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Effect of local damages on the buckling behaviour of pyramidal truss core sandwich panels

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ABSTRACT

Truss core sandwich panels have been widely investigated due to their superior mechanical performances. However, local defects or damages during preparation and service may reduce the strength significantly. The objective of this paper is to examine the imperfection sensitive of this kind of structures under in-plane compression. The elastic and plastic buckling behaviour of pyramidal truss core sandwich panels with local damages under in-plane compression are studied experimentally and numerically. Local damages including unbound nodes between lattice truss and the facesheet, missing lattice cells and holes in the facesheet are considered. In-plane compression tests of truss core sandwich panels with prefabricated local damages are conducted, and then a finite element model in conjunction with random number is developed to simulate the buckling behaviour of the panel with randomly distributed damages in a specific region. Experimental and numerical results show that, besides the damage extent, the location of unbound nodes and missing lattice cells have significant effect on the buckling strength of the pyramidal truss core sandwich panel. In addition, the local damage sensitiveness of sandwich panel with round holes in the facesheet is lower than that with square holes.

1. Introduction

Truss core sandwich panels, which possess combinations of load capacity and multi-functionality, are advanced structures that can be applied in industrial sectors such as ships, aircrafts, civil engineering and aerospace engineering. With the development of preparation technique, various types of lattice truss materials have been fabricated and have been extensively investigated for their basic mechanical properties and applications in energy absorption [1–9]. Nevertheless, the stiffness and strength of the truss core sandwich panel may decrease due to a variety of imperfections and local damages caused by their own structural complexity, immaturity of manufacturing process and severe service environment and load. Therefore it is necessary to examine the sensitivity of truss core sandwich panel to local damages, especially on their mechanical properties such as the buckling strength.

There have been some experimental and theoretical works focused on the behaviour of sandwich structures under bending and in-plane compression [10,11]. Hu et al. [11] reviewed and assessed various theories for modelling sandwich composites. By ignoring the bending stiffness of the core, the critical buckling load of the sandwich panel can be analytical solved, and it is a simple yet effective approach for predicting overall buckling load for sandwich panel [12]. However, for sandwich panels under in-plane compression, local buckling or other complex failure mode may happen except for the global buckling, and the finite element method with appropriate kinematic model for instability analysis is imperative [13–15]. When sandwich structures have initial imperfections, local damages have been a subject of major concern in engineering applications because of the associated problems of reduction in load-bearing capacity. The presence of the this kind of damages, which causes reductions in the bending stiffness and shear stiffness, will leads to the undesirable loss in the buckling strength. There have been many relevant studies on the imperfection sensitivity of the buckling behaviours of sandwich structures to local damages. Somers et al. [16] developed a theoretical model to predict the buckling load and the post-buckling behaviour of delaminated sandwich beams. It can be found from their studies that the sandwich construction is very sensitive to the presence of delaminations situated at the core-facesheet interface. Kwon et al. [17] analysed the compression behaviour of sandwich beams which have holes and delaminations between the skin and the core. Rasmus et al. [18] analysed the behaviour of the compression loaded sandwich beams that contains a debond by using a geometrically non-linear finite element model. The finite element model

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reveals that the sandwich column is very sensitive to the initial debond length and the local facesheet imperfection. The sensitivity results from two mechanisms: (a) interaction of local debond buckling and global buckling and (b) the development of a damaged zone at the debond crack tip. In addition, similar conclusions can be found from the related works [19–22].

Recently some works was also reported on the imperfection sensitive of lattice truss materials with missing lattice cells [23–26]. It can be found from these studies that the lattice truss material is more tolerant to local damages for the compression behaviours than open-cell foams [23,26]. Moreover, local damages take the form of unbound nodes also have less effect on the compression stiffness and peak strength of truss core sandwich panels. But shear properties of truss core sandwich panels are significantly degraded due to this kind of local damages [27]. As a result, this kind of local damages may reduce the buckling strength of truss core sandwich panels, which have poor shear stiffness. Yuan et al. [28] analysed the thermal buckling behaviour of pyramidal truss core sandwich panels experimentally. It can be found from the experimental result that the local damage during fabrication has a great effect on the critical thermal buckling temperature and the buckling mode of the sandwich panel. For other types of local damages, Sebaey et al. [29] studied the behaviour of pyramidal truss core sandwich panels with notched facesheet under biaxial compression through numerical simulation.

However, it is noticed that the sensitivity of the buckling behaviour of truss core sandwich panels to the extent and the type of damages has been rarely studied, especially when missing lattice truss cells and unbound nodes are located in a specific region. In the present paper, the response of pyramidal truss core sandwich panels with unbound nodes, missing lattice truss cells and holes in the facesheet subjected to in-plane compression are studied experimentally and numerically. The outline of this paper is as follows. In Section 2, the fabrication process of the specimen with prefabricated local damages and the experimental procedure are described. In Section 3, the finite element model in conjunction with random number is developed, and a series of numerical analysis are carried out to investigate effects of damage extent, damage type and damage location on the critical buckling load. Finally, some findings are collected and summarised in Section 4.

2. Experiments

In this section, in-plane compression experiments are conducted to investigate the effect of local damages on the buckling behaviour of the pyramidal truss core sandwich panel. The buckling load and the failure mode of the pyramidal truss core sandwich panel are obtained from the compression tester and the CCD camera respectively.

2.1. Fabrication of specimen

Defects in the pyramidal truss core sandwich panel during fabrication mainly include global geometric imperfections, local damages and flaws in the material microstructure. Previous researches have shown that local damages may weaken the shear strength and the buckling load of the truss core sandwich panel dramatically [27,28]. Specimen with prefabricated local damages of unbound nodes between facesheet and lattice truss core, and holes in the facesheet, are fabricated. So far, there have been some preparation methods to fabricate the truss core sandwich panel, including investment casting method, weaving method, wire cutting method, hot-pressing method and folding method [5,30–32]. Here the folding method is adopted due to its ease of fabrication, low-cost and suit for most metal truss cores.

As shown in Fig. 1, pyramidal truss cores with a relative density $\bar{\rho}$ of about 3% are fabricated from 0.7 mm thick stainless steel wire mesh. The stainless steel wire mesh was folded into pyramidal truss cores by using a punch-and-die pair of 60° angle. The brazing technique was chosen to join the truss core and facesheets and form the complete pyramidal truss core sandwich panel. The size of the specimen fabricated in the present paper are 250×250 mm. The truss core thickness is 7 mm and the facesheet thickness is 0.9 mm. Both the facesheet and the truss core are made of stainless steel. The protective coating is spread on the joint area of the truss core to make the prefabricated unbound nodes. Fig. 2 shows the sketch of the fabrication method. The types of prefabricated local damages can be shown in Fig. 3. Four types of specimen denoted “D1”–“D4” respectively, are prepared. “D1”–“D3” indicate the damaged pyramidal truss core sandwich panel with unbound nodes and “D4” indicate the specimen with round holes in the facesheet. D1 indicate the specimen with single-row unbound nodes that perpendicular to the loading direction. D2 and D3 are specimens with 6×11 and 4×7 unbound nodes that placed in the centre of the sandwich panel. D4 indicate the specimen has a round hole with a diameter of 15 mm in the facesheet.

2.2. Experimental procedure

In-plane compression tests were conducted in a 1000 kN capacity hydraulic universal testing machine WE-1000B. To make the sandwich panel properly aligned, all edges of the sandwich panel are cut off 10 mm by using the wire electrode-cutting. A pair of clamps made of solid steel is placed at each end of the specimen to provide a clamped boundary condition. A CCD camera is placed at one side of the sandwich panel to obtain the histories of failure mode. The loading rate of the compression crosshead is $2\ \mathrm{mm\ min}^{-1}$ and the sampling frequency of the CCD camera is 1 Hz.

2.3. Experimental results

Figs. 4–6 show the failure process of the perfect specimen, and specimens with local damages of D1 and D4. Fig. 7 shows failure modes of specimens with different local damages. Fig. 8 shows compression loads versus displacements. It is revealed from experimental results that, due to the geometrical configuration of the specimen, local yielding induced plastic buckling is the main failure mode of the specimen. Buckling loads of specimens with different types of local damages are 31–61 kN. Moreover, it should be noted that the buckling strength of the sandwich panel is very sensitive to the location of the unbound nodes. Unbound nodes distributed in the widthwise direction (perpendicular to the loading

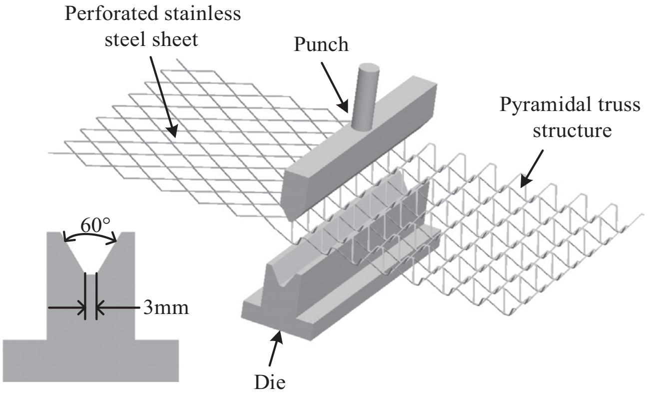


Fig. 1. Sketch of the punching operation to manufacture pyramidal truss cores.

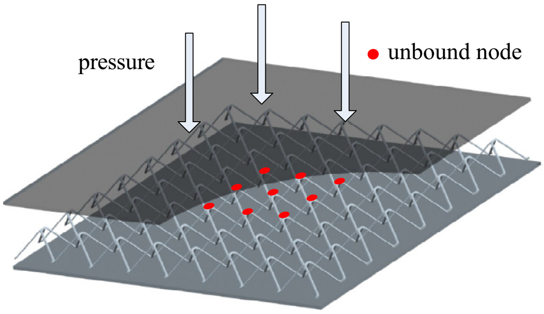


Fig. 2. Sketch of fabrication of sandwich pane with unbound nodes.

direction) will reduce the stability of the pyramidal truss core sandwich panel dramatically. Whereas damages of unbound nodes located in the centre area and round holes in the facesheet have little effect on the buckling strength of the truss core sandwich panel. It also should be noted that stochastic defects arise from the immature fabrication procedure may significantly harm the buckling load. For example, in Fig. 8 the peak load of the perfect specimen is obvious lower than that of specimen with damage of D3. Since stochastic defects are uncontrollable at the present stage, it is difficult to obtain the influence tendency of various damages merely from experiments. Therefore, to examine weather the truss core sandwich panel is always insensitive to a certain type of local damages and how local damages affect the buckling strength, effective numerical analysis is imperative.

3. Effect of local damages

3.1. Numerical model

In this section, a three dimensional finite element model is developed by the commercial software ABAQUS to simulate the buckling behaviour of pyramidal truss core sandwich panels with local damages under in-plane compression. The facesheet and truss cores are modelled with shell and beam element respectively. The finite element model is combined with a MATLAB program to automatically specify random damages of various extents in a given region. The geometry size and materials of the sandwich panel are basically in accordance with the specimen fabricated in the experiment. The geometric dimension of the sandwich panel with 25 columns and 14 rows in the finite element model is 230 × 230 × 8.8 mm. The size of rectangular cross section of the truss member is 1 × 0.7 mm. As shown in Fig. 9, regions of local damages investigated in the present work mainly includes: L1: rectangular distribution of damages with 11 columns and 5 rows located in the centre of the sandwich panel. L2: local damages with 3 columns and 14 rows distributed in a band aligned in the lengthwise direction (parallel to the loading direction). L3: local damages with 25 columns and 2 rows distributed in a band aligned in the widthwise direction.

Under in-plane compression load the sandwich panel may demonstrated two different buckling mechanisms: elastic buckling and plastic buckling. As shown in the experiment, the plastic buckling is the main failure mechanism of the specimen. Therefore, the elastic–plastic model is considered and the plastic buckling is firstly studied in the finite element model. Table 1 gives the comparison of buckling loads from the experiment with those from the finite element model. It can be seen that a good agreement is achieved. Then, a series of numerical investigations are carried out to further study the effect of locations and extent of local damages on the plastic buckling strength of the truss core sandwich panel.

3.2. Plastic buckling

3.2.1. Effect of unbound node

In this sub-section, the effect of unbound nodes on the buckling load of truss core sandwich panels under compression is studied. The extent of unbound nodes is represented by a parameter η denoting the ratio of the number of unbound nodes n to the total number of nodes that placed in one side of the sandwich panel N.

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

Fig. 10 shows buckling modes of sandwich panels with different locations of unbound nodes. For sandwich panels with unbound nodes in L1, facesheet buckling in the region of unbound nodes induced global buckling will be the main failure mode. A similar failure mode can be found in sandwich panel with unbound nodes in L2. The global buckling behaviour with uniform deformation in widthwise direction will be the main failure mode of sandwich panels with unbound nodes in L3. Fig. 11 shows normalised buckling loads of truss core sandwich panels with different number of unbound nodes. The buckling strength of pyramidal truss core sandwich panels is not sensitive to unbound node in region L1. When the unbound node of the sandwich panel has a proportion of about 8%, the buckling load declined to 99.3%. The buckling load declined to 84%, when the extent of unbound nodes increases to

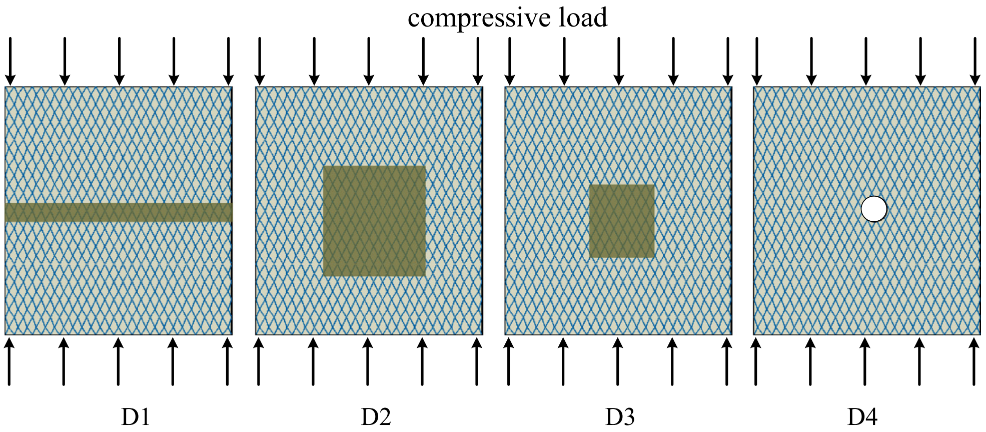


Fig. 3. Sketch of the experimental specimen with different damage types and locations: D1, specimen with single-row unbound nodes, D2, specimen with 6 × 11 unbound nodes that placed in the centre, D3, specimen with 4 × 7 unbound nodes that placed in the centre, D4, specimen with ∅15 mm round hole in the facesheet.

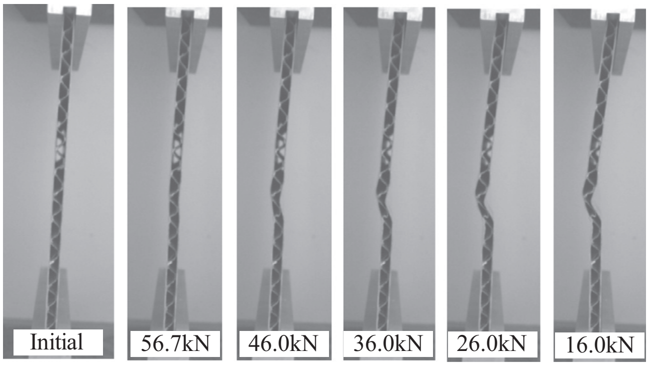


Fig. 4. Failure process of perfect truss core sandwich panel.

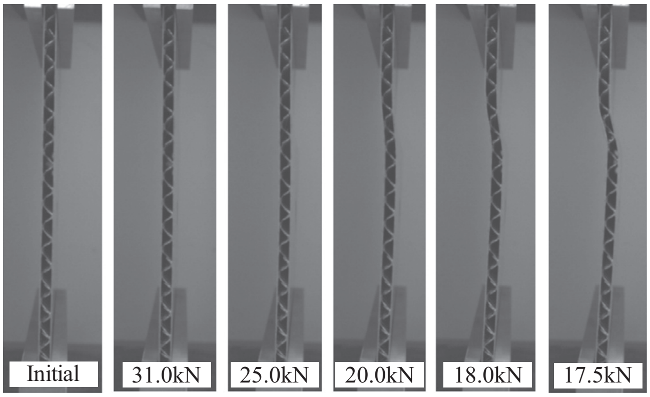


Fig. 5. Failure process of the specimen with local damages of D1.

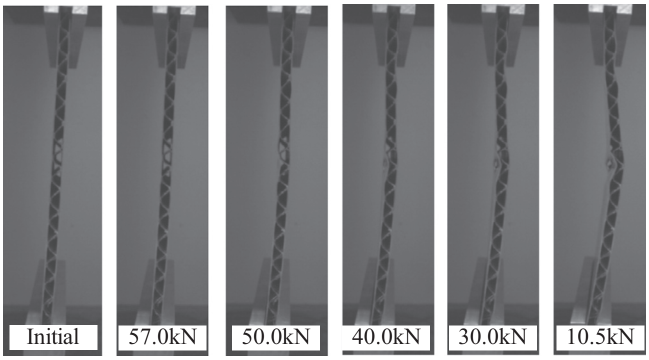


Fig. 6. Failure process of the specimen with local damages of D4.

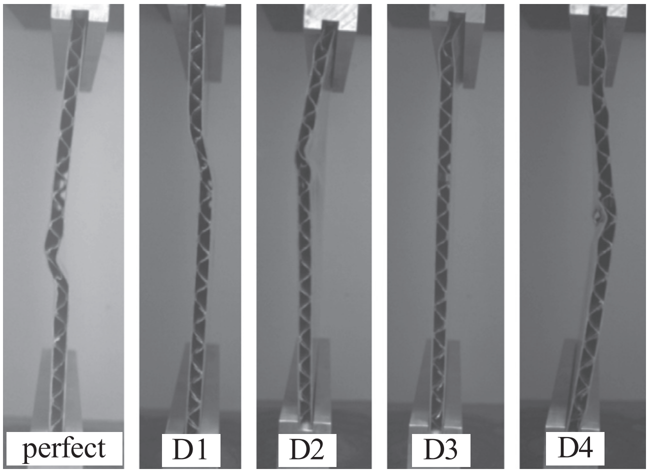


Fig. 7. Failure modes of specimens with different prefabricated local damages.

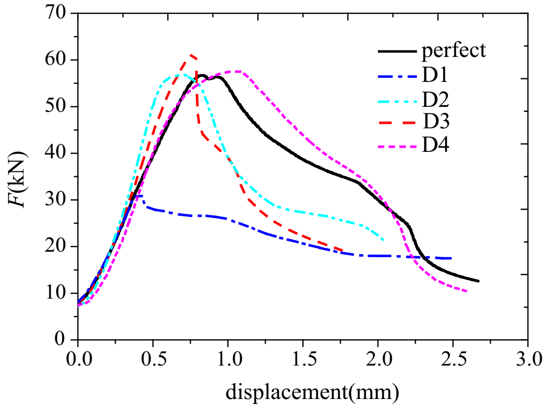


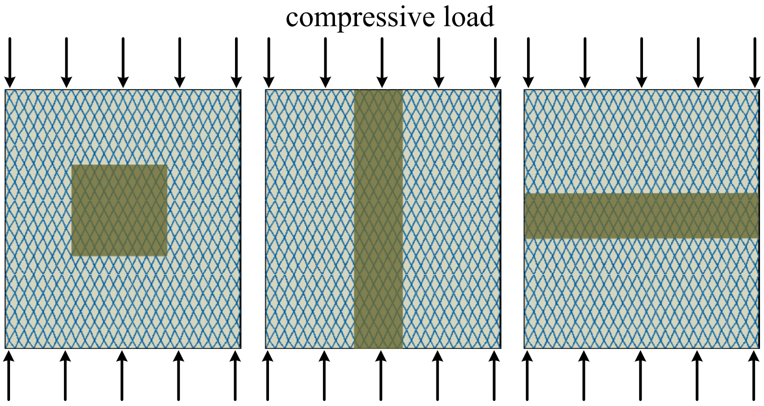
Fig. 8. Compressive loads versus displacements.

19%. Also, the buckling load is almost constant for the pyramidal truss core sandwich panel even when the number of unbound nodes in region L2 reaches 15%.

However, under the action of the external compressive load, which is lower than the critical buckling load for the truss core sandwich panel without local damages, the unbounded section along the widthwise direction is susceptible to local buckling which may lead to premature comprehensive failure of the sandwich panel. Therefore, unbound nodes in damage region L3 will reduce the critical buckling load of the truss core sandwich panel dramatically. The buckling strength declined to 70% when the unbound node of the sandwich panel has a proportion of about 7%. When the extent of unbound node increases to 14%, the buckling load declined to 40%. Therefore, a pyramidal truss core sandwich panel is very sensitive to the presence of through-the-width unbound nodes. Unbound nodes located in the centre area or lengthwise have less influence on the buckling strength of pyramidal truss core sandwich panel.

3.2.2. Effect of missing lattice cell

As with the unbound node, three different types of damage regions of missing lattice cells are also considered. In this subsection the damage extent parameter η is denoted by the ratio of the number of missing lattice cells to the total number of lattice cells. Fig. 12 shows failure modes of pyramidal truss core sandwich panels with different locations of missing lattice cells. For sandwich panels with missing lattice cells in L1, buckling of facesheet in the region of missing lattice cells induced global buckling is the main failure mode. Global buckling behaviour will happen in sandwich panels with local damages in the other two locations. The deformation along the widthwise direction is not uniform for sandwich panel with L2, but uniform for L3. Fig. 13 shows the buckling load of pyramidal truss core sandwich panels with different damage extents. It also can be found that missing lattice cells in region L1 have a moderate effect on the buckling load of sandwich panels. The critical buckling load declined to 81% when missing lattice truss cells of the sandwich panel has a proportion of about 15%. Missing lattice cells in damage region L2 have little effect on the buckling load of truss core sandwich panel. However, according to the reason stated in the study of unbound nodes, missing lattice cells in region L3 reduce the buckling load dramatically. The buckling load declined to 72% when the proportion of missing lattice

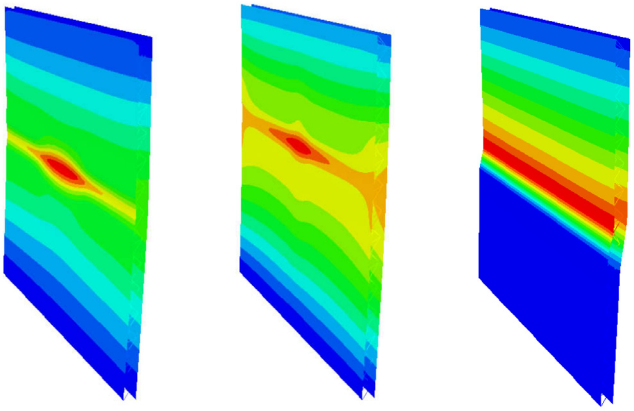


(a)L1 (b)L2 (c)L3

Fig. 9. Three typical damage regions studied in the FEM.

Table 1
Comparisons of critical buckling loads from experiment and FEM.

	Perfect (kN)	D1 (kN)	D2 (kN)	D3 (kN)	D4 (kN)
Experiment	56.7	31	56.8	61	57.5
FEM	64	45	56	63.5	60.5



(a)L1 (b)L2 (c)L3

Fig. 10. Buckling modes of truss core sandwich panels with unbound nodes of different locations.

truss cells is only about 4%. When the number of missing lattice truss cells increases to 14%, the buckling load declined to 38%. Therefore, the pyramidal truss core sandwich panel is very sensitive to the widthwise missing lattice cells, but not sensitive to damages in the other two regions. In addition, the influence of missing lattice truss cells to the critical buckling load of pyramidal truss core sandwich panels under in-plane compression is more severe compared with the damage of unbound nodes. It means that the lattice cell makes a contribution to the buckling strength of pyramidal truss core sandwich panels, even though it is not welded to the facesheet.

3.2.3. Effect of hole in the facesheet

For sandwich panel structures, holes are usually drilled in the facesheet for joining. The presence of these holes results in higher stress concentration in the facesheet. Therefore, the buckling strength of such a panel configuration experiences a reduction under compression. Fig. 14 shows failure modes of pyramidal truss core sandwich panels with square and round holes in the facesheet. Fig. 15 shows the buckling load of sandwich panels with different hole areas. The effect of square holes is more severe than that of round holes due to the stress concentration in the corners of the square hole.

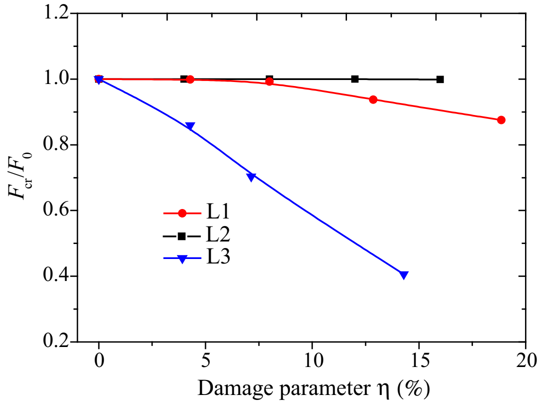
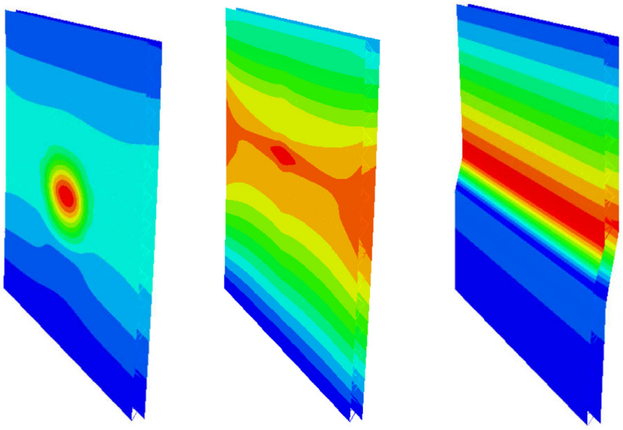


Fig. 11. Buckling loads of truss core sandwich panels with different number of unbound nodes.



(a)L1 (b)L2 (c)L3

Fig. 12. Buckling modes of truss core sandwich panels with missing lattice cells.

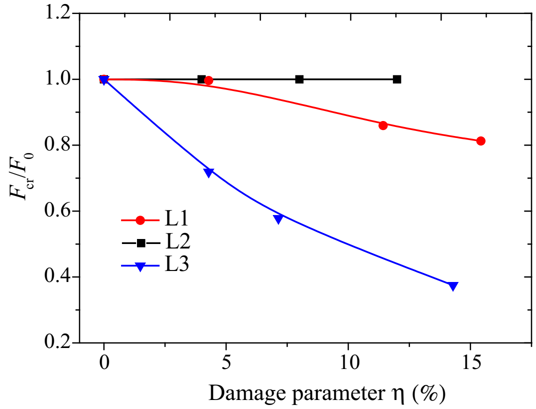


Fig. 13. Buckling loads of truss core sandwich panels with different number of missing lattice cells.

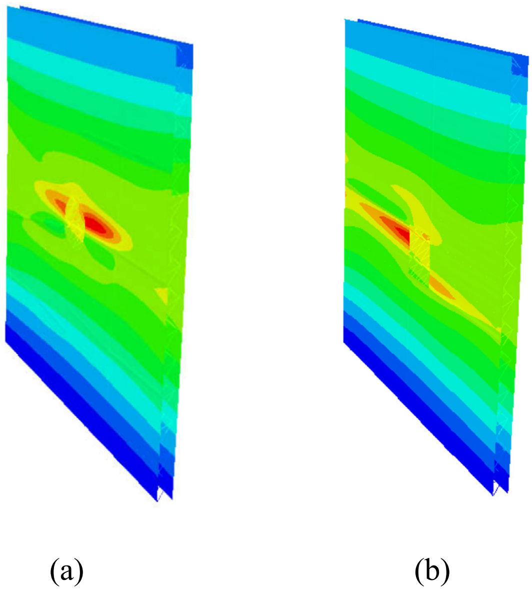


Fig. 14. Buckling modes of truss core sandwich panels with square and round holes in the facesheet.

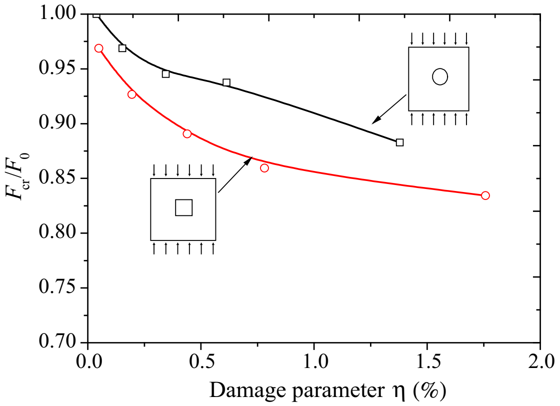


Fig. 15. Buckling loads of truss core sandwich panels with different sizes of holes.

3.3. Elastic buckling

3.3.1. Effect of random missing lattice cell

Besides the plastic buckling behaviour, the effect of local damages on the elastic buckling behaviour of sandwich panels has also been studied numerically. In this section, local random damages of removing lattice cells and holes in the facesheet are investigated. The numerical model was created automatically by using a series of Matlab scripts, which were then used to produce script files for the finite element model. Besides the three typical regions of local damages illustrated in Fig. 9, the case of random missing lattice cells in the entire region of the sandwich panel is also considered.

Fig. 16 shows the buckling load of sandwich panel with random missing lattice cells in the entire region. It can be found that this kind of damage has little effect on the buckling strength of the sandwich panel. However, as shown in Fig. 17, the damage of random missing lattice cells in L1 reduce the compression strength the of sandwich panel dramatically, which is different from the behaviour of plastic buckling. That is because the buckling mode transferred from global buckling to the facesheet buckling when the number of missing lattice cells reaches about 8%, and the presence of local facesheet buckling obviously harm the buckling load. Fig. 18 shows the critical load of sandwich panels with different number of missing lattice cells in L2. Like the response of plastic buckling, the sandwich panel is not sensitive to the local damage with location of L2. For sandwich panels with missing lattice cells in L3, random damages has little effect on the compressive strength when the damage extent below 8%, which is shown in Fig. 19. As the number increases, the random missing lattice cells will get together to form a single row in the direction perpendicular to the compressive load, and it reduces the buckling strength of truss core sandwich panel dramatically.

A comparison of critical buckling load reduction associated with the extent of random missing lattice cells in different locations is shown in Fig. 20. The sandwich panel is not sensitive to random missing lattice cells when it has a small number of random damages. When the extent increases, random missing lattice cells in L1 and L3 have great influence on the buckling strength of truss core sandwich panels under compression. By introducing about 14% random missing lattice cells, the strength reduction was up to 60% when they are in L1, whereas random damages in L3 reduced the strength by 80%.

3.3.2. Effect of hole in the facesheet

In addition, the effect of randomly distributed holes in the facesheet on the buckling strength of truss core sandwich panel

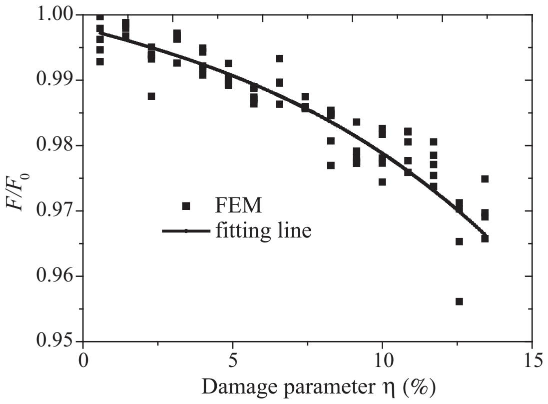


Fig. 16. Buckling loads of truss core sandwich panels with different number of missing lattice cells in the entire region.

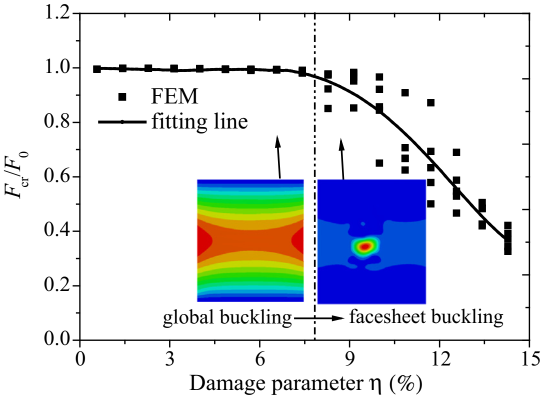


Fig. 17. Buckling loads of truss core sandwich panels with different number of missing lattice cells in L1.

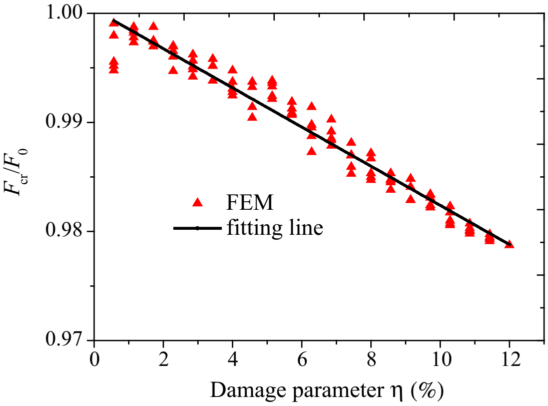


Fig. 18. Buckling loads of truss core sandwich panels with different missing lattice cells in L2.

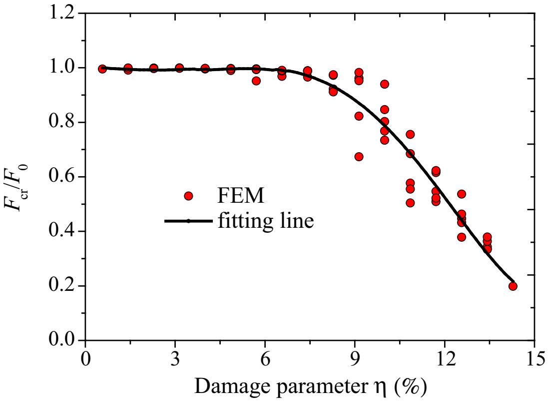


Fig. 19. Buckling loads of truss core sandwich panels with different missing lattice cells in L3.

is considered. Fig. 21 shows the critical load of sandwich panel with different size of round and square holes. The strength of the sandwich panel decreases linearly with increasing fraction of removed facesheet. It also can be seen that the effect of the square holes is more severe than that of round holes due to the stress concentration in the corners of the square hole. By introducing area reduction of 7%, the strength reduction was 13% for square holes and 11% for round holes.

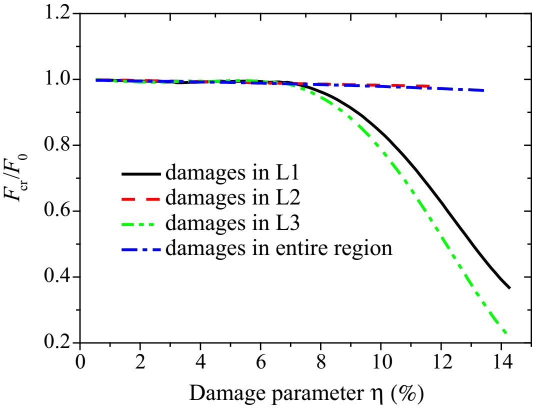


Fig. 20. Comparison of local damages sensitive of truss core sandwich panels with missing lattice cells in different locations.

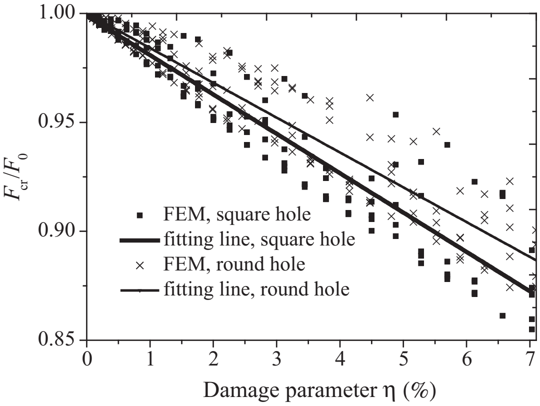


Fig. 21. Buckling loads of truss core sandwich panels with different sizes of holes in the facesheet.

4. Conclusions

In this study, effects of local damages on the buckling behaviour of pyramidal truss core sandwich panels under compression are studied experimentally and numerically. By applying protective coatings on nodal areas of lattice truss cells, pyramidal truss core sandwich panels with prefabricated damages are manufactured through stamping method and brazing technique. The buckling load and the failure mode of specimen with different prefabricated local damages are obtained by the compression tester and the CCD camera. Experimental results show that the sandwich panel is insensitive to local damages of unbound nodes distributed in the centre region and round holes in the facesheet, but sensitive to local damages of unbound nodes that perpendicular to the loading direction. The finite element model in conjunction with random program is developed to calculate the plastic and elastic buckling behaviour of truss core sandwich panel with different types of local damages. Effects of unbound nodes, missing lattice cells and holes in the facesheet are investigated. Results from the experiment and the finite element model show that the unbound nodes and missing lattice truss cells that parallel to the loading direction or placed in the centre region have little effect on the elastic and plastic buckling behaviour of truss core sandwich panel. However, the local buckling behaviour of facesheet due to the unbound nodes and missing lattice cells that perpendicular to the loading direction will reduce the buckling strength of the sandwich panel dramatically. As a result, the truss core sandwich panel is very sensitive to this kind of local damage. When the number of missing lattice truss cells increases to only 14%, the critical load declined 62% and 80% for the plastic buckling and elastic buckling behaviour respectively. In addition, the effect of square holes on the elastic and plastic buckling load of sandwich panel is larger than round holes, due to the severe stress concentration.

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