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RESEARCH ARTICLE

FAILURE OF ALUMINUM HONEYCOMB SANDWICH PANELS

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Abstract:

As an efficient lightweight structure, composite honeycomb sandwich panel has been widely utilized in many industries. The composite honeycomb sandwich structure with stringer reinforcement could even be a replacement quite sandwich structure. This paper investigated the damage and failure behavior of composite honeycomb sandwich structure with stringer reinforcement under in-plane compression condition. Three differing types of debonding damage of interface between sheet and core were considered the failure modes also because the entire failure process was obtained by numerical simulation. Advanced sandwich structure is typically an outsized thickness of honeycomb core bonded with composite sheets. With larger in-plane stiffness and strength, the material faceplate is especially wont to bear the axial load, bending moment and shearing action, while the honeycomb core, subject to bending and shear load, is especially wont to maintain the steadiness the relative position of sheets and transfer lateral load. With the benefits of high specific stiffness and specific strength, the structure can get high flexural stiffness and compressive yield strength under the condition of low relative density. The existence of interfacial debonding, local buckling will occur within the debonding area, and cause the ultimate broken. With the rise of the compression loading, the displacement of bulging outward increasing gradually and therefore the debonding propagation gradually extends to the interface of sheet/core near the initial debonding propagation of sheet/stiffener.

Keywords: Sandwich structure, Stringer reinforcement, Composite, Interfacial Debonding, Failure.

1. Introduction

Sandwich panels are popular in high performance applications where weight must be kept to minimum, for instance aeronautical structures, high-speed marine craft and racing cars. They're made from two stiff, strong skins separated by a light-weight core (Fig.1.).

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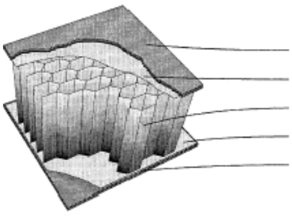

Fig.1. Honeycomb sandwich panel

Typical modes of failure are skin yielding, skin wrinkling, intra-cell dimpling, core shear or local indentation (where the load is applied to the panel). The critical failure mode and the corresponding failure load depend on the properties of the skin and core materials, on the geometry of the structure and the loading arrangement. A comprehensive introduction to the subject of sandwich construction and the development of theoretical analyses up to 1969 is given by Allen. Holt and Webber summarized developments and analyzed the elastic behavior of honeycomb sandwich beams, assuming linear elastic behavior for the skin and a rigid core. The faceplate and core of advanced sandwich structure are anisotropic, which may be a vital characteristic. Through the reasonable design of the composite faceplate or rational choose of the core structure, optimization sandwich structure are often designed and made to satisfy the precise needs of varied engineering applications[2]. The composite honeycomb sandwich structure with stringer reinforcement may be a new sort of sandwich structure, whose purpose is to further balance improve the axial and bending specific stiffness and specific strength of the structure, at an equivalent time increase the reliability of the structure.

Due to the characteristics of producing technology and therefore the intrinsic properties of the materials, the deboning defect is straightforward to occur within the interface between the core and therefore the sheets during service life [3]. As a result, the strength under static load is going to be decreased. Moreover, the failure mode of the sandwich structure is going to be more complicated, and therefore the defects will seriously affect the accuracy of strength prediction. For the composite honeycomb sandwich structure with stringer reinforcement, the effect of stiffener on the failure modes of sandwich structure is worth studying.

The equivalent of the fabric parameters and numerical model There are two main simulation methods for the sandwich structure [4]. For hierarchical model, each single layer of the structure is taken into account respectively, and therefore the constraints consistent with continuity for every interface also should tend appropriately to satisfy the wants of stresses generality for adjacent layers. For the equivalent single-layer model, the sheet and core are replaced by a single-layer with certain thickness. The unified expression of displacement field is given along whole thickness direction by using the deformation theory of plate and shell. For the hierarchical model, it has a large number of independent variables, while for the equivalent single-layer model, as the independent variables are less, it is commonly used in finite element method.

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To simplify the analysis, the equivalent single-layer model is adopted. The chosen aluminum honeycomb core of the sandwich structure is transformed to homogeneous orthotropic material in finite element modeling. There are a spread of equivalent ways for the elastic parameters of honeycomb core [5]. The equivalent elastic parameters of hexagonal honeycomb core proposed by Zhao Jin-Sen. [6] are adopted during this paper to derivate formula and calculate the equivalent material parameters of the simplified model. The equivalent formulas are as follows: Where Es and Gs are elastic parameters of the honeycomb core, l and t are wall length and wall thickness of a unit cell of the honeycomb core.

The equivalent properties of honeycomb core are given in image 1 below.

Tab.1 The equivalent properties of honeycomb core

Elastic Parameter（Gpa）						Poisson's ratio
E_1	E_2	E_3	G_{12}	G_{13}	G_{23}	v_{12}
0.31	0.31	1003	0.078	189	189	0.99

The traditional composite honeycomb sandwich structure consists of two composite sheets, adhesive layer and aluminum honeycomb core. For the stringer reinforced sandwich structure discussed during this paper, two buried aluminum stiffeners are contained. The adhesive layer is simulated by cohesive element in finite element analysis. The overall dimensions of the 2 sorts of sandwich structure are uniform, the length is 90 mm, the width is 50 mm, and therefore the total thickness of 15 mm, among which, the thickness of the honeycomb core is 12 mm, the thickness of adhesive layer is 0.1mm, and both of the thickness of the upper and lower sheets are 1.4 mm. The components size meets the wants of ASTM C364-99 standard. the upper and lower faceplates are composite laminates for the 2 quite sandwich structure, whose length and width directions are defined as x and y axis, respectively. The composite laminates features a total of 10 layers, the thickness of every layer is 0.14 mm, and therefore the stacking sequence is [0/0/45/-45/90]s . the fabric parameters of the composite laminates are shown in table 2. Additionally, the 2 buried aluminium stiffeners are 90mm long, 4mm in breadth, and 12mm tall. the space from the 2 stiffeners to the middle line of the sandwich structure is 12 mm. the fabric parameters of the aluminium stiffeners are shown in table 3.

Tab.2 Properties of T300/QY8911

Elastic Parameter（Gpa）				
E_1	$E_2 = E_3$	G_{12}=G_{13}	G_{23}	v_{12}
126	10.7	4.47	3.57	0.33
Strength Parameter（Mpa）				
X_T	X_C	X_T	Y_C	S
1548	1226	55.5	218	89.9

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Tab.3 Properties of the aluminum stringer

Properties (units)	Young's modulus (GPa)	Poisson's ratio ν_{12}
Aluminum stringer	69.5	0.33

The failure analysis of the sandwich structure

The linear buckling analysis

Lanczos vector method is adopted to research and compare the linear buckling deformation characteristics of composite honeycomb sandwich structure without reinforcement and with stringer reinforcement, respectively. The most buckling modes of two sorts of sandwich structure are calculated, which are shown in figure 1.In the above figure, we will see that the mainly buckling modes of the two sorts of sandwich structure are different under in-plane compression condition. Global buckling instability mainly occurs to the sandwich structure without reinforcement, while partial buckling mainly occurs to the sandwich structure with stringer near the free boundary on each side. The existence of the stiffener, the buckling deformation of the honeycomb core is inhibited, and therefore the overall stiffness of the structure is enhanced effectively. What's more, the buckling load of the sandwich structure with stringer is 525.71 KN, which is far above structure without reinforcement buckling load of 121.28 KN. Therefore, the stringer Reinforcement significantly improves the buckling bearing capacity of the composite honeycomb sandwich structure.

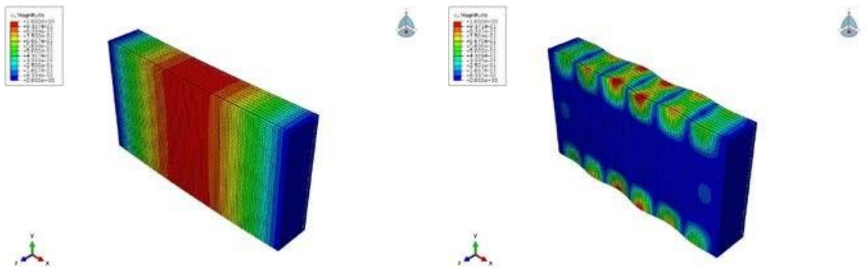

Fig.2 The first buckling mode of the composite honeycomb sandwich structure with and without stringer reinforcement

The nonlinear failure analysis Figure to shows the load-displacement response of two different composite honeycomb sandwich structures under in-plane compression condition by nonlinear buckling analysis. Through observation, we all know that the general axial stiffness of the structure changed little, and axial compression stiffness approximate to linear under in-plane compression condition. After reaching limit loading points, failure damage occurs to both of them to sorts of sandwich structure, and therefore the continue carrying capacity losts quickly. Trough comparison, we all know that the limit load of the sandwich structure with stringer reinforcement is 190.03 KN, which is far above that of the structure without reinforcement as 87.52 KN. Therefore, the stringer Reinforcement effectively improves ultimate bearing capacity of the composite honeycomb sandwich structure. Additionally, the precise strength of sandwich structure with stringer reinforcement is 1.05 times bigger than without reinforcement, which further evidences that composite honeycomb sandwich structure with stringer reinforcement has excellent structural performance.

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Fig.3 The load-displacement response of two different composite honeycomb sandwich structures

Honeycomb sandwich structures

Comparing the results of nonlinear failure analysis and therefore the linear buckling analysis respectively, we all know that the linear buckling load is bigger than the limit load for both of the two sorts of sandwich structure. Accordingly, the general stability of composite honeycomb sandwich structures under in-plane compression condition is high, and therefore the stiffness of the structure is further enhanced through stringer reinforcement. Therefore, the buckling failure isn't the most failure modes of the structure; strength and damage are the most factors dominate the failure modes of dish generally. The failure analysis of the sandwich structure with through interfacial debonding Considering a through-the-width sheet/core interfacial debonding in middle area of the reinforced composite honeycomb sandwich structure, and therefore the length of debonding is 30mm.

Figure 3 shows the load-displacement response of reinforced sandwich structure with a through-the-width interfacial debonding by nonlinear analysis. Analysis shows that, the connection between load and axial displacement keeps linear, and can lose load carrying capacity quickly when reaches the limit load. The limit load of the sandwich structure with stringer reinforcement and thru interfacial debonding is 97.72KN, which is far less than that of the right reinforced sandwich structure as 190.03 KN. Therefore, the through-the-width interfacial debonding reduces ultimate bearing capacity of the sandwich structure. Figure 4 shows the out-plane displacement of the sandwich structure with stringer reinforcement under the limit load. The result shows that local buckling occurred within the debonding area, and causes the ultimate broken. Also, because the stiffener improves the general stiffness, local buckling only occurs at the debonded sheet near each side of free boundary.

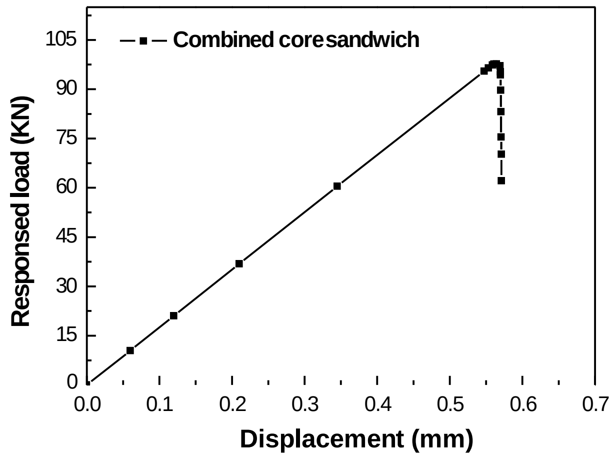

Fig.4 The load-displacement response of sandwich structure with stringer reinforcement and through-the-width interfacial debonding

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Fig.4 The out-plane displacement of the sandwich structure with stringer reinforcement under the limit load

Figure 4 shows a symmetrical through-the-width interfacial debonding propagation behavior located at both side of the core. Under compression load, partial buckling occurs within the upper and lower sheets within the zone of debonding. With the rise of compression load, the lower sheet in debonding area contacts the core quickly thus inhibits the failure and propagation of the adhesive layer. At an equivalent time, the upper sheet in debonding area bulges outward, free buckling occurs. Because the stiffness of the stiffener is above the honeycomb core, the debonding propagation starts at the interface between sheet and stiffener. With the rise of the compression loading, the displacement of bulging outward increasing gradually and therefore the debonding propagation gradually extends to the interface of sheet/core near the initial debonding propagation of sheet/stiffener.

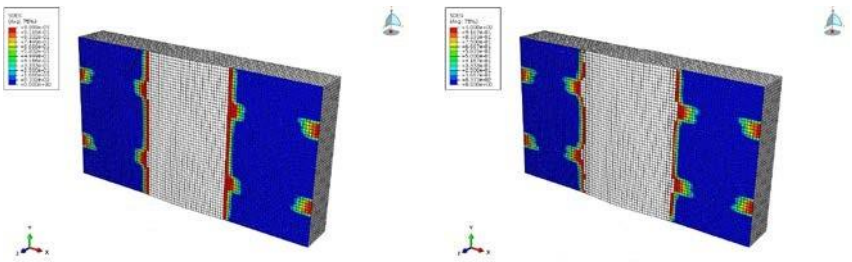

Fig.5 The propagation of symmetrical through-the-width interfacial debonding in sandwich structure with stringer reinforcement

2.3. Lay-Up Schemes of Sandwich Panels with Aluminium Honeycomb Core and CFRP Skins

To check the stacking sequence, fibre way, and the slice hardness on the worthiness of sandwich panels, the samplings all through this cram are segregated into three assemblages (Group A/Group B/Group C) as listed in Table 3. a complete of eight different lay-up schemes (A/B/C/D/E/F/G) are considered. The fibre directions with 15°, 30°, 45°, 60°, and 75° are mainly considered. the aim of A is to match and analyze the effect of fibre direction on the crashworthiness of sandwich panels. the aim of B is to match and analyze the effect of stacking sequence on the crashworthiness of sandwich panels. The aim of Group C is to match and analyze the effect of layer thickness on the crashworthiness of sandwich panels.

Lay-up schemes of sandwich panels.

Case	Stacking
Group A	
A	[45°/−45°/45°/−45°]
B	[30°/−30°/30°/−30°]
C	[60°/−60°/60°/−60°]
D	[75°/−75°/75°/−75°]
E	[60°/−15°/15°/−60°]
Group B	
A	[45°/−45°/45°/−45°]

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F [45°/−45°/−45°/45°]

Group C

A [45°/−45°/45°/−45°]

G [45°/−45°/45°]

H [45°/−45°]

3 Honeycomb Core Failure Predictions

This data presents analysis that predicts the honeycomb core capability during a joint using hi-fi nonlinear FEA within the Abaqus FEA solver. The analysis is more complex than the linear FEA presented in Section 2 but provides a stimulating method if capability for the honeycomb core is desired after it's begun to fail. Unit Cell Analysis The first step in analyzing a posh honeycomb joint is to start out with an easy model of a unit to demonstrate the capabilities of Abaqus FEA and understand the method which will be required for a full coupon model. Figure above shows the unit model that was created which contains about 2,500 nodes and elements.

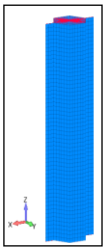

Figure 6: Unit Cell Finite Element Model for Abaqus FEA Demonstration

Modified Riks' method was chosen because the solver approaches thanks to its known ability to unravel post- buckling problems like honeycomb failure. This method is ideally fitted to simulations where the derivative of the load versus displacement changes sign or in other words where the load carried by the member reduces because it is displaced [8]. The modified Riks' method in Abaqus FEA solves for equilibrium using an arc length approach instead of the Newton's method utilized in traditional nonlinear analysis. The limitation of Newton's method for solving for equilibrium is that it requires a monotonic increase in load or displacement through each iterative step. In post-buckling analysis, a monotonic load increase is extremely unlikely. the overall arc length solve approach is summarized in Figure 5.1 and shows how it's ready to solve for equilibrium with imposing the monotonic load increase constraint using arc length along the curve as a further variable. Modified Riks' method was successfully employed by Bianchi, Aglietti, and Richardson to prove that shear buckling during a simple panel coupon matched the buckling of the same unit [9].

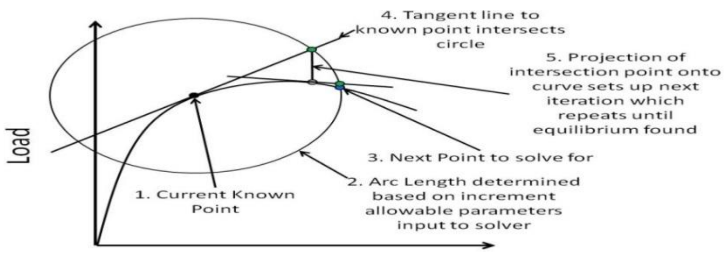

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Figure 5.1: Summary of Arc Length Method

The first step for the analysis is to define material properties for the Aluminum 5056-H39 honeycomb core utilized in the unit. Thanks to its use almost exclusively as a component of manufactured honeycomb, there's little data providing explicit strength properties for the fabric itself. A yield strength value of fifty ksi and an ultimate strength of 60 ksi were assumed supported similar materials and other tempers of Aluminum 5056. The stress-strain curve was fit around these values based upon the known Young's modulus of the fabric and a typical stress- strain pattern for aluminum alloys.

Figure above unit Model with Boundary Conditions and cargo Applied (Boundary Conditions Only Shown on Select Nodes along each edge for visual clarity)

After the imperfections are smeared onto the model, modified Riks' analysis is run in Abaqus FEA and therefore the deflected model contour plots are shown in Figure 3-5 and a stress-strain curve derived from the model's load versus displacement data is shown in Figure 5.2. This data qualitatively agrees with Bianchi's analysis on a special honeycomb core material type and shows that Riks' method may be a good candidate for attempting to simulate the core failure of a more complex joint coupon [12].

The Riks' method process described in executing the unit analysis was then repeated for the coupon model. the primary 500 eigenvalues from a linear buckling analysis were used for smearing the imperfections onto the core. there have been many eigenvalues because each cell membrane within the loaded zone can buckle in several ways and there are many cell walls buckling. Watching each shape and assigning a multiplier thereto was a tedious and time consuming process. Two sample eigenvectors are shown in the Figure.

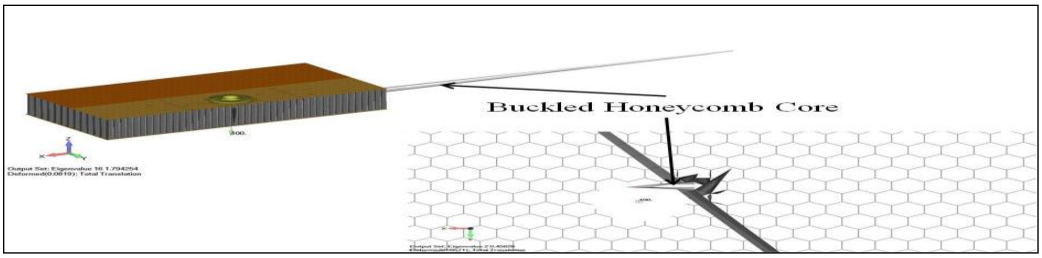

Figure 5.2: Images showing Sample Buckling Mode Shapes of the Coupon's Honeycomb Core

Riks' method was then attempted but failed thanks to element ratio errors as soon because the model began to step into a nonlinear region. there have been some relatively poorly formed elements within the face sheet caused by having to mesh a circular bushing with a hexagonal honeycomb core underneath it while trying to take care of even, square elements. After assessing at the geometry, the fitting was remeshed but care was taken to form the model symmetric about the bushing and also to locate the honeycomb core pattern during a location within the coupon Y-direction that was conducive to achieving a workable mesh. the primary mesh is shown in Figure and therefore the updated, symmetric mesh is shown in Figure .The general model remained about an equivalent size.

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Updated Mesh of Explicitly Modeled Honeycomb Core where Core was Meshed Symmetric across the Bushing's Center YZ-Plane

Riks' method was then applied and therefore the load versus displacement curve successfully simulated the nonlinear region as shown in .The core buckling wasn't triggered however and instead the core simply yielded under the shear load as shown in Figure. The model was also much stiffer than expected even within the linear region which may be seen by comparing the slopes of the test data versus the anticipated data. It should be noted that the displacement data within the test was recorded by measuring the load head displacement on the test machine instead of by using an extensometer. this suggests that the displacement within the model versus the test could also be different because the load head displacement are going to be increased albeit only slightly by the equipment within the load train instead of in only the coupon itself. An extensometer would have mitigated this issue by isolating the coupon and is suggested for future coupon testing.

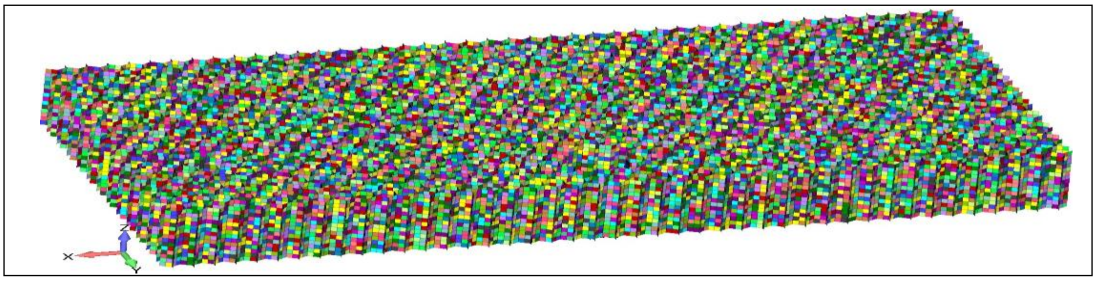

Image showing randomly Distributed Honeycomb Core Thickness Properties across the coupon (Colors Represent Different Properties)

The updated model was successful in allowing the core to fail in shear buckling which caused a load versus displacement curve that was very representative of the info from the coupon test as seen in Figure . After the successful run, it had been decided to see the sensitivity of the results to the core thickness distribution and node locations. Figure shows two additional curves from Figure with one having a ±10% core thickness distribution with no node location altering and therefore the other having a ±5% core thickness distribution with no node location altering. Both of those models buckled and therefore the results are very almost like the info obtained using the core when the node locations were altered. Figure shows a picture of the coupon model with the buckled honeycomb core within the Abaqus FEA viewer.

Results and Discussion:

Load-deflection behavior

Figs 1.1 -1.3 show the load against mid-span displacement curves of the SHC beams containing 10 mm crack length at the skin as compared with those crack-free under four-point bending. In the plots, P1 represents the crack-free control case. The load-displacement curves of both crack-free SHC beams and that containing skin crack for UD0/90 and TW0/UD0 specimens increased linearly until the maximum failure load. Meanwhile, the TW0/UD90 SHC beam specimens displayed a linear behavior up to a deflection of 6 mm, then, the curves extend with a small nonlinearity due to stiffness softening until failure. Sudden failure was observed for UD0/90-BC, UD0/90-SC, and all

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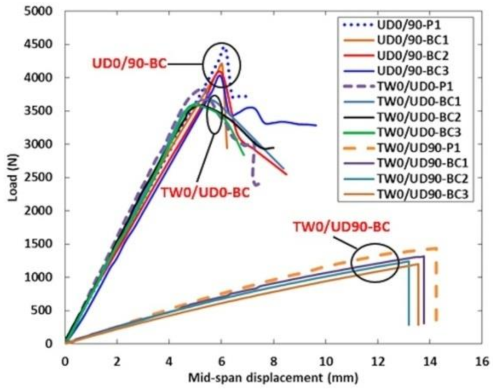
TW0/UD90 SHC beam specimens. The load-deflection curves dropped gradually for TW0/UD0-TC and UD0/90-TC SHC beam specimens. The average maximum failure load decreased to 6% for UD0/90 and TW0/UD0 SHC beam specimens while it reduced to 15% for TW0/UD90 specimens due to the presence of 10 mm face skin crack compared with the crack-free SHC beam specimens. This indicates that the presence of a 10 mm face crack has a slight effect on the load-displacement curves of SHC beams in the cases of flexural-compression, flexural tension, or shear cracks.



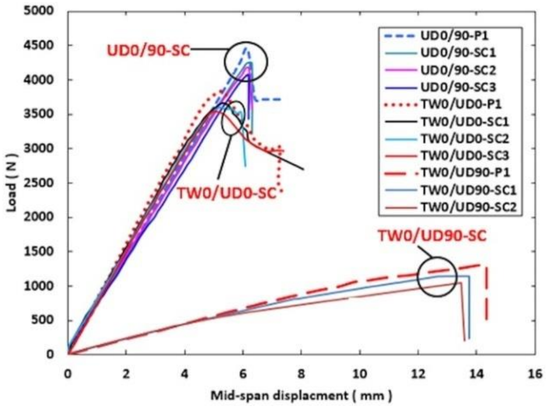
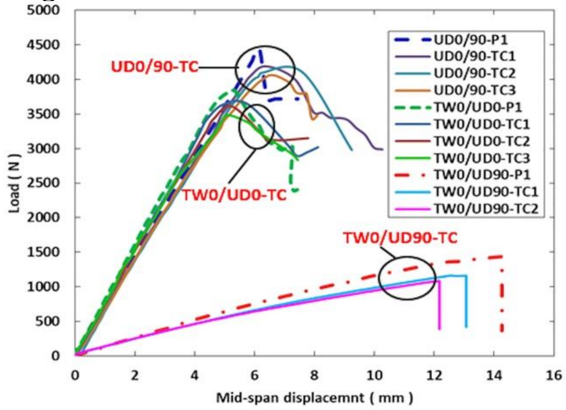


Fig-1.-1.3



Conclusion:

Reinforced by stringer reinforcement, the general stiffness of the composite Honeycomb Sandwich Structure with Stringer Reinforcement is enhanced effectively, the buckling and supreme bearing capacity are improved. Under in-plane compression condition, the buckling failure isn't the most failure modes of the structure, while strength conditions are main factors controlling the sandwich structure damage generally. The existence of interfacial debonding, local buckling will occur within the debonding area, and cause the ultimate broken. With the rise of the compression loading, the displacement of bulging outward increasing gradually and therefore the deboning propagation gradually extends to the interface of sheet/core near the initial debonding propagation of sheet/stiffener.

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