

The strength characteristics of aluminum honeycomb sandwich panels

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Abstract

Aluminum sandwich construction has been recognized as a promising concept for structural design of lightweight transportation systems such as aircraft, high-speed trains and fast ships. The aim of the present study is to investigate the strength characteristics of aluminum sandwich panels with aluminum honeycomb core theoretically and experimentally. A series of strength tests are carried out on aluminum honeycomb-cored sandwich panel specimen in three point bending, axial compression and lateral crushing loads. Simplified theories are applied to analyze bending deformation, buckling/ultimate strength and crushing strength of honeycomb sandwich panels subject to the corresponding load component. The structural failure characteristics of aluminum sandwich panels are discussed. The test data developed are documented. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Aluminium sandwich panel; Honeycomb core; Ultimate strength; Crushing strength

1. Introduction

For design and construction of lightweight transportation systems such as satellites, aircraft, high-speed trains and fast ferries, structural weight saving is one of the major considerations. To meet this requirement, sandwich construction is fre-

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Nomenclature

a	length of a sandwich panel or span of a sandwich beam
A	virtual area of a unit honeycomb core at the cross section parallel to the facing skin plane ($=L \cdot W$)
a_1, a_2	constants depending on panel dimensions, initial imperfection, etc.
A_c	cross sectional area of honeycomb core cell in the vertical direction ($=b \cdot h_c$)
b	breadth of the sandwich panel or beam
C	a constant representing the shear effects due to honeycomb core, on the resisting bending moment
d	breadth of one edge of honeycomb core cell
E_{eq}	equivalent elastic modulus
E_f	elastic (Young's) modulus of the facing material
E_c	elastic (Young's) modulus of the core material
G_{ca}	average value of elastic shear modulus of the honeycomb core cell, e.g., for both L - and W -directions ($=\frac{G_{cL}+G_{cW}}{2}$)
G_{cL}	elastic shear modulus of honeycomb core in the L -direction
G_{cW}	elastic shear modulus of honeycomb core in the W -direction
G_{eq}	equivalent shear modulus
G_f	shear modulus of facing skin
h	height of sandwich panel including facing skins ($=h_c+2t_f$)
h_c	height of honeycomb core
I_f	moment of inertia of facing skins of honeycomb sandwich panel
L	$=2d(1+\cos\frac{\alpha}{2})$
m	total mass of the honeycomb sandwich panel
m_f	mass of facing materials ($=2abt_f \cdot \rho_f$)
m_c	mass of honeycomb core ($=abh_c \cdot \rho_{ca}$)
M	bending moment of a simply supported honeycomb sandwich beam
P	applied load on the honeycomb sandwich beam
P_m	mean crushing load of honeycomb core
P_o	critical load of the honeycomb sandwich beam
P_{uc}	maximum load of honeycomb core under lateral crushing load
R	radius of the tip of supports and indenter in three point bending test
S	distance between two edges of honeycomb core hexagon (i.e., cell size), see Fig. 2
T	total plastic energy dissipation until the structure stops crushing
t_c	wall thickness of honeycomb core cell
t_{eq}	equivalent thickness
t_f	thickness of facing skin (assuming that both skins are of same each other)

w	mid-span deflection of the sandwich beam
W	$=2(t_c+d\cdot\sin\frac{\alpha}{2})$
α	angle of honeycomb core hexagon, may be taken as $\frac{2\pi}{3}$
β	$=\frac{b}{t_{eq}}\sqrt{\frac{\sigma_{fo}}{E_{eq}}}$
$\delta_{\max}$	maximum crushed distance
ν_c	Poisson's ration of honeycomb core material
ρ_c	density of honeycomb core material, taken as 2.7 g/cm ³ for aluminum alloys
ρ_{ca}	average density of honeycomb cores over an entire sandwich panel
ρ_f	density of facing material, taken as 2.7 g/cm ³ for aluminum alloys
σ_{co}	yield stress of honeycomb core material
σ_f	bending stress of facing skin for a sandwich beam
σ_{fo}	yield stress of facing material
σ_m	mean crashing strength under lateral crushing loads
σ_u	ultimate strength of the sandwich panel in axial compression
σ_{uc}	maximum strength of the sandwich panel in lateral crashing loads
τ_c	vertical shear stress of honeycomb core for a sandwich beam

quently used instead of increasing material thickness. This type of construction consists of thin two facing layers separated by a core material. Potential materials for sandwich facings are aluminum alloys, high tensile steels, titanium and composites depending on the specific mission requirement. Several types of core shapes and core material have been applied to the construction of sandwich structures. Among them, the honeycomb core that consists of very thin foils in the form of hexagonal cells perpendicular to the facings is the most popular.

A sandwich construction provides excellent structural efficiency, i.e., with high ratio of strength to weight. Other advantages offered by sandwich construction are elimination of welding, superior insulating qualities and design versatility. Even if the concept of sandwich construction is not very new, it has primarily been adopted for non-strength part of structures in the last decade. This is because there are a variety of problem areas to be overcome when the sandwich construction is applied to design of dynamically loaded structures. To enhance the attractiveness of sandwich construction, it is thus essential to better understand the local strength characteristics of individual sandwich panel/beam members.

The aim of the present study is to investigate the strength characteristics of honeycomb-cored sandwich panels made of aluminum alloy material among others. Noteworthy theoretical and experimental studies on linear elastic and nonlinear behavior of aluminum sandwich panels have been previously carried out by other investigators.

Kelsey et al. [1] derived simple theoretical expressions of the shear modulus of honeycomb sandwich cores. Witherell [2] performed an extensive theoretical study for structural design of an air cushion vehicle hull structure using aluminum honeycomb sandwich panels. Okuto et al. [3] showed the validity of the so-called equivalent plate thickness method in which a honeycomb sandwich panel subjected to in-plane loads is approximately replaced by a single skin panel with equivalent plate thickness. Elasto-plastic bending behavior of sandwich panels was studied by Kobayashi et al. [4]. An experimental study was undertaken by Yeh and Wu [5] to investigate the buckling strength characteristics of aluminum honeycomb sandwich panels in axial compression. The characteristics of the energy absorption capacity of bare honeycomb cores under lateral crushing loads have been studied by Kunimo et al. [6,7] both theoretically and experimentally.

While existing previous investigations including the ones cited above are quite useful, there still remain some problem areas to be overcome if one is to enhance the attractiveness of the sandwich construction method, while several other potential problems have been or are being solved. Primary among the concerns are some known obstacles to using sandwich construction for strength members in dynamically loaded structures. Sandwich laminates are not isotropic. The facing skin on the laterally loaded side of the sandwich panel may buckle due to bending. The buckling and collapse strength characteristics of sandwich panels are not yet fully understood. Debonding or delamination between the center core and outer facing plates is also a likely concern. Sandwich panels can also be suspect in resisting impact loads. Some of the impact energy dissipation characteristics of honeycomb cores remain unclear. Fatigue is a crucial problem to be solved in order to more effectively incorporate sandwich panels into the design and construction of large weight critical structures.

Since physical phenomena defining the structural failures of aluminum honeycomb-cored sandwich panels are quite complex, more experimental studies are needed to clarify their strength characteristics. In the present study, we wish to make new contributions to some of the problems, e.g., related to buckling, collapse and crushing behavior of aluminum honeycomb sandwich panels. For that purpose, a series of strength tests, namely three point bending tests, buckling/collapse tests and lateral crushing tests are carried out on an aluminum honeycomb-cored sandwich panel specimen. A theoretical study is also undertaken to analyze the elasto-plastic bending behavior, buckling/ultimate strength and crushing strength of sandwich panels subject to the corresponding load component. The test data developed are documented.

2. Characteristics of aluminum honeycomb sandwich construction

The conventional single skin structure, see Fig. 1(a), which is of single plates reinforced with main frames and stiffeners normally necessitates a fair amount of welding, and has a considerable length of weld seams. Further, the lighter but thinner plates employed tend to increase weld distortions that may in some cases require

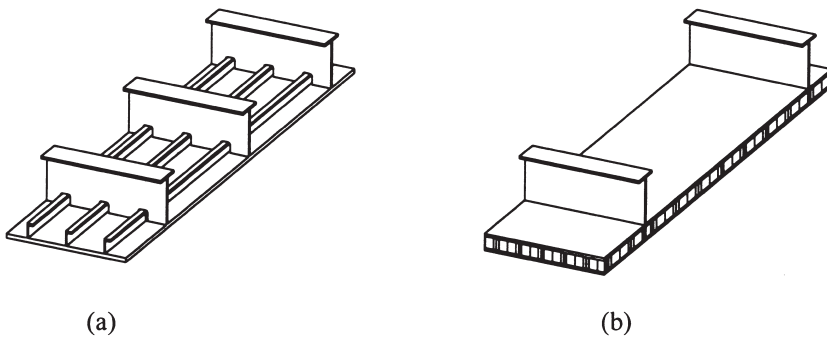


Fig. 1. Single skin and sandwich construction. (a) Single skin (b) Sandwich.

more fabrication work to rectify. More weld seams also mean a greater number of fatigue initiation locations as well. Meanwhile, an aluminum honeycomb sandwich construction, see Fig. 1(b), which a honeycomb core is sandwiched by two outer facing skins is better able to cope with such difficulties.

Two methods, namely brazing and adhesive bonding, are currently being used for joining aluminum alloy facing material and honeycomb core. In these methods, brazing sheets or adhesive films are inserted between the core and facing skins, and the panel is heated in a furnace resulting in bonding. Such panels have certain advantages due to their comparatively low cost, high strength to weight ratio and good energy absorbing capabilities. In using aluminum honeycomb sandwich panels for construction of a structure, no stiffeners are welded to plates, and also connections of the main support frames are simplified, both of which greatly reduce the need for complicated welding. A reduced amount of weld seams and the higher rigidity of the panels both lessen weld distortions. Frame spacing can be increased due to the higher rigidity of the sandwich panels, thus providing added structural weight savings in the structure.

It is for these reasons that the sandwich construction has been widely adopted for large weight critical structures. Honeycomb-cored sandwich panels have been used as strength members of satellites or aircraft, thus efficiently reducing their structural weight. In the railroad industry, passenger coaches of high-speed trains such as the TGV in France and Shinkansen in Japan have been designed and fabricated using aluminum honeycomb sandwich panels. Recently, attempts to use aluminum sandwich panels as strength members of high-speed vessel hulls have also been made [8,9].

For design of structures using aluminum honeycomb sandwich panels, basic structural properties should be first defined. Fig. 2 shows the aluminum honeycomb-cored sandwich panel considered in the present study. For simplicity, the facings are assumed to have equal thickness t_f , and the core height is denoted h_c . Fig. 3 shows one unit of the honeycomb core. In Fig. 3, the L and W directions are taken in the directions parallel and normal to corrugation, respectively.

The facing skins of a sandwich panel can be regarded as the flanges of an I-beam, since they carry the bending stresses to which the panel is subjected with one facing skin in compression, and the other in tension. Similarly, the core corresponds to the

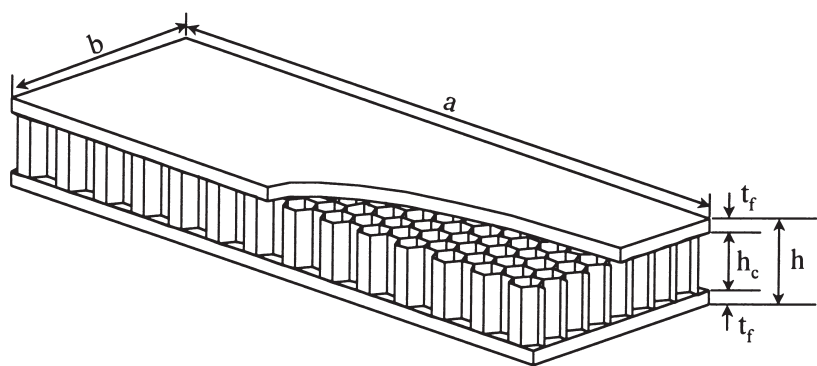


Fig. 2. Honeycomb-cored sandwich panel.

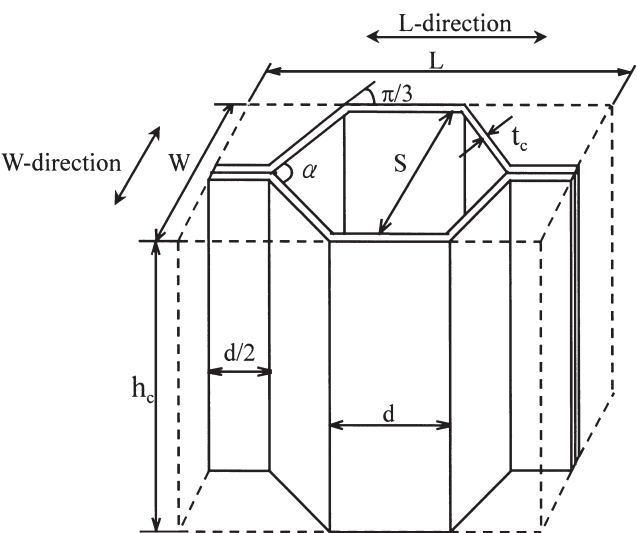


Fig. 3. A honeycomb-core unit.

web of the I-beam. It is assumed that the core carries no longitudinal stress and resists the shear forces. The core holds the facing skins apart such that the stiffness of the structure is increased. A core to skin joint rigidly joins the sandwich components and allows them to act as one unit with high torsional and bending rigidity.

The moment of inertia of the facing skins for a honeycomb sandwich panel can be calculated by

$$I_f = \frac{h^3 - h_c^3}{12} \cdot b$$

(1)

The virtual area of a unit honeycomb core at the cross section parallel to the facing skin plane is given by

$$A=L \cdot W \quad (2)$$

One major reason why aluminum honeycomb sandwich panels are of interest is due to their lightweight characteristics. Therefore, it is of crucial importance to accurately predict the weight of aluminum honeycomb sandwich panels so that performance measures for sandwich construction, e.g., strength to weight ratio, can be correctly computed. The mass of the aluminum honeycomb sandwich panel can be estimated from

$$m=m_f+m_c \quad (3)$$

By neglecting the contribution of materials used for joining honeycomb core cells, such as adhesives, to the total weight of honeycomb cores, the average density of honeycomb cores can be obtained from

$$\rho_{ca}=\frac{8dt_c}{A} \cdot \rho_c \cong \frac{8}{3\sqrt{3}} \cdot \frac{t_c}{d} \cdot \rho_c \quad (4)$$

Eq. (4) indicates that the average core density is expressed in terms of wall thickness and edge breadth of honeycomb core as well as the material density itself. Thus, ρ_{ca} can be used as a useful parameter in representing the strength properties of a honeycomb core.

3. Strength tests of aluminum honeycomb sandwich panels

Theoretically, a variety of possible failure modes for aluminum honeycomb sandwich panels can be considered when they are used as strength members in the dynamically loaded structure. They include elasto-plastic large deflection due to bending, buckling/collapse in axial compression, folding of honeycomb cores under lateral impact pressure and debonding between the center core and facing plates.

To investigate the structural failure characteristics mentioned above, three types of experiments, namely three point bending tests, buckling/collapse tests under (in-plane) axial compression, and crushing tests under lateral pressure, are undertaken in the present study using an aluminum honeycomb-cored sandwich panel specimen.

All test specimens consist of two materials, namely A3003–H19 for honeycomb cores and A5083–H321 for facing skins, even though the overall dimensions or profiles of the specimen may differ from specimen to specimen. Table 1 shows the mechanical properties of the aluminum honeycomb core which were provided by the core manufacturer. It is seen from Table 1 that the shear strength and modulus of the core in the *L*-direction are significantly larger than those in the *W*-direction.

Table 1
Mechanical properties of aluminum honeycomb core material A3003-H19

Item	Core density (kg/m ³)	
	54.4	83.2
0.2% yield stress (MPa)	190	190
Elongation %	4.0	4.0
Compressive strength (MPa)	2.5	4.6
Compressive modulus (MPa)	540	1000
Shear strength, <i>L</i> (MPa)	1.4	2.4
Shear strength, <i>W</i> (MPa)	0.85	1.50
Shear modulus, <i>L</i> (MPa)	260	440
Shear modulus, <i>W</i> (MPa)	130	220

Table 2
Mechanical properties of facing plate material A5083-H321

Young’s modulus (MPa)	Yield strength (Mpa) (Mpa)	Tensile strength (MPa) (MPa)	Elongation at rupture (%)
71,070	268	367	13

Table 2 shows mechanical properties for the facing plate material A5083–H321, which were obtained from tensile tests performed in the present study using a flat specimen.

3.1. Three point bending tests

To investigate the characteristics of bending behavior of aluminum honeycomb sandwich panels and also to analyze the shear effects of honeycomb core, three point bending tests are carried out. Fig. 4 shows the schematic view of the three point

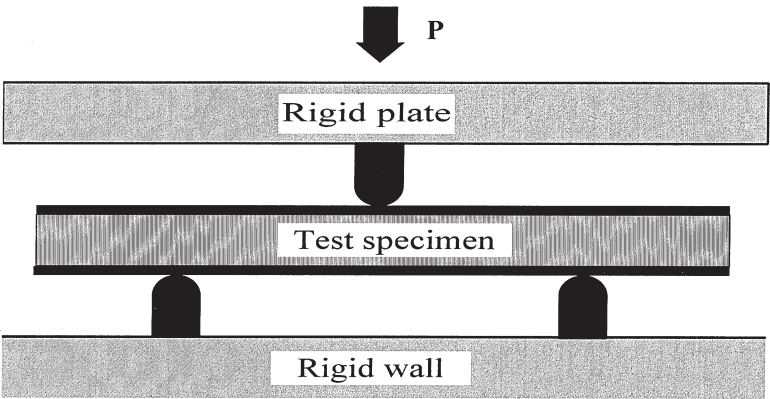


Fig. 4. Schematic view of the three point bending test set-up.

Table 3
Dimensions of three point bending test specimen^a

Item	Specimen	3PB1	3PB2
Core	Material	A3003-H19	A3003-H19
	Cell size (mm)	6.35	6.35
	Thickness (mm)	0.0381	0.0635
	Height (mm)	12.7	12.7
	Density (kg/m ³)	54.4	83.2
Facing	Material	A5083-H321	A5083-H321
	Thickness (mm)	3.0	3.0
Weight	Grams	499.5	510.5

^a $b=100$ mm, $L=500$ mm

bending test set-up. As indicated in Fig. 4, the tip of supports and indenter have a round shape with $R=20$ mm.

Two specimens with the same facing material but with different thickness of honeycomb core denoted by 3PB1 and 3PB2 as indicated in Table 3 are tested in three point bending. The overall dimensions of each test specimen are the same. The experiments were carried out in a quasi-static manner with a loading speed of about 0.05 mm/second using the 500 kN dynamic loading actuator system installed at the Ship Structural Mechanics Laboratory of the Pusan National University in Korea. The loading system is controlled by a personal computer. The data sets relating the loads and the mid-span deflection of the panel specimen are automatically detected and directly recorded on to the hard disk of the computer in real time as the stroke of the actuator advances.

Fig. 5 shows the relationship between loads and mid-span deflection for specimen

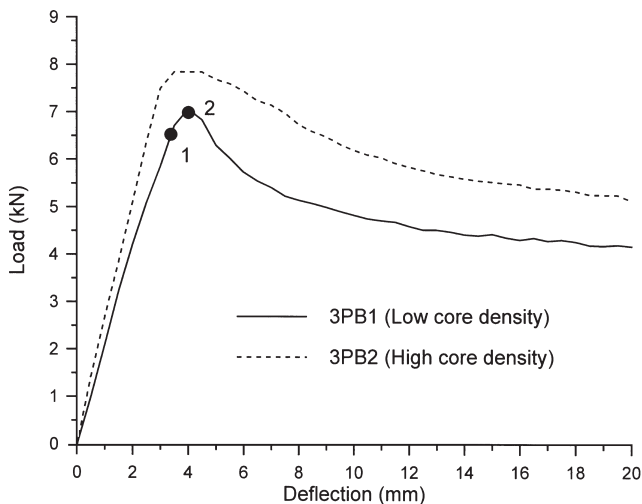


Fig. 5. Load-deflection curves for the three point bending test specimen.

3PB1 and 3PB2. In this figure, the linear elastic behavior is evident until the load approaches about 6.5 kN at point 1. After that, local plasticity occurs around the loading point and the behavior becomes elasto-plastic. With further increase in applied loads, plastic failure occurs at the honeycomb cell under the round bar, see point 2 of Fig. 5.

From these experiments, we observe that with an increase in the thickness of honeycomb core cell, the start of plastic deformation can be delayed, resulting in an increase of ultimate strength. It is also seen from Fig. 5 that the slope of the curve, i.e., bending stiffness, subsequent to plastic buckling becomes more moderate with the increase in the thickness of honeycomb core cell. This implies that undesirable effects of instability in the structure after collapse can be reduced by using a core of larger thickness.

Fig. 6 shows the deformed shape of the specimen 3PB2 after testing. From this photograph, one can see that while the crushing of the core near the load point is noticeable, it occurs without any significant local dent or deformation at the load point itself.

3.2. Buckling and ultimate collapse tests under axial compression

For flat steel, the buckling and ultimate strengths of plates and stiffened plating have been studied by many researchers. Several related theoretical, numerical, and empirical formulations for strength predictions have been suggested in the past with reasonable accuracy. On the other hand, similar research work on buckling/ultimate strength of aluminum sandwich panels is limited. Hence we in this study carried



Fig. 6. Deformed shape of the specimen 3PB2 after testing.

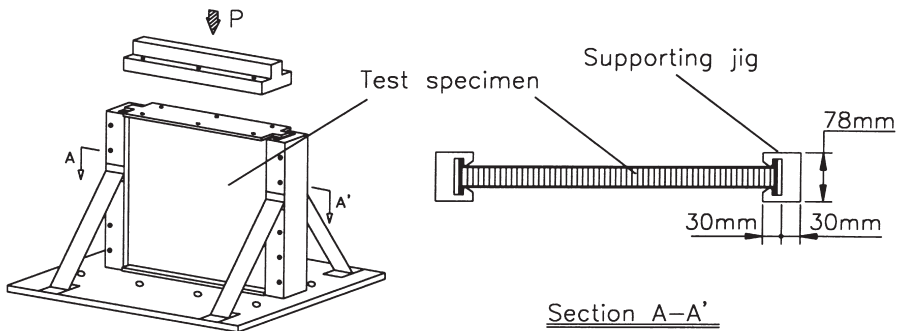


Fig. 7. Schematic view of the buckling/collapse strength test set-up.

out some needed experiments to better understand buckling and ultimate strength characteristics of aluminum honeycomb sandwich panels.

Fig. 7 shows a schematic view of the buckling/collapse strength test set-up. Four specimens are tested with varying height and cell wall thickness of honeycomb core, and panel aspect ratio, but with the facing skin material and the core cell size being the same each. Table 4 indicates the specifications of the test specimen used. The experiments were carried out using the universal test equipment available at the Ship Structural Mechanics Laboratory of Pusan National University. The maximum load capacity of the equipment is 1000 kN. The test set-up is designed so that the boundary conditions of the specimen are simply supported along their four edges.

Fig. 8(a) shows the deformed shape of the specimen UDC11C12 with the higher core (i.e., 25.4 mm or 1 inch core) after testing which was cut along loading direction to see the cross section. We can see the delamination between core and facing skins

Table 4
Dimensions of the buckling/collapse test specimen

Item/Specimen	UDC11C12	UDC11C21	UDC11C22	UDC12C11
Dimension				
a (mm)	500	500	500	500
b (mm)	500	500	500	250
h (mm)	31.4	18.7	18.7	31.4
Skin				
Material	A5083	A5083	A5083	A5083
Thickness (mm)	3.0	3.0	3.0	3.0
Core				
Material	A3003	A3003	A3003	A3003
Thickness (mm)	0.0381	0.0635	0.0381	0.0381
Height (mm)	25.4	12.7	12.7	25.4
Density (kg/m ³)	54.4	83.2	54.4	54.4
Cell size (mm)	6.35	6.35	6.35	6.35
Ultimate strength (kN)	725	371	330	312

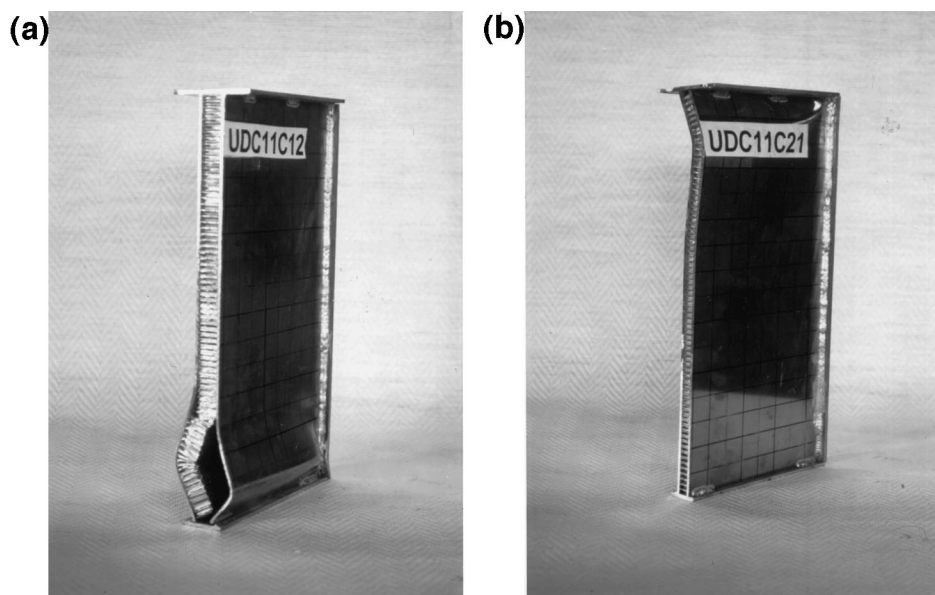


Fig. 8. Deformed shape of the buckling/collapse strength specimen cut along loading direction after testing. (a) UDC11C12 ($h_c=25.4\text{mm}$), (b) UDC11C21 ($h_c=12.7\text{mm}$)

in this figure. It is evident that the facing skin is deformed symmetrically with respect to the center line of the core. On the other hand, Fig. 8(b) shows the deformed shape of specimen UDC11C21 with half the height of core as in the previous specimen, Fig. 8(a) (i.e., 12.7 mm or half inch core). In this case, the specimen is seen to be deformed as a unit, similar to a thin single plate.

One may expect a large difference in strength between the above two cases. This will be mostly due to the differences in their flexural rigidities, as there is no difference between the two specimens except for their core heights. This is confirmed in Fig. 9. The ultimate strength of specimen UDC11C12 with a core height of one inch is about 725 kN, while the strength of UDC11C22 with its core height of half inch is 332 kN, i.e., 46% of the one inch case. The dramatic decrease of internal force after collapse as shown in Fig. 9 is due to delamination. It is evident that quality control and strength of the joints between facing skins and core would be very important to the collapse strength of sandwich panels. On the other hand, it is seen that the influence of core cell thickness on ultimate strength under axial compression is small, as shown in Fig. 10.

Fig. 11 shows the influence of aspect ratio on the collapse behavior of aluminum sandwich panels subject to axial compression. It is seen from this figure that the aspect ratio is also an influential factor affecting the collapse strengths of aluminum sandwich panels but perhaps not the most crucial. Further study is required to more accurately define the effects of aspect ratio.

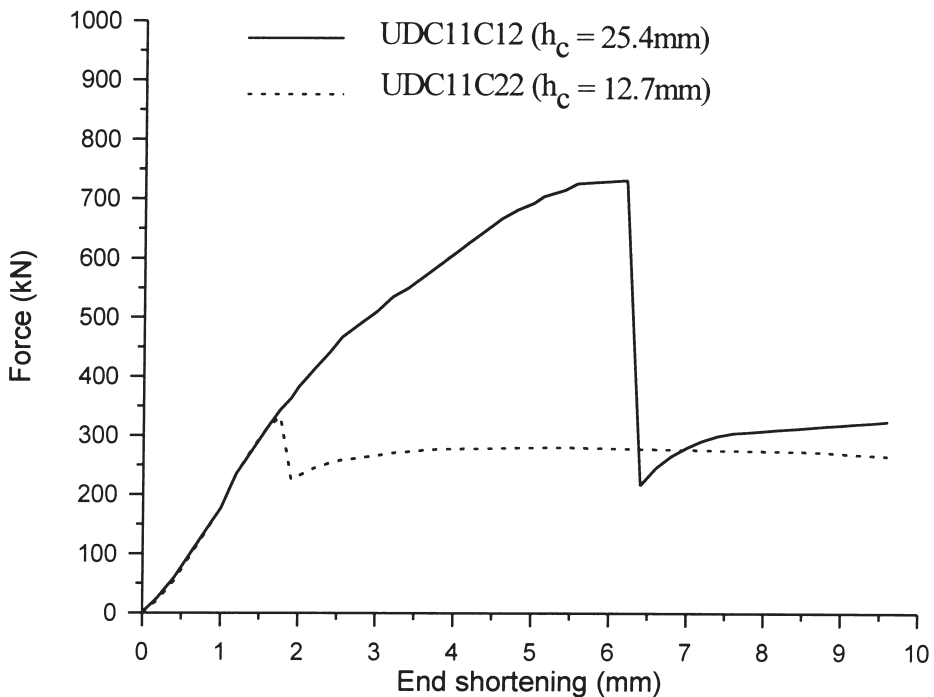


Fig. 9. Influence of core height on the collapse behavior of aluminum sandwich panels subject to uniaxial compression.

3.3. Crushing tests under lateral pressure

The sandwich panels are subjected to lateral impact pressure, e.g., resulting from hydrostatic pressure, slamming, collision and concentrated heavy loads when they are used as strength members in the dynamically loaded structures such as high speed vessel hulls. When thin walled structures are in such accidental loading situations as collisions, they can suffer deformations which are considerably larger than the wall thickness, and folding and contact of the walls may occur. In such cases, the safety evaluation of the structures is usually performed by utilizing a method based on energy absorption capacity. This approach can approximately estimate the magnitude of damage (or deformation) by postulating that the work absorbed must be equal to the initial kinetic energy.

To enhance the energy absorption capacity based safety assessment procedure for design of light weight structure using aluminum honeycomb sandwich panels, it is of crucial importance to better understand the crushing strength characteristics of the panels.

Fig. 12 shows the schematic view of the crushing test set-up of our study. The test specimen is put on the rigid floor and a rigid plate is pushed down by the dynamic loading actuator which incidentally is part of the same machine used for

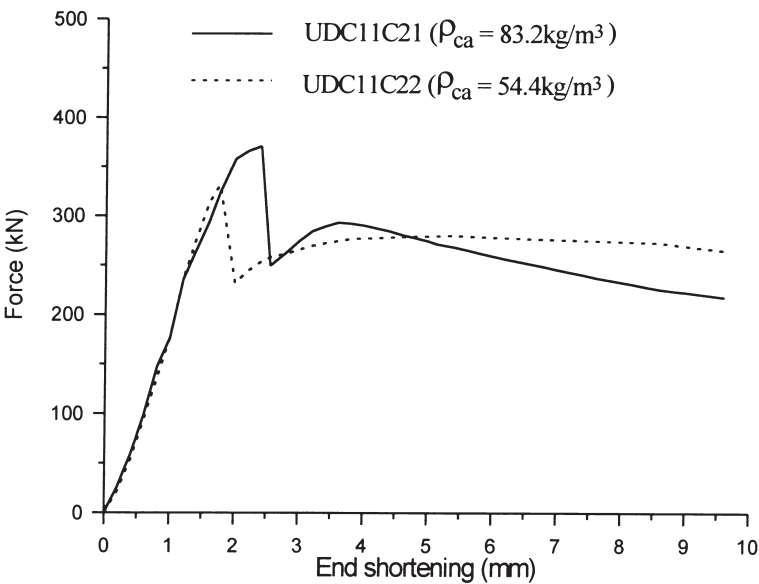


Fig. 10. Influence of core wall thickness on the collapse behavior of aluminum sandwich panels subject to uniaxial compression.

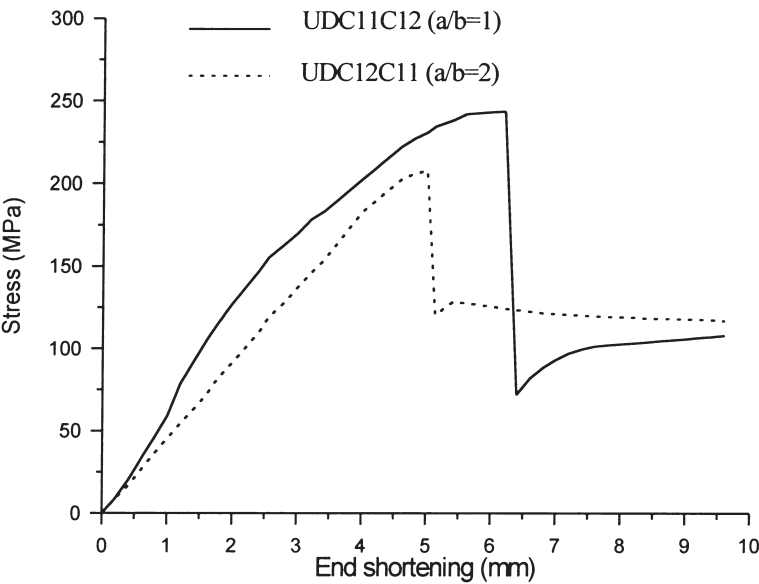


Fig. 11. Influence of aspect ratio on the collapse behavior of aluminum sandwich panels subject to uniaxial compression.

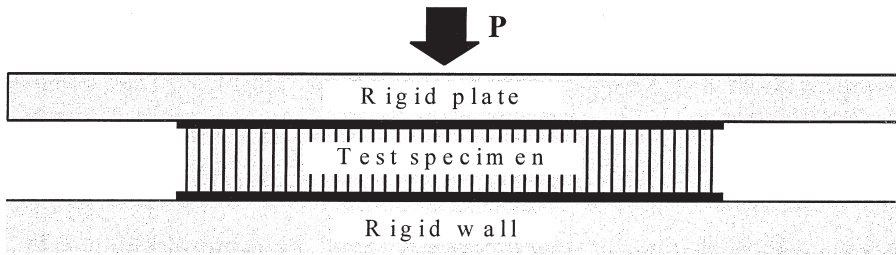


Fig. 12. Schematic view of the crushing test set-up.

the three point bending tests above. The lateral crushing load was increased until the honeycomb core is completely crushed so that it behaves as a rigid body. The loading speed was kept at 0.05 mm/sec. The data sets relating the crushing loads and the indentation are automatically recorded on to the hard disk of a computer. Three specimens are tested varying height and cell wall thickness of honeycomb core. Table 5 indicates the specifications of the test specimen.

Fig. 13 shows the load versus indentation curves obtained for the test specimen under lateral crushing loads. After the maximum load is reached the panels unload rapidly because the walls of the core cell are partly folded. With an increase in the deformation, the force increases again if the folded walls come in contact with the adjacent ones. This response appears repeatedly until the walls of honeycomb core cell are folded completely, even if this is not observed clearly in Fig. 13 because the wall thickness and height of core for the present test specimen are very small. It is seen from Fig. 13 that unlike the cases under bending the honeycomb core height is not a critical variable on the behavior of honeycomb sandwich panels under lateral pressure loads. As would be expected, however, the wall thickness of the honeycomb core cell is a crucial parameter affecting the strength of sandwich panels under crushing loads.

Table 5
Dimensions of the crushing test specimen

Property	Specimen	LP1	LP2	LP3
Core	Material	A3003	A3003	A3003
	Cell size (mm)	6.35	6.35	6.35
	Thickness (mm)	0.0381	0.0635	0.0381
	Height (mm)	25.4	12.7	12.7
	Density (kg/m ³)	54.4	83.2	54.4
Facing	Material	A5083	A5083	A5083
	Thickness (mm)	3.0	3.0	3.0

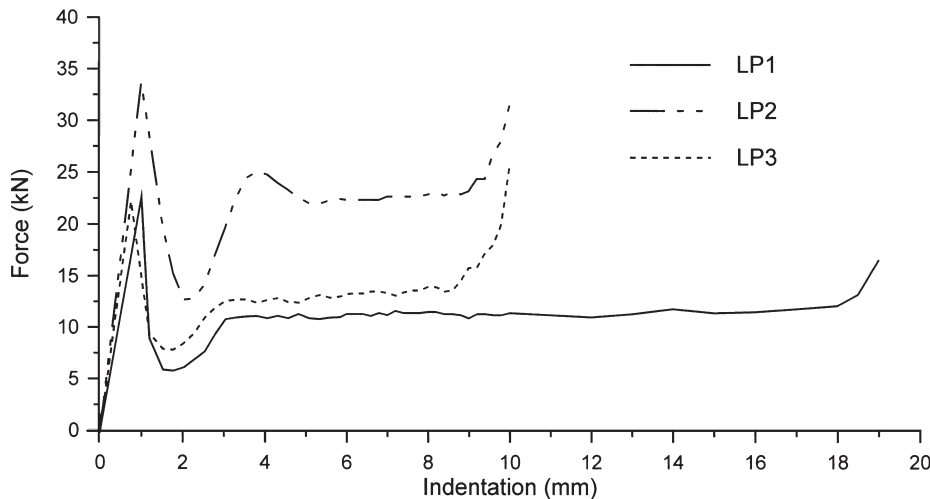


Fig. 13. Load versus indentation curves of the crushing test specimen.

4. Theoretical analysis of the test sandwich panels

Quick strength estimation methods are required in the preliminary structural design stage. For this purpose, the present study attempts to predict the strength of aluminum honeycomb sandwich panels using simplified approaches.

4.1. Bending behavior

A simplified method is employed for the analysis of bending behavior for the present sandwich panel specimen. A simply supported honeycomb sandwich beam subjected to a line load at its mid-span is considered as shown in Fig. 14. Fig. 15 shows assumed stress distribution at the mid-span cross section of the honeycomb sandwich beam. It is assumed that the facing plate carries only bending stresses σ_f .

When the thickness t_f of facing plates is small, the variation of bending stress through plate thickness direction may be ignored. It is also supposed that the honeycomb core carries only the vertical shear stresses τ_c . Considering the rotational

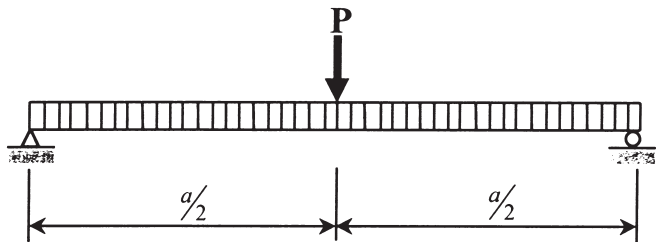


Fig. 14. A simply supported honeycomb sandwich beam.

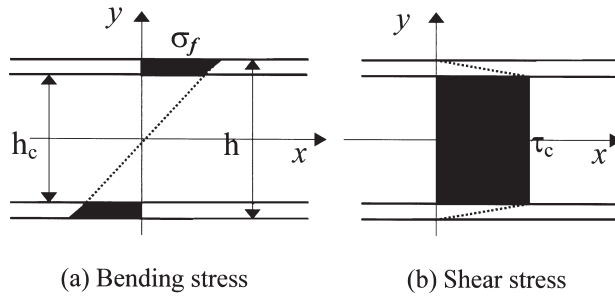


Fig. 15. Idealized distributions of bending and shear stresses in an aluminum sandwich beam.

restraints between facing plates and core, the distribution of shear stresses τ_c is assumed to be uniform through the core depth h_c .

Kelsey et al. [1] provide a formula of the mid-span deflection for the sandwich beam in the linear elastic regime as follows:

$$w = \frac{Pa^3}{48EI_f} + \frac{Pa}{4A_c G_{ca}} \quad (5)$$

The first term of the right hand side in Eq. (5) is due to bending effect alone and the second one accounts for the shear effect. In Fig. 16, a comparison of theoretical predictions (i.e., between load and mid-span deflection) using Eq. (5) is made against the experimental results for the present test specimen under bending. The theoretical results neglecting shear effects are also compared in the figure. It is seen that Eq. (5) predicts the linear elastic bending response of aluminum honeycomb sandwich beam well. It is clear that the shear stress related effects brought on by the honeycomb core cannot be neglected.

A simplified formula for predicting the critical value of applied loads is also studied. Considering the assumed stress distribution shown in Fig. 15, the bending moment of a simply supported honeycomb sandwich beam can be approximately calculated by integrating the first moment of the bending stress with regard to the neutral axis as follows:

$$M = C \cdot \frac{bh^2\sigma_f}{4} \left\{ 1 - \left(\frac{h_c}{h} \right)^2 \right\} = \frac{Pa}{4} \quad (6)$$

where C is a constant representing the shear effects due to honeycomb core on the resistive bending moment.

The constant C in the above may be obtained from Eq. (5) by assuming that the shear effects of cores for panel strength are likely to be similar to those for panel stiffness. This results in

$$C = \frac{C_1}{C_1 + C_2} \quad (7)$$

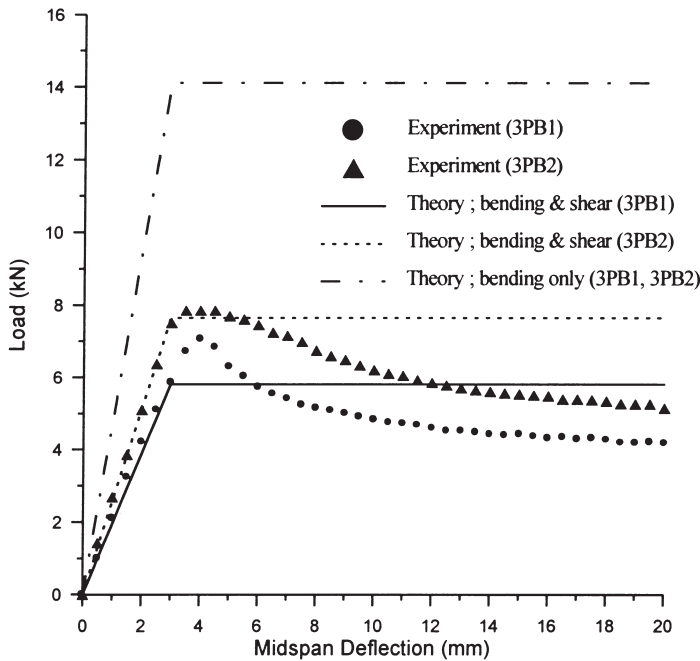


Fig. 16. Comparison of theoretical solutions with experimental results for the three point bending test specimen.

where, $C_1 = \frac{a^3}{48E_f I_f}$, $C_2 = \frac{a}{4A_c G_{ca}}$

The critical load is obtained when the bending stress of facing plate reaches the yield stress, i.e., $\sigma_f = \sigma_{fo}$. Therefore, by replacing P by P_o , Eq. (7) leads us to the following critical load.

$$P_o = C \cdot \frac{bh^2 \sigma_{fo}}{a} \cdot \left\{ 1 - \left(\frac{h_c}{h} \right)^2 \right\} \quad (8)$$

Fig. 16 plots the critical load behavior obtained by Eqs. (5) and (8) for the present test specimen. It is seen that Eq. (8) provides a reasonably accurate and quick prediction of the critical load for honeycomb sandwich panel beams under bending.

4.2. Ultimate compressive strength

We now illustrate the calculation of the ultimate strength for honeycomb sandwich panels under axial compression. An equivalent single plate approach in which the honeycomb sandwich panel is replaced by an equivalent single skin panel in the

strength calculation is employed. Fig. 17 represents a schematic concept of the equivalent single skin approach.

To replace the honeycomb sandwich panel by the equivalent single skin plate, two methods, namely the equivalent rigidity method and the equivalent weight method, may be considered. In the former (i.e., equivalent rigidity method), plate thickness and elastic modulus are defined such that the rigidity of the sandwich panel is equivalent to that of the single skin panel. In the latter method, dimensions of the equivalent single skin panel are defined so that the structural weight is equal.

The equivalent material properties of the single skin panel with the equivalent rigidity can be estimated from the following equations, see for example Kaneko and Takeuchi [10]. The rigidity of the panel with equal facing skin thickness is considered separately for in-plane tension, bending and shear:

In tension:

$$2t_f E_f = t_{eq} E_{eq} \quad (9a)$$

In bending:

$$\frac{1}{12}[(h_c + 2t_f)^3 - h_c^3] E_f = \frac{1}{12} t_{eq}^3 E_{eq} \quad (9b)$$

In shear:

$$2t_f G_f = t_{eq} G_{eq} \quad (9c)$$

The values t_{eq} , E_{eq} and G_{eq} which one obtains by solving the above equations are as follows:

$$t_{eq} = \sqrt{3h_c^2 + 6h_c t_f + 4t_f^2} \quad (10a)$$

$$E_{eq} = \frac{2t_f}{t_{eq}} E_f \quad (10b)$$

$$G_{eq} = \frac{2t_f}{t_{eq}} G_f \quad (10c)$$

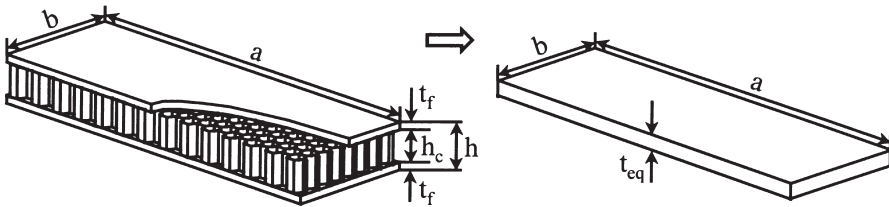


Fig. 17. A schematic of the equivalent single skin approach.

On the other hand, the equivalent plate thickness t_{eq} of the single skin plate based on equal weight may be calculated from

$$L \cdot W \cdot t_{eq} \cdot \rho_f = L \cdot W \cdot 2t_f \cdot \rho_f + L \cdot W \cdot h_c \cdot \rho_{ca} \quad (11a)$$

resulting in

$$t_{eq} = \frac{2t_f \cdot \rho_f + h_c \cdot \rho_{ca}}{\rho_f} \quad (11b)$$

The elastic and shear moduli of the equivalent single skin panel are assumed to equal those of facing skin materials, namely

$$E_{eq} = E_f, \quad G_{eq} = G_f \quad (12)$$

In our study, a form of the Frankland equation is used to predict the ultimate strength of the aluminum sandwich panel under uni-axial compression together with the apparent thickness and moduli as obtained above. Thus we have

$$\frac{\sigma_u}{\sigma_{fo}} = \frac{a_1}{\beta} - \frac{a_2}{\beta^2} \quad \text{for } \beta \leq 1, \quad = 1.0 \quad \text{for } \beta > 1 \quad (13)$$

where a_1 and a_2 are constants depending on the plate boundary conditions. Faulkner [11] proposes $a_1=2.0$, $a_2=1.0$ for simply supported plates and $a_1=2.25$, $a_2=1.25$ for clamped plates.

Figs. 18 and 19 show a comparison of the ultimate sandwich panel strengths obtained by the equivalent single skin panel approach plotted against the experimental results. Since the boundary conditions for our test specimen are simply supported, the constants in Eq. (13) are taken as $a_1=2.0$ and $a_2=1.0$ in the strength calculations.

In Figs. 18 and 19, theoretical strength predictions are made by the equivalent single skin panel approach based on the equal rigidity and equal weight methods, respectively. It is seen from these comparisons that the equivalent rigidity method tends to overestimate the ultimate strengths, while the equivalent weight method underestimates them. When the core height is relatively small the equivalent weight method provides better results. For the sandwich panels with a higher honeycomb core, the equivalent rigidity method may predict the ultimate compressive strengths more reasonably. Appropriate theoretical and experimental studies are needed to better define the critical ratio of core height to facing thickness separating the applicability regimes of the two simplified methods discussed above.

4.3. Mean crushing strength

Fig. 20 shows a typical load versus indentation curve for a thin-walled structure subjected to predominantly compressive loads. In a usual loading situation where the magnitude of deformations is small, the internal force will rapidly drop after the

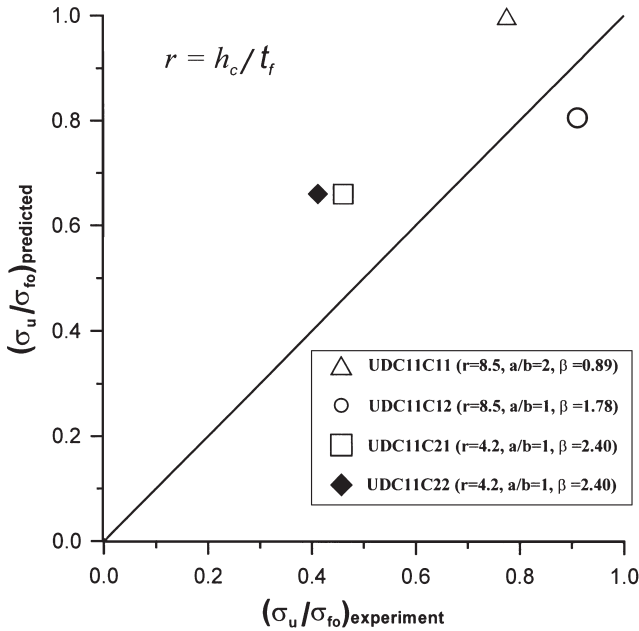


Fig. 18. Comparison of ultimate compressive strength predictions with experiments using the equivalent single skin approach with the equivalent rigidity.

maximum (or ultimate) load is reached. As the deformation continues, folding of the walls occurs. If the walls come in contact each other, the internal force will rise until the adjacent walls fold. This response is repeated until the folding of the walls ends. The completely folded structure then behaves as a rigid body. The area under the curve shown represents the total energy absorbed by the structure.

When the internal energy is dissipated in the structural deformations, the mean crushing strength is obtained from the energy equilibrium condition as

$$P_m = \frac{T}{\delta_{\max}} \quad (14)$$

To evaluate the crushing damage of structures, it is necessary to obtain the real force versus deformation relationship for the structure. The crushing behavior of structures is normally complex, and it is very hard to obtain the real force versus deformation relationship of structures by using an analytical or even a numerical approach. Only experiments will give the real force versus deformation relationship of structures under crushing loads, but this is not always practical, and may be even impossible for large sized structures. In some cases, however, we may not have to calculate the real force versus deformation relationship because, if the mean crushing strength is known, the deformation or crushed length can be estimated by postulating equalizing of the absorbed energy and the initial kinetic energy.

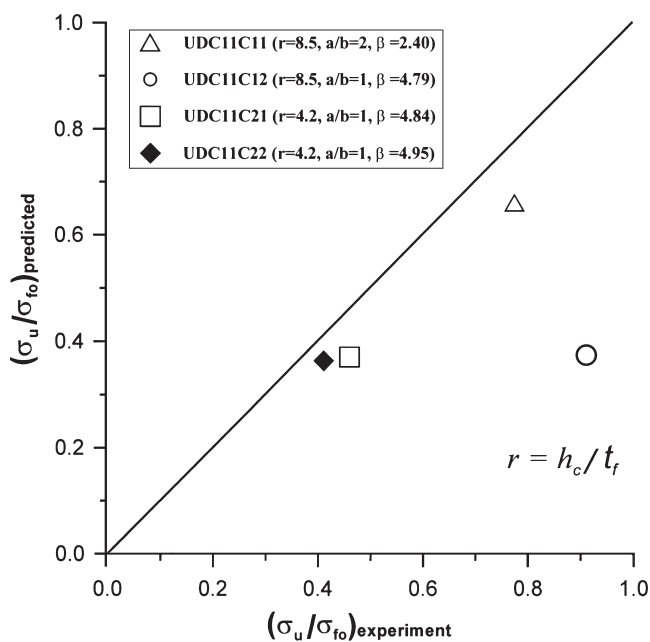


Fig. 19. Comparison of ultimate compressive strength predictions with experiments using the equivalent single skin approach with the equal weight.

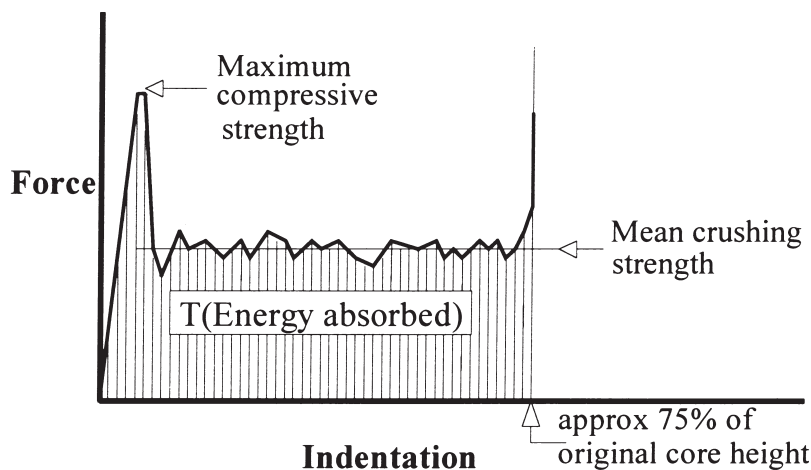


Fig. 20. Schematic representation of a typical force versus indentation curve for a thin-walled structure subject to crushing loads.

Table 6 summarizes maximum compressive and mean crushing strengths obtained for the three aluminum sandwich panel specimens tested in the present study. It is known that the typical maximum crushed distance of unstiffened single steel plates is about 75% of the original member length [12,13]. For the present aluminum sandwich panel specimen, the maximum crushed distance was actually about 70% of the original length as indicated in Table 6.

The formula for predicting the maximum compressive load of honeycomb core alone (i.e., without facing skins) under lateral crushing loads derived by Kunimoto and Yamada [6] is used in our study, namely

$$P_{uc} = 8dt_c \left[\frac{\pi^2 E_c \sigma_{co}^2}{3(1-\nu_c^2)} \left(\frac{t_c}{d} \right)^2 \right]^{1/3} \quad (15)$$

To predict the mean crushing load for the bare honeycomb core under crushing loads, Wierzbicki [14] derived the following simplified formula which is used in our study:

$$P_m = 16.56A \cdot \sigma_{co} \cdot \left(\frac{t_c}{S} \right)^{5/3} \quad (16)$$

Figs. 21 and 22 compare the calculated maximum and mean crushing loads with experimental results, respectively, as a function of the average core density. Experimental results obtained for the bare honeycomb core by Hexcel [15] are also compared.

In Fig. 21, the data marked by solid circles are maximum compressive strengths from experiments on an aluminum honeycomb sandwich specimen with facing skins, while the data marked by squares show experimental strength values from tests of a honeycomb core alone. A comparison of the maximum compressive strengths for the core alone and sandwich specimen with facing skins show that while the trends of strengths in both cases are quite similar, there is in fact a substantial increase in strength for the specimen with facing skins. This appears to be from the stabilizing

Table 6
Maximum compressive and mean crushing strength of test specimen

Item	Specimen	LP1	LP2	LP3
Core	Designation ^a	3.4-1/4-15	5.2-1/4-25	3.4-1/4-15
	Depth (mm)	25.4	12.7	12.7
Full Crush ^b	Max. indent. (mm)	17.9	9.1	8.8
	Effect.crushing distance (%)	70.5	71.6	69.2
	Crush strength (MPa)	1.1	2.3	1.3

^a Honeycomb designation: Density (lb/ft³)-cell size (inches)-gage(inches×10⁻⁴).

^b Full crush represents the condition where the load-displacement curve rapidly rises, indicative of a crushed rigid body or completely crushed honeycomb core.

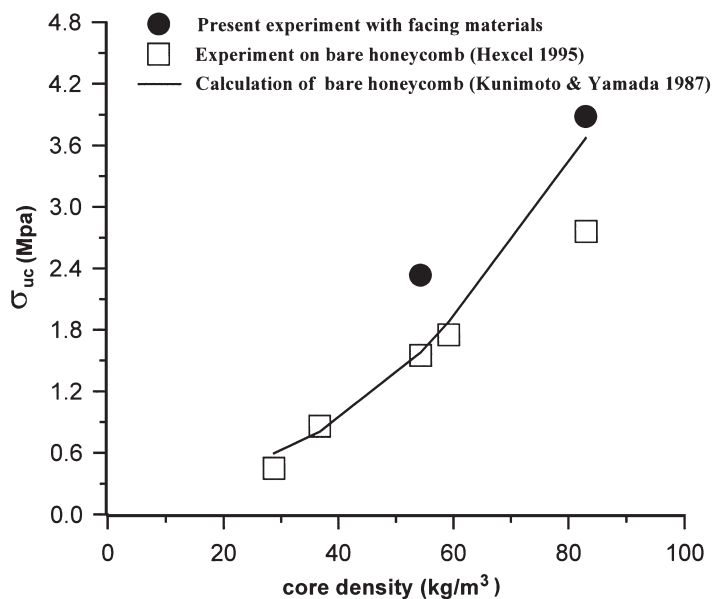


Fig. 21. Effects of core density on the maximum compressive strength under lateral pressure.

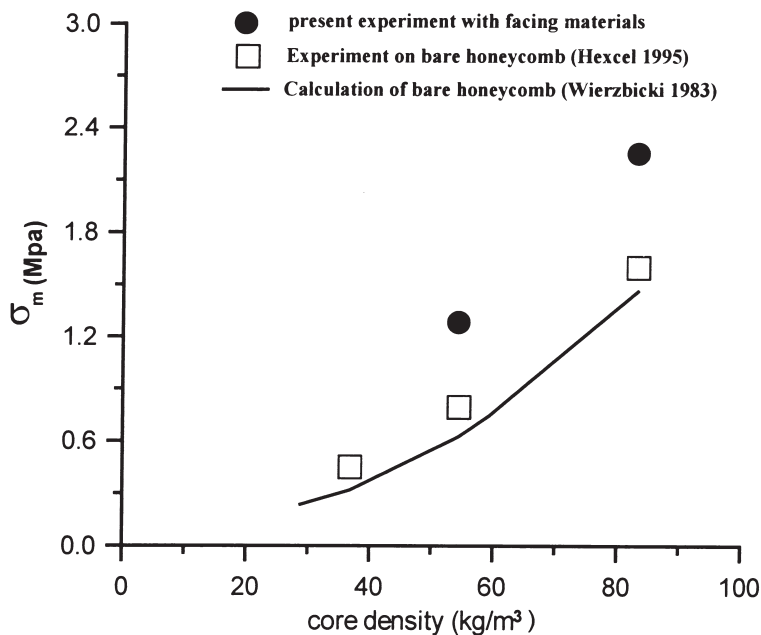


Fig. 22. Effects of core density on the mean crushing strength under lateral pressure.

effect of the facing skins during the process of crushing. The same trend was also previously reported in experiments by Goldsmith and Sackman [16].

The mean crushing strength of the honeycomb panel is one of the most important properties on which the energy absorbing capability of the entire structure will depend. For the sandwich, this strength depends on the yield strength of the bare core as well as geometrical dimensions such as cell size and wall thickness. Since the density of the honeycomb is in turn affected by the geometrical dimensions of the honeycomb, the crushing strength also has a strong relationship with the density, as evident from the results of Fig. 22. The calculated mean crushing strengths of the bare honeycomb as shown in Fig. 22 are obtained using Eq. (16). It is also seen from Fig. 22 that the calculated mean crushing strengths for the bare honeycomb core match the corresponding experimental data from Hexcel well. Also, there is again seen, an increase in strength of aluminum sandwich panels compared to that of the honeycomb core itself, due to much the same reasons as previously stated in the case of maximum compressive strength.

5. Concluding remarks

A sandwich construction, which consists of two thin facing layers separated by a thick core, offers various advantages for design of weight critical structures. Depending on the specific mission requirements of the structures, aluminum alloys, high tensile steels, titanium or composites are used as the material of facing skins. Several core shapes and materials may be utilized in the construction of the sandwich. Among them, it has been known that the aluminum honeycomb core has excellent properties with regard to weight savings and fabrication costs.

Even if the concept of the sandwich construction is not very new, it has so far been applied to the design of light weight structures restrictively. The sandwich panels have primarily been used as non-strength parts of the structures in the last decade. This is due to the fact that there are still various problem areas to be overcome in order to enhance the attractiveness of the sandwich construction, several of which have been or are being solved.

The aim of the present study has been to make a new contribution to some of the problems, i.e., related to buckling, collapse and crushing behavior of aluminum honeycomb sandwich panels. For that purpose, a series of strength tests, namely three point bending tests, buckling/collapse tests and lateral crushing tests were carried out on aluminum honeycomb-cored sandwich panel specimen. Theoretical study was also undertaken to analyze elasto-plastic bending behavior, buckling/ultimate strength and crushing strength of sandwich panels subject to the corresponding load component.

Based on the results presented, the following conclusions can be drawn:

1. From the three point bending tests on the aluminum honeycomb sandwich beam specimen varying the honeycomb core cell thickness, it was observed that with an increase in the thickness of honeycomb core cell, the start of plastic deformation could be delayed, resulting in increase of ultimate strength. Also, the sand-

wich beam bending stiffness subsequent to plastic buckling becomes more moderate as the thickness of honeycomb core cell increases. This would imply that undesirable effects of instability in the structure after collapse can be reduced by using a larger thickness of core.

2. From the axial compression collapse tests on the aluminum honeycomb sandwich panel specimen, varying various potential influential parameters, namely the core height, core cell thickness and panel aspect ratio, it was observed that the core height would be a crucial parameter affecting the sandwich panel ultimate compressive strength. Also, the delamination between core and facing layers could occur when the height of core became large. A dramatic decrease of internal force after collapse was observed to occur by such delamination. It is thus evident that quality control and strength of the joints between facing layers and the core would be very important to the collapse strength of sandwich panels. On the other hand, it was seen that the influence of core cell thickness on ultimate strength under axial compression would be small. The influence of aspect ratio on the collapse behavior of aluminum sandwich panels subject to axial compression may also be an influential factor affecting the collapse strengths of aluminum sandwich panels even if it is not the most crucial.
3. From the crushing tests on the aluminum honeycomb sandwich panel specimens under lateral crushing loads varying the cell thickness and height of honeycomb core, it is seen that the core height is not an influential parameter on the crushing behavior of honeycomb core. As would be expected, however, the wall thickness of a honeycomb core cell is a critical variable affecting the crushing strength of sandwich panels subject to lateral pressure loads. A substantial increase in crushing strength for the specimen was obtained by facing skins when compared with the tests for the bare honeycomb core. This would appear to be from the stabilizing effect of the facing skins during the process of crushing.
4. Several simplified methods were studied to analyze the deformation and strength behavior of aluminum honeycomb sandwich panels. It was evident that when evaluating the bending stiffness of a honeycomb sandwich beam the shear stress related effects brought on by the honeycomb core should not be neglected. The ultimate load of the honeycomb sandwich beam was found to be reasonably well predicted by assuming that the beam would reach the ultimate limit state when part of the facing layers yield. Even in the sandwich beam ultimate load predictions, however, the effects of shear stresses due to core should be taken into account.
5. The equivalent single skin panel approach, together with either equal rigidity or equal weight, may possibly be used for predicting the ultimate strength of honeycomb sandwich panels under axial compression. The equal weight based method may be available only for the honeycomb sandwich panels with smaller value of core height to facing layer thickness ratio, while the equal rigidity based method may provide more reasonable results for the panels with a larger value of core height to facing layer thickness ratio.
6. Reasonable predictions of crushing loads for bare a honeycomb core were possible by using certain simple crushing strength formulations, but further study is needed

in this regard in order to take into account the influence of facing layers on the crushing behavior.

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