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Performance Assessment of Sandwich Structures with Debonds and Dents

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Abstract -A sandwich construction is a special form of the laminated composite consisting of light weight core, sandwiched between two stiff thin face sheets. Due to high stiffness to weight ratio, sandwich construction is widely adopted in aerospace industries. As a process dependent bonded structure, the most severe defects associated with sandwich construction are debond (skin core bond failure) and dent (locally deformed skin associated with core crushing). Reasons for debond may be attributed to initial manufacturing flaws or in service loads and dent can be caused by tool drops or impacts by foreign objects. This paper presents an evaluation on the performance of honeycomb sandwich cantilever beam with the presence of debond or dent, using layered finite element models. Dent is idealized by accounting core crushing in the core thickness along with the eccentricity of the skin. Debond is idealized using multilaminate modeling at debond location with contact element between the laminates. Vibration and buckling behavior of metallic honeycomb sandwich beam with and without damage are carried out. Buckling load factor, natural frequency, mode shape and modal strain energy are evaluated using finite element package ANSYS 13.0. Study shows that debond affect the performance of the structure more severely than dent. Reduction in the fundamental frequencies due to the presence of dent or debond is not significant for the case considered. But the debond reduces the buckling load factor significantly. Dent of size 8-20% of core thickness shows 13% reduction in buckling load capacity of the sandwich column. But debond of the same size reduced the buckling load capacity by about 90%. This underscores the importance of detecting these damages in the initiation level itself to avoid catastrophic failures. Influence of the damages on fundamental frequencies, mode shape and modal strain energy are examined. Effectiveness of these parameters as a damage detection tool for sandwich structure is also assessed.

Keywords- Buckling, Debond Dent, Finite Element Method, Frequency, Honeycomb and Sandwich Cantilever Beam.

1 INTRODUCTION

SANDWICH structures consist of two thin, stiff and strong face sheets (skin sheets) attached to the top and bottom side of a thick, light weight, low modulus core. Generally face sheets are adhesively bonded to the core to obtain load transfer between the components. The faces will act together to form an efficient stress couple or resisting moment counteracting the external bending moment. The core resist shear and stabilize the faces against the buckling and wrinkling. The bond between the faces and the core must be strong enough to resist the shear and tensile stress set up between them. A typical honeycomb sandwich panel is as shown in Fig. 1. Sandwich constructions are used almost in every industrial sector ranging from buildings to aerospace applications because of their low density, high specific stiffness and strength. Strength and stiffness of honeycomb sandwich structure are reduced by the presence of debond and dent. As a process dependent bonded structure, the most severe defects associated with sandwich construction are debond and dent, where debond is the bond failure between skin and core and dent is local deformation of skin associated with core crushing. One of the reason for debond may be large dissimilarities in the properties of the constituent skin and the core materials. Debond also may occur due to the initial manufacturing flaws and inter-laminar stress created by the impact load or eccentricities in structural load paths. Dent can be caused by tool drops or impacts by foreign objects, birds etc.

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This paper presents an evaluation on the performance of honeycomb sandwich structures with the presence of debond or dent using layered finite element models. Dent is idealized by accounting core crushing in the core thickness along with the eccentricity of the skin. Debond is idealized using multilaminate modeling at debond location with contact element between the laminates. In both cases continued loading of the structure can cause crack growth in the debond area, i.e. it leads to the crack propagation in the interface between core and face. It also changes the parameters like buckling load factor, natural frequency, mode shape, strain energy etc. The various literature surveys in this topic showed that the detection of such damages in the early stages is an important aspect to avoid catastrophic failure.

Pandey *et al* [1] have demonstrated that curvature mode shape can be used for identifying and locating damage in a structure by analyzing a cantilever and simply supported beam models. Jiang *et al* [2] have investigated the dynamic analysis of free undamped vibration behavior of honeycomb structures with debond in order to study the natural frequency of these structures using Finite Element software ‘MSE/ NASTRAN’. An experimental damage identification procedure was developed based on structural dynamic response and using smart sensors by comparing dynamic responses of healthy and damaged Fibre Reinforced Polymer (FRP) sandwich beams [3]. An experimental verification of a method was presented for prediction of location and size of multiple cracks based on natural frequency measurements in slender cantilever beams with 2-3 normal edge cracks [4]. Li *et al* [5] have found a methodology to detect crack location and size which takes advantage of wavelet Finite Element Method in the modal analysis by measuring natural frequencies. Alavandi [6] brought out that the strain energy based damage detection was found to be efficient compared to other methods which

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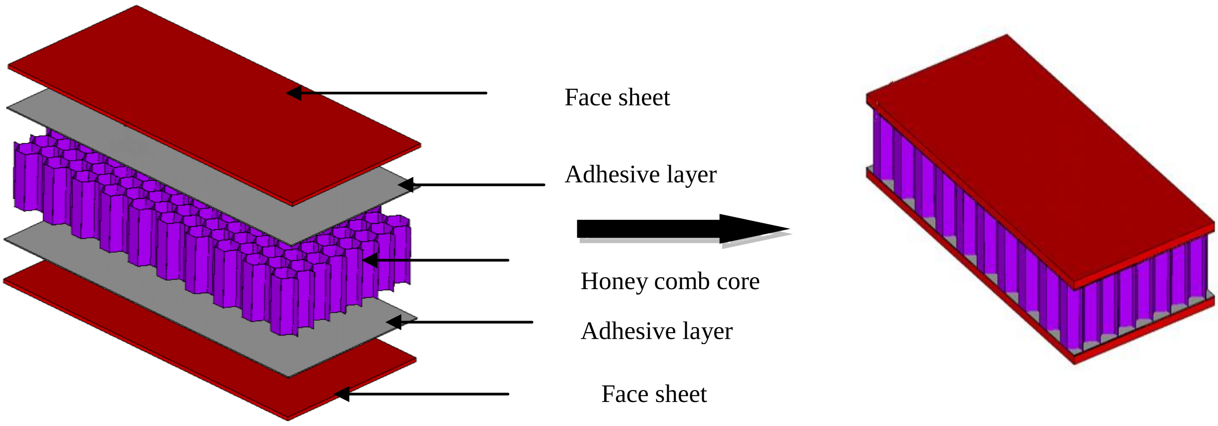

Fig.1. A typical sandwich structure and its different layers.

consider the modal strain energy changes in each structural element before and after the damage formation. An experimental and numerical curvature mode shape analysis was carried out to detect the presence, location and size of delamination in composite laminated plates using smart piezoelectric materials and modern instrumentation like Scanning Laser Vibrometer (SLV) [7]. A new damage identification method namely Element Modal Strain Damage Index (EMSDI) was developed based on measured modal displacements. The EMSDI utilizes the element shape function avoiding the problems associated with numerical differentiation procedure in modal curvature method [8]. Chiu *et al* [9] presented a set of numerical results on the use of lamb waves for monitoring crack growth in the lower wing skin adhesively bonded with a composite repair patch and gave a demonstration about the interaction of stress waves with structural defects and the probability of detection of these defects existing in a geometrically varying section of an aircraft structure. Manoj Kumar *et al* [10] performed a vibration based damage identification method based on changes in modal strain energies before and after the occurrence of damage in a sandwich composite beam. Natural frequency and mode shapes were calculated with the influence of location, size and type of debonding zone of the sandwich plates with various boundary conditions using a commercial Finite Element code ‘ABAQUS’ and the results of free vibration analysis were compared both for intact and debonded sandwich plates[11]. An experimental study on the effects of multi-site damage on the vibration response of honeycomb sandwich beams was carried out. The shifts between the modal parameters of damaged and undamaged specimens were found [12]. Free vibration analysis in sandwich plates containing single or multiple debonding was conducted and identified the size, location and number of debonding zones on the basis of changes in dynamic characteristics such as natural frequencies and corresponding mode shapes by comparing results with sandwich plates without debond by using finite element code ‘ABAQUS’ [13]. A three dimensional finite element with an embedded interface was developed for analyzing the laminated composite structure and a well organized procedure for the identification of delamination in laminated composite beams was brought out[14]. The aim of the study conducted by Caminero *et al* [15] was to assess the use of different online monitoring techniques such as Digital Image Correlation (DIC) and Lamp waves, in order to study the performance and damage detection in bonded composite repairs.

In this paper, Modal analysis and buckling analysis are conducted using layered finite element modeling of sandwich cantilever beam with and without damage (Debond or dent). The influence of size, location and number of damaged zones on buckling and vibration parameters are investigated.

2 MODELING OF SANDWICH STRUCTURE

Layered shell finite elements are used across the aerospace industry to model composites and sandwich constructions due to its computational efficiency, accuracy and easiness in the modeling complex structural configurations. Typical layered shell element (Shell 91-ANSYS^{TM}) and its model are as shown in Fig. 2. Here the stiffness matrix of the finite element is derived based on the lamination theory.

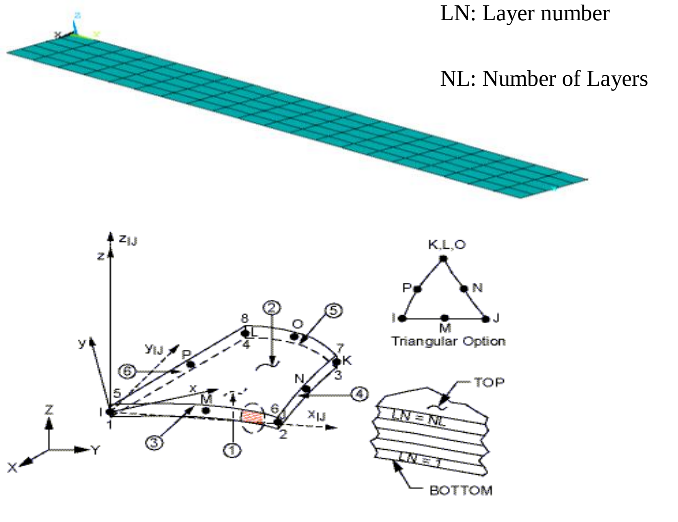

Fig.2. Layered shell model of honeycomb sandwich panel utilizing the 8 noded layered shell finite elements.

3.1 Modeling of debond

Fig. 3. shows a sandwich model with debond. Multilayered model used for idealizing the debond is as shown in Fig. 4. In finite element model, the defect free zone (Region 1) of sandwich

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structure is modeled as three layered shell. In the debond zone, two regions of layers are generated; one representing the debonded skin and the other representing the two layered skin-core. Subsequently, two layers of top zone (Region 2) and one layer of bottom zone (Region 3) are simulated with zero material properties to avoid error in neutral axis positioning. This results in making only the top skin active in the top section and core and bottom skin are active in the bottom section. The merging of nodes of both sets is given only at the boundary of the debond zone so that within the zone of defect, both the sections are distinct simulating the debond.

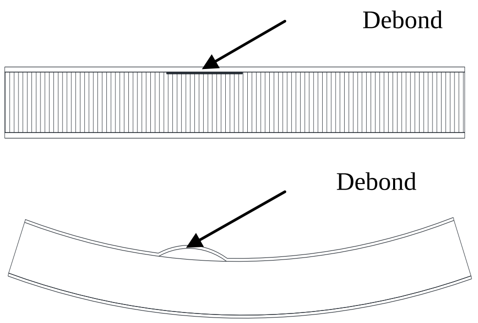

Fig.3. Sandwich structure with debond. The projection of skin layer representing the debond.

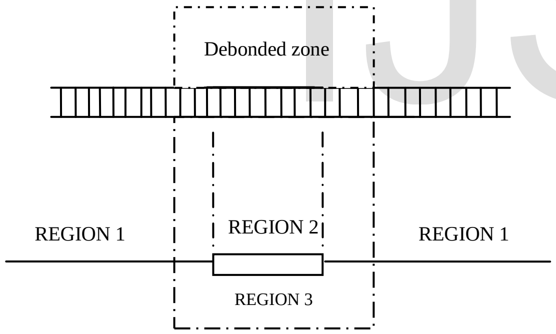

Fig.4. Debond simulation in finite element model. Region 1: Three layer sandwich; Region 2: Single layer representing debonded skin; Region 3; Two layer representing debonded core and skin

3.2 Modeling of dent

Fig.5. shows a sandwich model with dent. Multilayered model used for idealizing the dent also is as shown in Fig.6. The defect free zone (Region1) of sandwich structure is modeled as three layered shell and the dent zone (Region2) is modeled as four layered shell by introducing dent as a core thickness reduction. At the dent location the core thickness is reduced and the fourth layer is simulated with zero material properties to avoid neutral axis shift. Thus the top layer behaves like dent location and the bottom skin- reduced core-skin portion behave like region1. Merging of nodes is done for the whole structure.

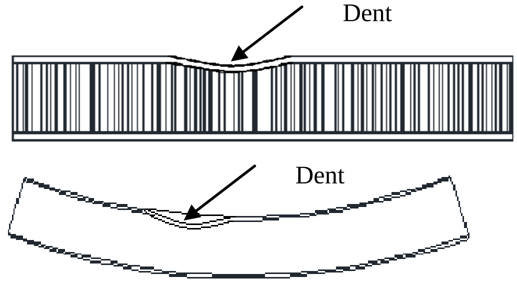

Fig.5.Sandwich structure with dent. The depression on the surface of the sandwich structure representing the dent.

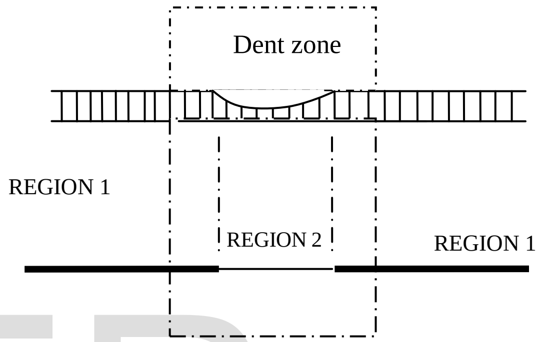

Fig.6. Dent simulation in FE model. Region1: Three layer sandwich; Region 2: Three layer sandwich with reduced thickness of core with additional dummy layer to correct bottom face location.

4 CASE STUDY

The case study is carried out on sandwich cantilever beam. Buckling and vibration parameters are evaluated. Vibration parameters include frequency, mode shape and modal strain energy.

4.1 Sandwich Cantilever Beam

A metallic honeycomb sandwich cantilever beam (850x100x23.46mm) with and without debond or dent is considered for the study. The specimen and boundary conditions considered for the present study are as shown in Fig. 7. The skin and core of sandwich panel are of AA 2014 T6 and AA5056 142 type. The thickness of the skin sheet is 0.3 mm and the core layer is 22.86 mm. Mass of the cantilever beam is 0.342 kg. The material properties are given in table 1.

TABLE 1

MATERIAL PROPERTIES OF SKIN AND CORE

Components	Elastic Constants
Face sheet	E_f = 68670 MPa, ρ=2800kg/ m³, =0.3
Core	Gyz=400 MPa, Gxz=220 MPa, ρ=67kg/m³ =0.3

E_f = Elastic Modulus of Face Sheet,ρ =Density,υ=Poisson's Ratio, Gyz= Shear Modulus in yz direction, Gxz= Shear Modulus in xz direction.

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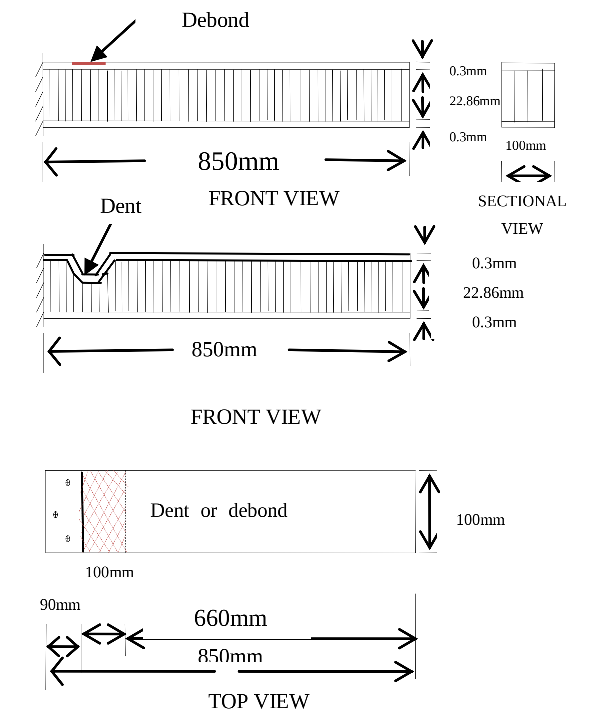

Fig.7. Configurations of the sandwich cantilever beam with debond or dent.

Fig.8 & 9 show the layered finite element (8 noded Shell 281 element) idealization of intact, debonded and dented honeycomb sandwich cantilever beam respectively. The model consists of 435 elements. The size of the debond is 100mm x 100mm and the same size of dent is modeled by reducing core thickness by 2mm & 5mm from the total core thickness of 22.86mm. There are two dent cases considered on separate beams, one having 2mm dent size and the other having 5mm dent size.

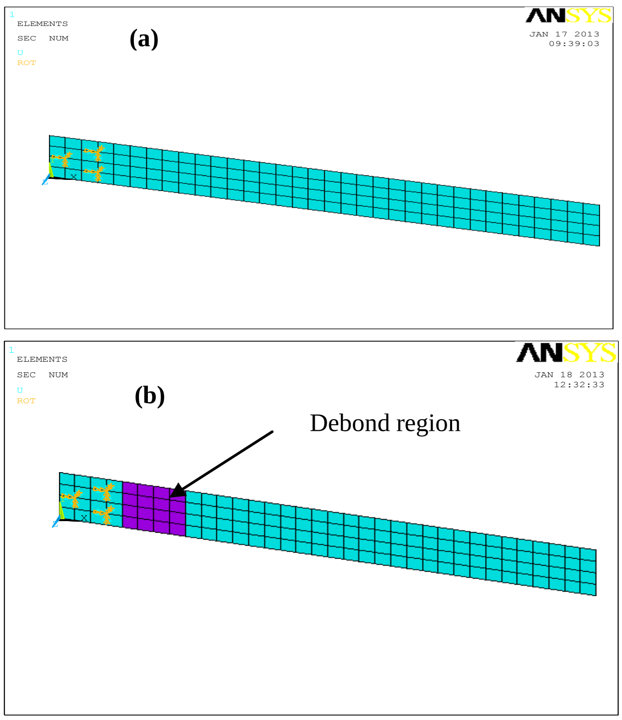

Fig.8. FE idealization of cantilever sandwich beam: (a) Undamaged beam; (b) Sandwich beam with debond

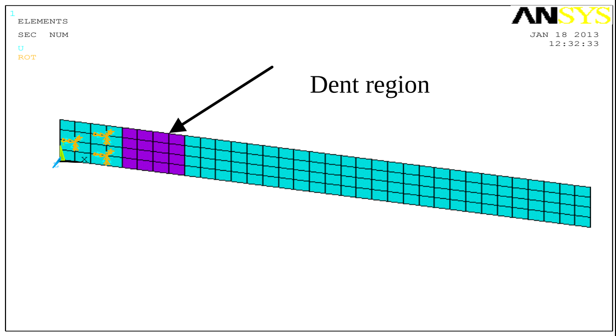

Fig.9. FE idealization of cantilever sandwich beam with dent.

4.2 Modal analysis and result discussion

Modal analysis is carried out in both intact and damaged sandwich cantilever beam in order to find out how the damage affect the natural frequency and to idealize the mode shape variations in intact and damaged beams. Table.2 shows the natural frequency comparison for the first three modes.

TABLE 2

NATURAL FREQUENCY (Hz) OF INTACT AND DAMAGED SANDWICH CANTILEVER BEAMS

Mode	Intact	Debond	2mmDent	5mm Dent
I	33.15	31.97	32.09	30.02
II	79.58	80.04	79.98	79.76
III	204.89	129.68	202.90	199.12

Reduction in natural frequencies corresponding to the damaged cases is noticed. However, localization and size of the damages are not identifiable from this natural frequency data. The mode shape comparison (for the first mode only) for all cantilever cases are as shown in the Fig. 10. The change in mode shape pattern for the first mode is depicted in the figure.

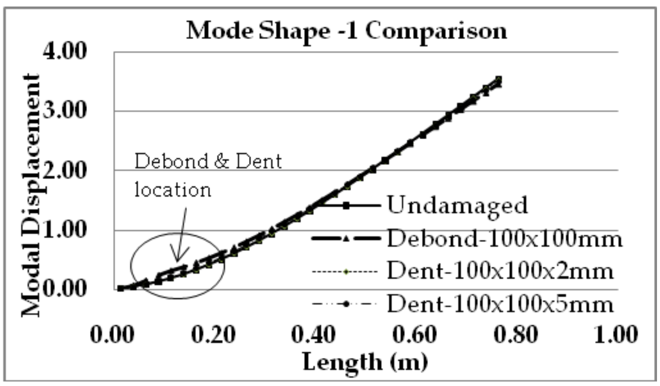

Fig.10. Mode shape comparison of undamaged and damaged cantilever beams (for the first mode)

It may be noted that the magnitude of displacement is reduced for the damaged case compared with undamaged case. While comparing damaged sandwich beam with the undamaged one, the

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debonded sandwich beam shows a clear variation in first mode itself. This proves that the debond case is critical than dent case. The change in mode shape only gives an idea about the presence of damage in the structure but it could not give an exact location and size of the damage. In order to find out location and size of the damage, modal strain energy (MSE) data of two modes are extracted as shown in the Fig. 11 and Fig.12 for the debond and dent respectively.

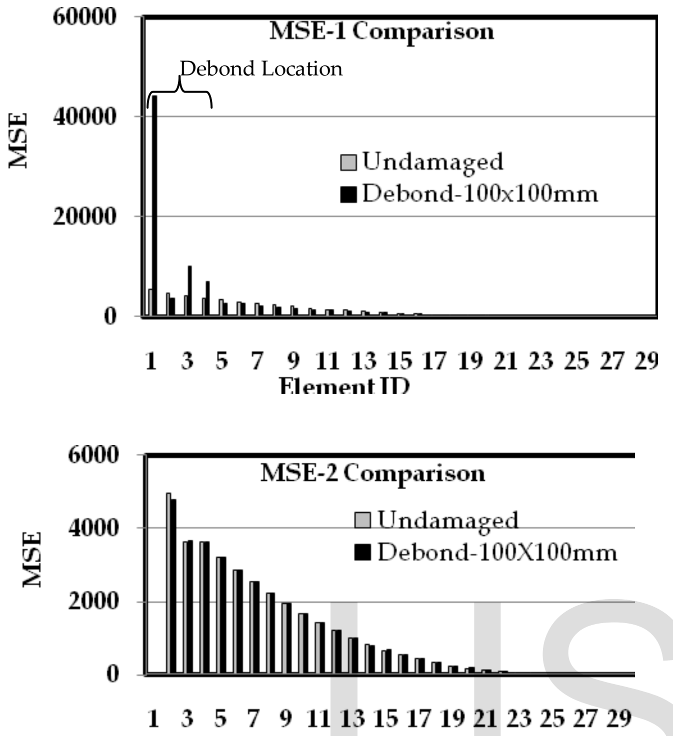

Fig.11. Modal strain energy comparison of undamaged and debonded cantilever beam.

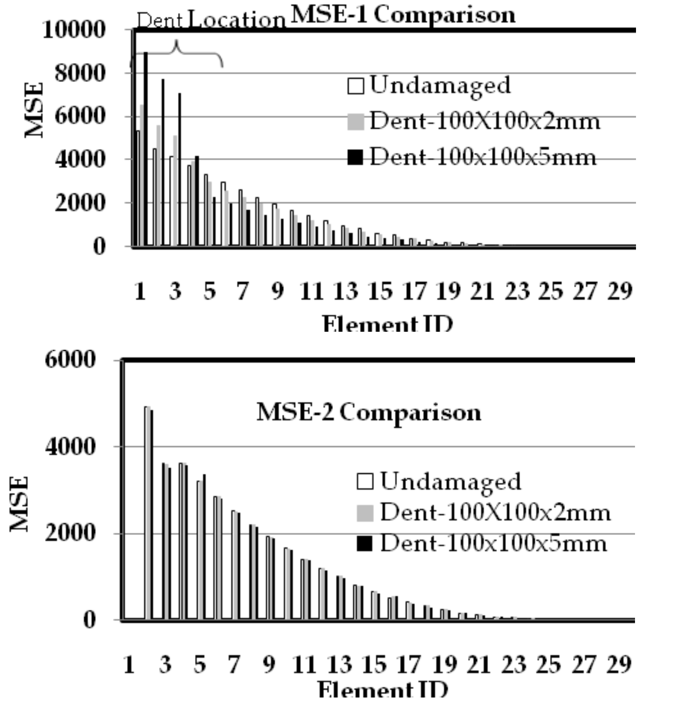

Fig.12. Modal strain energy comparison of undamaged and dented cantilever beam.

Presence of debond caused significant variation in the modal strain energy for the first mode (Fig. 11) at debond location. The dent caused variation in the strain energy but which less in magnitude compared to debond case (Fig. 12). Both the case, maximum variation is observed near to the debond location. The figures show that the location and extent of damage is clearly visible from modal strain energy distribution. .

4.3 Buckling analysis and result discussion

The buckling behavior of the both undamaged and damaged sandwich column have been studied by applying an axial load of 1000N at its one end. The analysis is conducted on intact, debonded and dented column. The dimensions and material properties of the column are same as that of the sandwich cantilever beam. The obtained buckling factors for all the cases are shown in the table 3.

TABLE 3

BUCKLING LOAD FACTOR COMPARISON FOR INTACT AND DAMAGED SANDWICH CANTILEVER BEAM

Mode	Intact	Debond	2mm Dent	5mm Dent
I	2.18	0.14	2.09	1.89

The results from the above table showed that the buckling load factor is reduced by about 90% for the debond case and for about13% is reduced for the dent of size 8-20% of the core thickness. Hence it is clear that the debond is critical than the dent in the sandwich structures. This reduction in load carrying capacity of structure due to the presence of debond will lead to catastrophic failure of structure, and hence early detection of damage is very important. This proves the importance of online monitoring in sandwich structures.

4 CONCLUSION

In the present work, Finite Element modeling of metallic honeycomb sandwich column with and without debond/dent has been demonstrated and assessed the performance of the structure in the presence of damage by conducting vibration and buckling analysis. The parameters extracted include buckling load factor, natural frequency, mode shape and modal strain energy. These parameters are considered for their usefulness as damage detection tools. In summary the following conclusions from the viewpoint of sensitivity of the dynamic and buckling characteristics can be drawn. Firstly, both changes in natural frequency and mode shapes are sensitive to the presence of damage within the structure but less sensitive in identifying the damage location and its size. Secondly, modal strain energy is found to be an effective tool for finding number of elements affected by the damage. Thirdly, the buckling load factor is reduced by about 90% for the debond case and by about 13% for the dent of size 8-20% of the core thickness. This result proved that debond is more critical than dent in sandwich column. Fourthly, the reduction in load carrying capacity of the axial sandwich column in the presence of debond/ dent pointing out the importance of on-line monitoring of sandwich structures for damaged to avoid premature failures.

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