl Electromagn Mech 2010;33(3–4):1565–72.
[22] Hu JS, Hwu C. Free vibration of delaminated composite sandwich beams. AIAA J 1995;33(10):1911–8.
[23] Kim HY, Hwang W. Effect of debonding on natural frequencies and frequency response functions of honeycomb sandwich beams. Compos Struct 2002;55(1):51–62.
[24] Burlayenko VN, Sadowski T. Influence of skin/core debonding on free vibration behavior of foam and honeycomb cored sandwich plates. Int J Non-Linear Mech 2010;45(10):959–68.
[25] Baba BO, Thoppul S. An experimental investigation of free vibration response of curved sandwich beam with face/core debond. J Reinf Plast Compos 2010;29(12):3208–18.
[26] Sokolinsky VS, Bremenb HF, Lesko JJ, Nutt SR. Higher-order free vibrations of sandwich beams with a locally damaged core. Int J Solids Struct 2004;41(22–23):6529–47.
[27] Wang B, Wu LZ, Ma L, Sun YG, Du SY. Mechanical behavior of the sandwich structures with carbon fiber-reinforced pyramidal lattice truss core. Mater Des 2010;31(5):2659–63.
[28] Wang SX, Wu LZ, Ma L. Low-velocity impact characteristics of carbon fiber composites lattice core sandwich structures. Adv Mater Res 2009;127(79–82):127–30.