Mechanical response and strength characteristics of aluminum honeycomb sandwich panels for infrastructure engineering

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Abstract. The use of aluminium sandwich panels has been increased in a certain number of engineering applications from infrastructure systems and transportation to aircraft and naval engineering. Due to their structural efficiency these materials are ideal for applications where ratio of strength to weight is of crucial importance. In the current study the investigation of the strength characteristics of aluminium sandwich panels with aluminium honeycomb core and different types of skins is performed using both analytical models and experimental procedures. A series of strength tests such as tension, shear, three point bending and double cantilever beam were conducted on aluminium honeycomb-cored sandwich panel specimens with five different skins in order to examine the mode of failure and the mechanical behaviour of the structural elements. The experimental findings are compared to theoretical values while an attempt for the explanation of the mechanisms leading to failure such as buckling, delamination or debonding between core and skins is performed. The results occurring from the study are very useful for the enhancement of the mechanical behaviour of sandwich constructions, thus more intensive work must be carried out in order to understand the physical mechanisms leading to strength characteristics of sandwich panels.

1. Introduction

Lightweight structures demand minimum structural weight in combination with excellent specific properties. This is the case where sandwich components are ideal for load bearing applications and weight saving.

Sandwich components consist of two facing layers (skins) separated by a core material. In most cases the skins are aluminium, reinforced polymers or metals depending on the application. In addition, the core material can be a lightweight polymer foam or even a geometrically more complex material such as aluminium, sheet or polymer honeycomb.

These constructions usually suffer from debonding and delamination [1, 2] between skin and core occurring either from bending tensile or compressive loading. A common kind of failure is buckling of the skins mainly occurring mainly from compressive or bending loading resulting once more in delamination between core and skin. Anisotropy and non-homogeneity are also some of the difficulties that arise when modelling the mechanical behaviour of these materials. On the other hand sandwich panel are promising materials in resisting impact loads and fatigue [3, 4].

Many theoretical, numerical and experimental studies on the mechanical response of aluminum sandwich panels can be found in literature by other investigators. Most of them concentrate either on
the adhesion between skin and core of the sandwich panel and its effect on the overall response of the structure or the techniques used for the determination of the strength parameters of the material.

The aim of the present study is the investigation of the mechanical strength of aluminum honeycomb-cored sandwich panels made from different kind of skin materials at different loading modes. More precisely six different type of skins were tested in three point bending as well as double cantilever beam (DCB) loading modes in order to determine experimentally the bending strength and the adhesive strength of the sandwich structure expressed by the interlaminar fracture energy respectively.

2. Theoretical background
When using aluminum honeycomb sandwich panels in structures some basic structural properties should be first determined. Fig. 1 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. 2 shows one unit of the honeycomb core. Fig. 3 shows the aluminum honeycomb-cored sandwich panel considered in the present study directions parallel and normal to corrugation, respectively.

![Figure 1. Honeycomb sandwich panel [4].](image1)

![Figure 2. A honeycomb-core cell [4].](image2)

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 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:
\[ I = \frac{h^3 - h_c^3}{12}b \]  

(1)

where \( h \) is the overall thickness of the sandwich panel, \( h_c \) is the thickness of the core and \( b \) is the width of the sandwich panel.

To calculate the section modulus, the following formula applies:

\[ W = \frac{I}{y} \]  

(2)

where \( I \) is moment of inertia and \( y \) is the distance from centroid to top or bottom edge of the rectangle.

The rigidity \( R \) of the sandwich structure can be estimate as

\[ R = EI \]  

(3)

where \( E \) is the modulus of elasticity and \( I \) is the moment of inertia.

Aluminum honeycomb sandwich panels are of interest due to their superiority in their lightweight characteristics. Therefore, it is of crucial importance to 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 the following formula as:

\[ m = m_f + m_c \]  

(4)

The core shear ultimate strength of a sandwich structure can be calculated as follows:

\[ F_{s,ult} = \frac{P_{\text{max}}}{(d + c)b} \]  

(5)

Where \( F_{s,ult} \) is the core shear ultimate strength, \( P_{\text{max}} \) is the maximum force prior to failure, \( t \) is the nominal facing thickness, \( d \) is the sandwich thickness, \( c \) is the core thickness and \( b \) is the sandwich width.

The strain energy release rate of a perfectly built-in double cantilever beam can be estimated using the Modified Beam Theory (MBT) Method as follows:

\[ G_I = \frac{3P\delta}{2ba} \]  

(6)

Where, \( P \) is the load, \( d \) is the load point displacement, \( b \) is the specimen width and \( a \) is the delamination length.

The above mentioned expression will overestimate \( G_I \) because the beam is not perfectly built-in (that is, rotation may occur at the delamination front). One way of correcting for this rotation is to treat the DCB as if it contained a slightly longer delamination, \( a + |D| \), where \( D \) may be determined experimentally by generating a least squares plot of the cube root of compliance, \( C^{1/3} \), as a function of delamination length. The compliance, \( C \), is the ratio of the load point displacement to the applied load, \( d/P \). The values used to generate this plot should be the load and displacements corresponding to the visually observed delamination onset on the edge and all the propagation values. Calculation of the Mode I interlaminar fracture toughness can be regarded as follows:
\[ G_f = \frac{3P\delta}{2b(a + |\Delta|)} \]  

This approach also allows the modulus, \( E_{if} \), to be determined as follows:

\[ E_{if} = \frac{64(a + |\Delta|)^2 p}{\delta bh^3} \]  

3. Materials and methods

Six different kinds of aluminium honeycomb panels with various skins were used in the current study provided that the core of the sandwich panel remained the same in all tests. The description of the materials used in each skin is presented in Table 1. Additionally all skins were pasted using the same adhesive medium in order to investigate the influence of skin in the strength of the sandwich structure.

Mechanical tests conducted in specimens in order to determine the strength characteristics of honeycomb sandwich panels. More precisely, three point bending tests were performed (Figure 3) in order to define the core shear properties of sandwich constructions by beam flexure according to C393/C393M-11 Standard Test Method [5] while double cantilever beam tests (Figure 4) were conducted according to D 5528-1 [6].

Specimens from honeycomb plates were cut in the desired dimensions for all type of skins. A polishing procedure of the cutting edges was applied in order to avoid possible local failures of the specimens. All tests were conducted in an INSTRON 3380 Universal Testing Machine with a load capacity of 10 kN.

Typical values of moment of inertia \( I \), rigidity \( EI \) and section modulus \( W \) for each type of honeycomb plate are shown in Table 2. The type of skin in each honeycomb plate as well as its structure based on the compound that was used defines the macroscopic mechanical strength properties of the honeycomb test coupons.

| Skin/Commercial name of material | Short description |
|---------------------------------|-------------------|
| Silicate sand surface (Silicate Sand) | A natural quartz with special transparent resins with SiO2 in exceptional chemical purity exceeding 99.5% designed for uses, such as wall cladding, blinds, pergolas and interior masonry. |
| Modified wood (Rezysta) | A compound of rice husks, salt and mineral oils, exhibiting great mechanical stress and thermal resistance that does not swell, grey, crack or splinter, making it a perfect all-weather solution for indoor and outdoor applications. |
| Aluminum alloy | A corrosion resistant aluminium alloy used for infrastructure applications. |
| Acrylic solid (Solid Surface) | A resilient, durable acrylic solid non porous product resistant to bacteria, mold and viruses, making it ideal for healthcare facilities. |
| Strong steel alloy (Corten) | A very strong steel alloy that creates a self-protection "skin" known as patina, thus protecting it from further oxidization. |
| Metal-clay material (Kerlock) | A compound of two diverse materials, such as metal and clay, bonded together in a permanent fusion with applicability in a number of uses ranging from kitchen counters to cladding walls. |
Figure 3. Representation of a three-point bending test.

Figure 4. Schematic representation of double cantilever beam with piano hidges.

Table 2. Values of moment of inertia $I$, rigidity $EJ$ and section modulus $W$ for each type of honeycomb plate.

| Type of skin            | Moment of Inertia $J$ (cm$^4$/m) | Rigidity $EJ$ (kNcm$^2$/m) | Section Modulus $W$ (cm$^3$/m) |
|-------------------------|----------------------------------|-----------------------------|-------------------------------|
| Silicate sand surface   | 35,9                             | 55490                       | 32,7                          |
| Modified wood           | 63,3                             | 13774                       | 55,8                          |
| Aluminum alloy          | 26,9                             | 94924                       | 25,3                          |
| Acrylic solid           | 54,3                             | 19987                       | 48,7                          |
| Strong steel alloy      | 20,4                             | 49447                       | 20,4                          |
| Metal-clay material     | 60,9                             | 7831                        | 56,7                          |

4. Results and discussion

Typical compressive load versus compressive extension graphs occurring from three point bending tests for each type of skin in the testing procedure are depicted in Figure 4. All experiments performed at tensile loading mode, exhibited an extensive elastic behaviour followed by a portion of inelastic response up to the point of ultimate loading.

In all cases the point of failure assumed to be the measurement of loading in the first crack event. The estimated values of ultimate shear strength $F_s^{ul}$, skin ultimate tensile strength $SUTS$, and adhesive strength $G_{ic}$ are shown in Table 3. It is obvious that there is no skin material that provides the optimum values for all properties.
Table 3. Estimated values of ultimate shear strength $F_{s\text{ult}}$, Skin ultimate tensile strength SUTS, modulus of elasticity $E$ and adhesive strength $G_{ic}$.

| Type of skin          | Ultimate shear strength $F_{s\text{ult}}$ (MPa) | Skin ultimate 3PB strength (SUTS) (N/mm$^2$) | Modulus of elasticity $E$ (N/mm$^2$) | Adhesive strength $G_{ic}$ (KJ/m$^2$) |
|----------------------|---------------------------------------------|---------------------------------------------|--------------------------------------|---------------------------------------|
| Silicate sand surface| 0.3198                                      | 81.1                                        | 15457                                | 4.18                                  |
| Modified wood        | 0.3903                                      | 17.1                                        | 2176                                 | 3.36                                  |
| Aluminum alloy       | 0.3180                                      | 159.31                                      | 35288                                | 0.51                                  |
| Acrylic solid        | 0.3198                                      | 20.48                                       | 3681                                 | 0.69                                  |
| Strong steel alloy   | 0.3568                                      | 269.04                                      | 24239                                | 4.38                                  |
| Metal-clay material  | 0.5586                                      | 20.4                                        | 1286                                 | 2.45                                  |

However, honeycomb test coupons with aluminium or metal-based skin exhibit the highest values in ultimate tensile strength and modulus of elasticity [7]. On the other hand shear strength is rather not affected dramatically by the type of the skin as that property is dependent on the adhesion between core and skin denoting a very strong interconnection of the skin surface with honeycomb in all cases mainly due to the skin-honeycomb core assembly technique applied by the provider. Last but not least the adhesive strength seems to be deteriorated in some cases by the smoothness in the surface of the skin such as in the case of acrylic solid and aluminum alloy. As a general remark the smoother the surface of the skin the lower the value of adhesive strength.

![Graphs](image-url)
Figure 5. Graphs of compressive load versus compressive extension at aluminium honeycomb test coupons occurring from three point bending tests at for different type of skins.

(a) Modified wood

(b) Aluminium alloy

(c) Acrylic solid

(d) Strong steel alloy

(e) Strong steel alloy

(f) Metal-clay material
Figure 6. Graphs of load versus extension at aluminium honeycomb test coupons occurring from double cantilever beam tests for different type of skins

5. Conclusions
Three point bending and double cantilever beam tests were conducted in order to determine mechanical bending strength characteristics and interlaminar fracture energy. The results indicate that the type of surface processing and addition of specific layers in the skin in order to achieve specific properties may affect the mechanical characteristics of the honeycomb structure.

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References
[1] Okuto K, Namba K, Mizukoshi H, Hiyama. Y 1991, The analysis and design of honeycomb welded structures, *J Light Met Welding* **29**(8), 361–8.
[2] Kobayashi H, Daimaruya M, Okuto K 1994, Elasto-plastic bending deformation of welded honeycomb sandwich panel, *J Japan Soc Mech Engrs* 1994 **60**(572), 1011–1016.
[3] Crupi V, Epasto G, Guglielmino E 2012, Collapse modes in aluminum honeycomb sandwich panels under bending and impact loading, *Int. J Imp. Eng.* **43**, 6-15.
[4] Paik J K, Thayamballi A K, Gyu Sung Kim G S 1999, The strength characteristics of aluminium honeycomb sandwich panels, *Thin-Walled Structures* **35**, 205–231.
[5] Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure, ASTM International, Designation: C393/C393M.
[6] Standard Test Method for Mode I Interlaminar Fracture Toughness of Unidirectional Fiber-Reinforced Polymer Matrix Composites, Designation: D 5528 – 01 (Reapproved 2007).
[7] S.Rajkumar S 2021, Strength and stiffness characteristics of A3003 aluminum honeycomb core sandwich panels, *Mater Today: Proceeds* **37**, 1140–1145.