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THE BEHAVIOUR OF SQUARE SANDWICH PANEL PART I: UNDER STATIC LOADING

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Abstract. This series of papers on behaviour of square sandwich panel consists of two parts. In part I, the performance and behaviour of the square sandwich panel under static loading was first examined. The sandwich panel was centrally loaded by using hemispherical and flat indenters on their respective support units. The panel materials used specifically for this project are mild steel skin and PVC foam namely R55 and polyurethane (PU) foam cores. The aim of this study is to obtain experimental evidence of the failure modes of square sandwich panels under concentrated load at the centre of panels, simply supported at the four edge corners for the square panel. After static tests, the whole curves for each panel were determined. The relation between the observed damage development, the property of degradation during the static test of the panels was investigated. In part II, the dynamic tests will be conducted in order to determine the performance, behaviour, effect of foam's type and the correlation between input energy from static and dynamic tests.

Keywords: Square sandwich panel, PU foam, PVC foam (R55), failure modes

Abstrak. Kajian mengenai panel apit segi empat terdiri daripada dua bahagian. Dalam bahagian pertama, prestasi dan kelakuan panel apit segi empat yang dikenakan beban statik dikaji. Panel apit ini sokong oleh unit sokongan dan dikenakan bebanan dibahagian tengahnya dengan menggunakan penakuk separa bulat dan penakuk rata. Panel apit spesifik yang digunakan untuk projek ini ialah kepingan keluli lembut, foam PVC yang dinamakan R55 dan teras daripada busa poli uretana (PU). Tujuan kajian ini adalah untuk mendapatkan bukti secara eksperimen tentang corak serta jenis kegagalan panel apit segi empat yang dikenakan beban tumpu di tengah-tengahnya dan disokong pada setiap bucunya. Selepas ujian statik dilakukan, lengkungan bagi setiap panel ditentukan. Hubungan antara pertumbuhan kerosakan dan kelakuan kerosakan semasa ujian statik ke atas panel dikaji. Dalam bahagian kedua, ujian dinamik dijalankan untuk menentukan prestasi, kelakuan, dan kesan bagi jenis busa serta hubungan antara tenaga masukan daripada ujian statik dan dinamik.

Kata kunci: Panel apit segi empat, foam PU, foam PVC (R55), mod kegagalan

1.0 INTRODUCTION

A sandwich panel can be characterized as a composite that constitutes of two faces separated by and linked to a core that is less stiff and less dense. The faces and the core are usually connected by adhesive that provides structural continuity across the

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depth panel. The important role of the faces of a sandwich panel is to bear tensile, compressive, flexural and shear stress resultants that act parallel to the plane of the panel. Faces may also act to distribute localized loads and reactions to the softer and weaker core. The core of a sandwich panel separates the faces and holds them in steady position. It gives the shear load path between the faces and together with skin, it carries loads or reaction that are applied normal to the plane of the panel. An ample range of skin and core materials are available in large number of combinations. It can be a beam, a panel or any other special shape. The skin can be of metal, wood, plastic, FRP composites or any other structural material. Likewise, cores may be made of honeycomb, corrugated or foamed cellular materials. Considerably good structural integrity with less weight. It has been very useful in offshore panel structure and in aircraft industry where minimizing weight is important.

The development of study on sandwich plates was initiated by the study of monolithic plates. The collapse loads of rigid-plastic plates are determined by limit analysis. The early works on the general theory of limit analysis were developed by Onat *et al*. [1] as a major component of the theoretical approach of perfectly plastic solid in many fields. Later, comprehensive study on the relationship of load and displacement of plates, namely square and circular, with different boundary condition were given in few references [2-4]. The perfect-plastic theory derives its simplicity from two assumptions; that the material is perfectly plastic i.e. no strain hardening and that there is no significant changes in geometry which would affect the equilibrium equation of structure. According to this theory, the plastic collapse of structure takes place at constant load i.e. no deformation takes place until a 'limit' is reached which followed by continuous deformation. In general, it requires a plastic deformation mechanism to be formed. When the limit is reached, bending deformation is concentrated at yield hinges. The deformation of the structure becomes possible only when yield hinges have developed several times to transform the structure into mechanism.

When the ratio of plate thickness to plate radius is relatively small, in order for the plastic deformation to continue, once initiated, presumably some increase in applied load would be required. These effects are due to membrane action. At the initial stages of deformation of the plates, bending action always predominates over membrane action. Consequently, near to collapse or deformation, the associated stretching at the middle cannot take place due to the absent of deformation.

The main purpose of this analysis is finding the flow limit under given types of loading. The load intensity at the flow limit is called the load carrying capacity of structure. The load carrying capacity of perfectly plastic circular plates has been discussed by Hopkins and Prager [5]. In these analysis, a limiting condition for the strength of the material has to be assumed in order to obtain a collapse load; the most commonly criteria used are Tresca and Von Mises. The application of these criteria to yielding of plates is discussed by Hopkins [6]. The problems of plate with simply supported or built in at edge and subjected to simple symmetric loading are discussed by Hopkins and Prager [5] using the Tresca yield condition.

Calladine [7] proposed a new promising approach to simplify the analysis of large deflection of plates in plastic range. The idea is basically to trace approximately the deflection history of a plate by means of succession of upper bound calculation, made by considering the structure to be three-dimensional body of perfectly plastic material. His theoretical approach has been particularly chosen for the present study as the theoretical approach for comparison of the experimental works.

In square sandwich panels study, the theory of elastic bending and buckling that takes transverse shear effect in the core into account appears to have been developed by several authors [8]. They published a series of reports on the elastic bending and buckling of isotropic sandwich panels. Allen [9] presented a comprehensive discussion on the general sandwich construction. He also discussed sandwich panels subjected to uniformly distributed load over the whole area of the top skin. The analysis of simply supported sandwich panel with centrally point loading is deduced from above as a local distributed over a circle (indenter size) at the centre of the top skin.

The literature about wrinkling problem is less than that bending problem. Gough, Elam and De Bruyne [10] were the first to analyze the problem in the strut stability which is applicable to anti-symmetrical wrinkling of sandwich struts. Hoff and Mautner [11] made the same kind of analysis for symmetrical wrinkling of sandwich struts. The effect of initial irregularities on wrinkling behaviour of the faces in relation to the tensile strength of adhesive was first discussed by Wan [12].

Type of failure modes of sandwich panels were discussed by Ashby and Gibson [13]. To remain mathematical simplicity, they focus the study on sandwich beams. Swanson and Kim [14], Mines and Alias [15], Traintafillou and Gibson [16] and a few other authors as well as Allen [9] conducted works on failures of sandwich beams.

Sandwich beams subjected to bending can fail in several ways. The tension and compression faces may fail uniaxially, by either yielding or fracturing, and the compression face may buckle locally, by either wrinkling or dimpling. Wrinkling involves local buckling of the face into the core, causing compression of the core. The core also can fail. The most common mode of core failure is shear [17-19]. Other possible modes are tensile or compressive yield and if the core made a brittle material, tensile fracture. Finally, the bond between the face and the core can fail; since resin adhesives are usually brittle, debonding is by brittle fracture [20].

In several of the failure modes described above, the load at which failure occurs depends on several factors that may contribute to the specific type of failure modes. These factors are: face thickness, core material, core thickness, size of indenter, shape of indenter, type of loading, type of support etc. The aim of this study is to obtain experimental evidence of the failure modes of square sandwich panels under concentrated load at the center of panels, simply supported at the four edge corners for the square panel (Figure 1).

Several researchers have studied a variety of failure modes of sandwich beams, but very few has published works on sandwich panels. As for sandwich beams; bending,

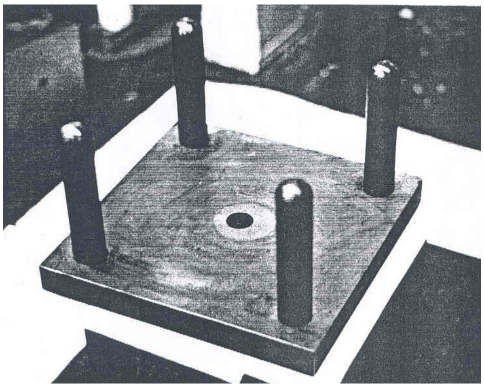

Figure 1 Support jig for square panels

core shear, and face wrinkling was described by Allen [9], Ashby and Gibson [13], Sayight [21] and Platema [22]. The failure modes are discussed to great depth by Allen [9] and, Ashby and Gibson [13] in their books. Almost all the theoretical are found to be formulae in elastic regime and currently are focusing into plastic regime. Previous literatures will be reviewed and the theoretical basis chosen are presented. The technical properties of the materials used and the test under taken will be described. It also discuss the method used for manufacturing the sandwich panels and the experimental set up and the procedures under taken in static tests of the sandwich panels. The results of the static experimental tests will be discussed in respectively with emphasis on illustrating the failure modes of the square sandwich panels.

2.0 THEORETICAL APPROACH

Consider a circular plate perfectly plastic material, radius r and thickness h, simply supported at its edge and carrying a central load P. For simplicity, P is treated as a point load, but it must be borne in mind that this is an idealization of a load spread over a region, sufficiently large for failure not to occur locally.

Limit analysis theory indicates a conical mode of plastic collapse, so consider a mode of deformation of the plate in which a typical radial cross-section rotates as a rigid body an instantaneous centre I as shown in Figure 2. The plate is shown to be supported on rollers, so that as the deflection develops the edge of the plates is able to move horizontally. In the deflected position, for small plastics deflection there will be a thin horizontal element disc of the plate at point I, at some height Z, which is not strained in bending. In order not to violate the geometrical restraint at the support, the pivot point must lie on a vertical line through the support point.

If the cross-section rotates rigidly through an incremental angle (or at an angular velocity α) as shown, rotation of elements in the horizontal plane through I shows them not to be extending or contracting but a point such as F which moves downwards and also radially outwards a distance $y\alpha$, where y is the distance of F below the plane

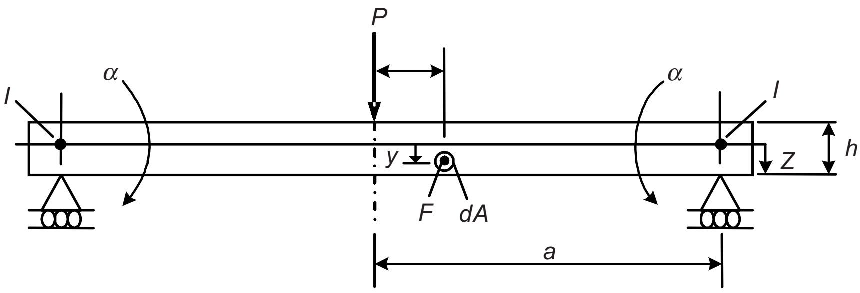

Figure 2 Symbol of upper-bound calculation in Calladine's theory

defined by I, indicated in Figure 2. If y is positive, the element will be subjected to compressive hoop yield stress σ_o and if it is negative to tensile hoop stress. The hoop of material corresponding to F, therefore, undergoes a circumferential strain increment,

$$\varepsilon_\theta = \left[y \frac{\alpha}{x} \right] \tag{1}$$

where x is the perpendicular distance from the axis of the plate. If dA is a small cross-sectional area associated with point F, the volume of the corresponding hoop is $dV = 2\pi \times dA$, so the plastic work dissipated in the elementary hoop is given by,

$$\sigma_o e_\theta dV = 2\pi\sigma_o y\alpha dA \tag{2}$$

where σ_o is the yield stress of the material in tension or compression. Integrating over the radial cross-section and equating to the work done by the load P in its corresponding descent,

$$PR\alpha = 2\pi\sigma_o\alpha \int |y| dA \tag{3}$$

In the integration, area is regarded as essentially positive, and the modulus sign is introduced because the work done in either tensile or compressive plastic deformation is positive.

Equation (3) gives the lowest upper bound when the value of the integral is least. It is easy to show that the value of the integral is least. It is easy to show that the condition for this (in general, for arbitrary areas) in the simply supported edge, is that the line I divides the radial cross section into two equal areas. In other words, by considering the stress distribution on a diametral plane, see Figure 3, it is evident that for equilibrium the compressive force above I must equal the trapezoidal areas. In the present example therefore the optimum position for I is at the centre surface of plate, this gives:

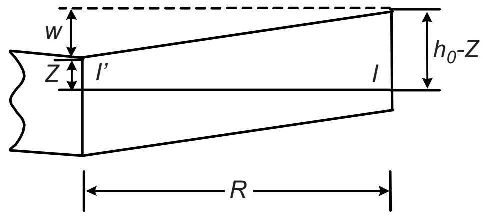

Figure 3 Diametral plane

$$\int_A |y| \, dA = R\frac{h_o^2}{2} \tag{4}$$

so Equation (3) gives:

$$P = \pi\sigma_o \frac{h_o^2}{2} \tag{5}$$

This is precisely the result given by the limit analysis theory, viz. $P = 2\pi M_o$ where M_o is the full plastic bending moment per unit length and h is the thickness of the beam.

$$M_o = \sigma_o \frac{h_o^2}{4} \tag{6}$$

Calculation of the minimum upper bound is in principle no more difficult when the plate has deformed into a shallow cone. When the centre of the plate has descended a distance $d < h$, the area diagram is shown in Figure 4(a). Performing the integration $\int |y| dA$ by taking first moment of rectangular and triangle areas about the current axis I-I', and summing, we find that for $d/h < 1.0$,

$$P = P_o\left[1 + \frac{1}{3}\left(\frac{d}{h}\right)^2\right] \tag{7}$$

For central deflection larger than the thickness of the plate the appropriate area diagram is shown in Figure 4(c); so for $d/h > 1.0$ it leads to the result:

$$P = P_o\left[\frac{d}{h} + \frac{1}{3}\left(\frac{d}{h}\right)\right] \tag{8}$$

In sandwich panel analysis, it is a matter to adapt the area method to deal with a sandwich of this sort. For a conical mode of deformation the appropriate diagram for $\delta < h/2$ and $\delta > h/2$ respectively, are shown in Figure 5.

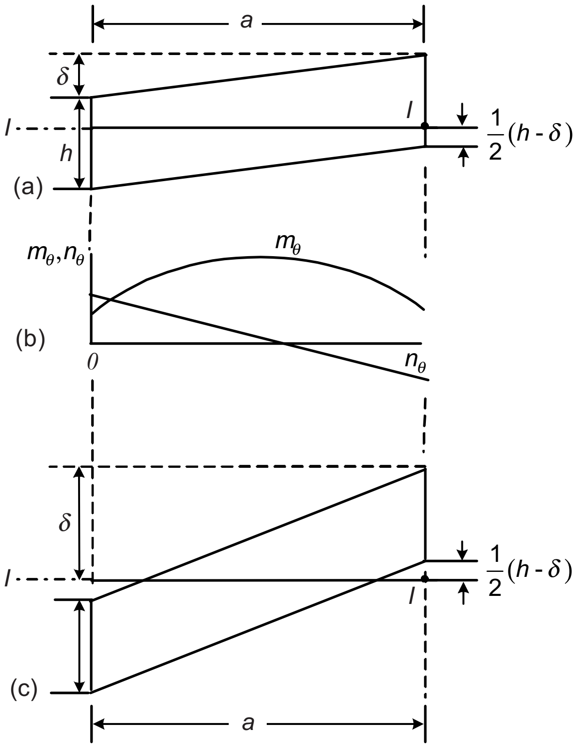

Figure 4 Area diagrams for supported circular plate ((a) and (c)); suggested circumferential bending and direct stress resultants (b)

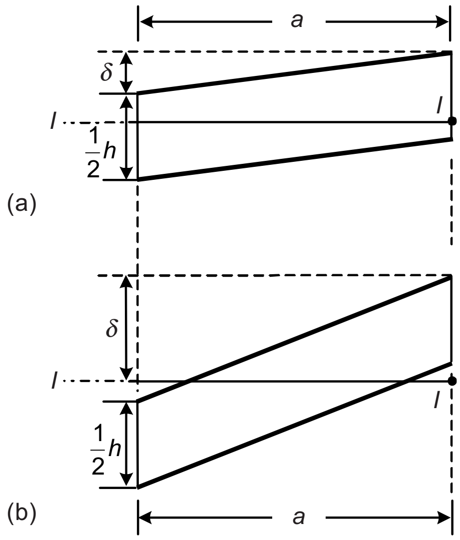

Figure 5 Area diagrams for simply supported circular sandwich plates. The relevant areas are shown as bold lines

The equal area rule still applies but does not determine uniquely the position of I for $s < h/2$, for which we find:

$$P = P_o\left[\frac{\delta}{h} + 1\frac{h}{4\delta}\right] \tag{9}$$

3.0 MATERIALS, PREPARATION OF SAMPLES, TEST EQUIPMENT AND PROCEDURES

3.1 Materials

Materials selection for the sandwich construction is constrained by the application requirement, availability and cost. In this project, steel skin and two different types of cellular foam cores one PU foam and one PVC foam are used. Polyester resin was selected as the adhesive between the skin and the core. The specifications of the materials used in sandwich panel are:

(a) Skin: Mild steel sheet metal of thickness 0.9 mm.
(b) Foams: (i) Cellular foam closed cell of rigid PVC foam sheet namely R55, sheet thickness of 25 mm and density of 61 kg/m^3.
 (ii) Polyurethane foam sheet namely PU foam, sheet thickness of 25 mm and density of 30 kg/m^3.
(c) Resin: Scott Bader, Crystic 491 PA (preaccelerated chemical resistant, isophthalic polyester resin).
(d) Hardener: Catalyst, methyl ethyl ketone 50% in phlegmatize (1% proportion).

The mechanical properties of the mild steel skin and the foams used for cores are presented in this section. Uniaxial tensile tests were performed to get the load deflection curve using the Instron testing machine model 4507. The tensile specimen dimensions were as specified to the British Standard (BS16). The results of the tensile tests are shown in Table 1:

Table 1 Results of Tensile Tests on Mild Steel Skin

Description	Yield Load (kN)	Max Load (kN)	Yield Stress (MPa)	Young Modulus (GPa)
Specimen 1	1.9	3.3	181.1	209.8
Specimen 2	1.8	3.2	172.2	203.0
Mean	1.9	3.3	176.7	206.4

A series of compressive tests were made on the R55 and PU foam cores according to standard ASTM D1621-00. The cores material was cut into cubes (25 mm × 25 mm × 25 mm) and compressive test were performed on them along *x*, *y*, *z* directions using the Instron testing machine model 4507. The density of each type of the core material was obtained by measuring the mass of each specimen using an electronic balance and measuring the volume of each specimen according to standard ASTM D1622-98. The results are displayed in Table 2:

Table 2 Mechanical Properties of Foam Cores

Core Material	Density (kg/m^3)	Direction	σ_c(MPa)	E_c(MPa)
		x	0.161	2.87
PU foam	29.09	y	0.153	2.53
		z	0.196	3.08
		x	0.784	30.80
R55	61.85	y	0.738	27.67
		z	0.803	32.53

σ_c: compressive yield stress; E_c: compressive Youngs' modulus

3.2 Tests Samples

The manufacturing procedure consisted of making the skin first. The mild steel sheet was measured and cut square panels (300 mm × 300 mm) by a press. Then the mild steel sheet was machined to the correct size using a lathe. One face of the square steel plate was then roughened manually using rough sandpaper and 'sandstone'. The rough surface is required to give adequate bonding between the resin/core and the steel skin. The R55 and PU core sheets (25 mm thickness) were measured and cut into the require size (square 300 mm × 300 mm) using a band saw. The adhesive was prepared by mixing and stirring the hardener with the polyester resin at 1% composition i.e. 1 ml catalyst to 100 ml resin. Both faces of the cores were being coated evenly with the resin using a brush and allowed partially cured for 5 minutes. During that time, the roughened surface of the steel plates was also coated with the resin. The respective surfaces of the cores and the skin were then stuck together to each other. Careful attention was given to align the skins and the core to prevent skins and the core of the sandwich panel slipping on each other. Finally the complete sandwich panel was held between two clamping plates, with a special kind of plastic sheets were placed in between two clamping plates to prevent them from sticking to each other trough resin extruded from the bonding faces before a sufficient number of weights were put on top of the structure. The weights were to provide enough pressure for foam to stick on the skin properly as well as to extrude the air bubbles and excess resin between the skin and the foam core. The weights should be moderate to avoid the deformation of foam core. A weights of approximately 5 kg was used for panels with 25 mm thick PU foam.

3.3 Static Test

Static tests were carried out first to determine the energy required to produce certain failure modes. The central loading of the square panels using hemispherical and flat indenters was carried out at a crosshead speed of 2 mm/sec on their respective support units. The equipments that were required to do the best were a computer controlled Instron testing machine model 4500, LVDT (displacement transducer) and *X*-*Y* plotter. The parameters measured in this test were the load applied (kN), top and bottom skin displacement (mm). Basically, the sandwich specimen was placed on top the support jig and the indenter would give the required force, which was supplied by the Instron machine, to the centre of the top skin of the specimen. Forcing the indenter, which was originally placed just on the top skin which was selected as the zero-basis of displacement, to go down at the certain rate (2 mm/min) would cause the centre part of the sandwich specimen to deflect downwards too. A very careful visual observation on the types of failure modes occurred during the test was made. At the moment the project was done, the Instron machine can only captured two signal simultaneously namely top skin displacement (mm) and the force (kN) required. Thus, an LVDT had to be used to measured the third signal i.e. bottom skin displacement. This LVDT was connected to the *X*-*Y* plotter to get displacement profile on a graph paper. The signal captured by the Instron testing machine i.e. indenter/top skin displacement, the force values and the signal captured by the LVDT on the graph paper were then being transferred to a computer package to get the results be summarized as in Figure 8 -11.

4.0 RESULTS OF STATIC TESTS

4.1 Experimental Results on The Skins

The static tests on single and double skins were performed on the square specimens. The results are presented in Figure 6.

In the square specimens, the main type of failure mode for plate finally folded into a 'V' canal shape (Figure 7).

4.2 Experimental Results on Sandwich Panels

In this project, four quasi-static tests on sandwich panels were performed. Two were using PU foam core and the other two were using R55 core. Then, one of the specimens that were using PU foam was loaded with flat indenter and the other one with hemispherical indenter and so thus the R55 specimen. All of the tests were carried out

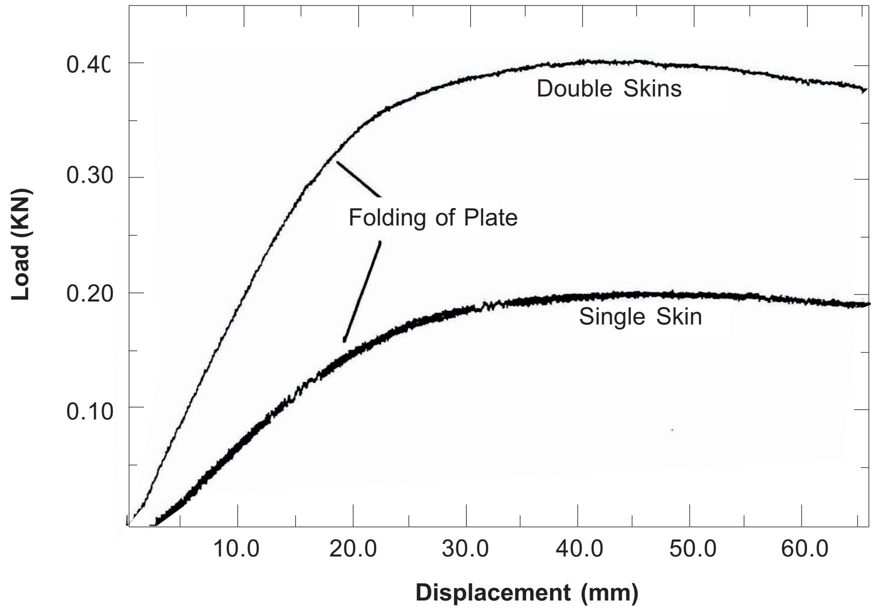

Figure 6 Results of static tests on square single and double skins under hemispherical indenter

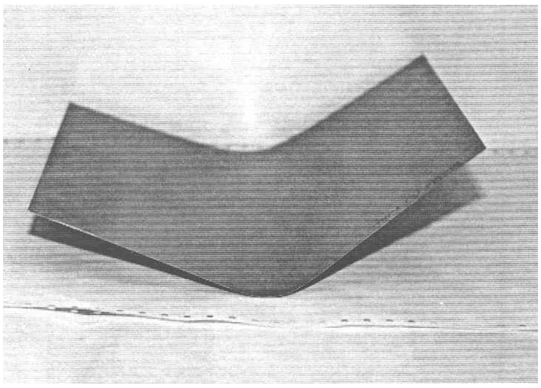

Figure 7 Folding of square skin

under cross head speed of 2 mm/min. The diameters of the flat and the hemispherical indenter were 25 mm.

The results on square panels are presented in Figures 8 -11. The respective load-deflection curves are shown with emphasis on illustrating the observed failure modes.

Table 3 shows the data of maximum load, energy to maximum load and energy to top skin displacement of 40 mm for various samples. The energy data were found by calculating the area under the load versus displacement curves up to the specified point.

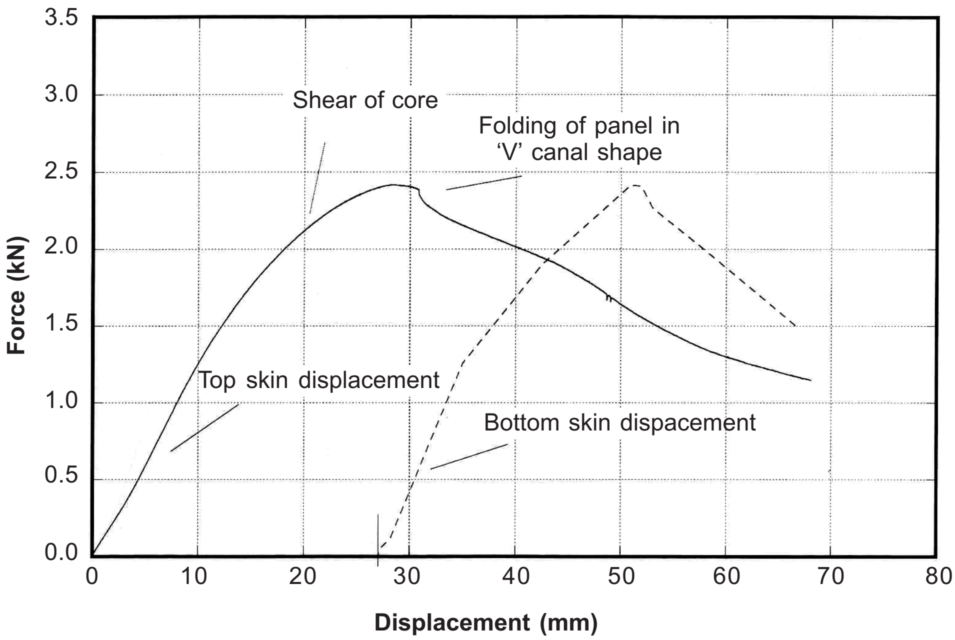

Figure 8 Result of static test on square PU panel under hemispherical indenter

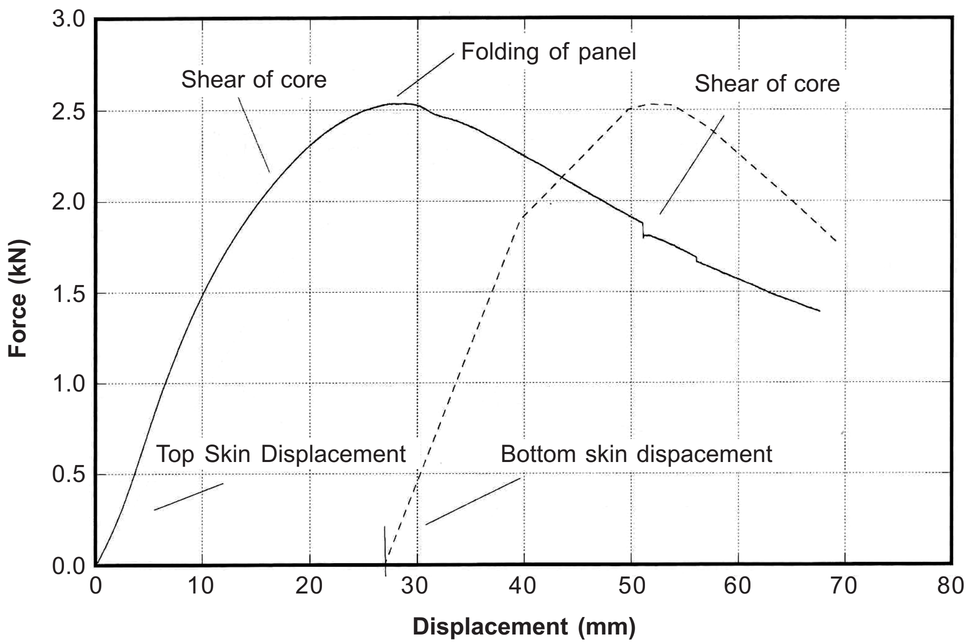

Figure 9 Result of static test on square PU panel under flat indenter

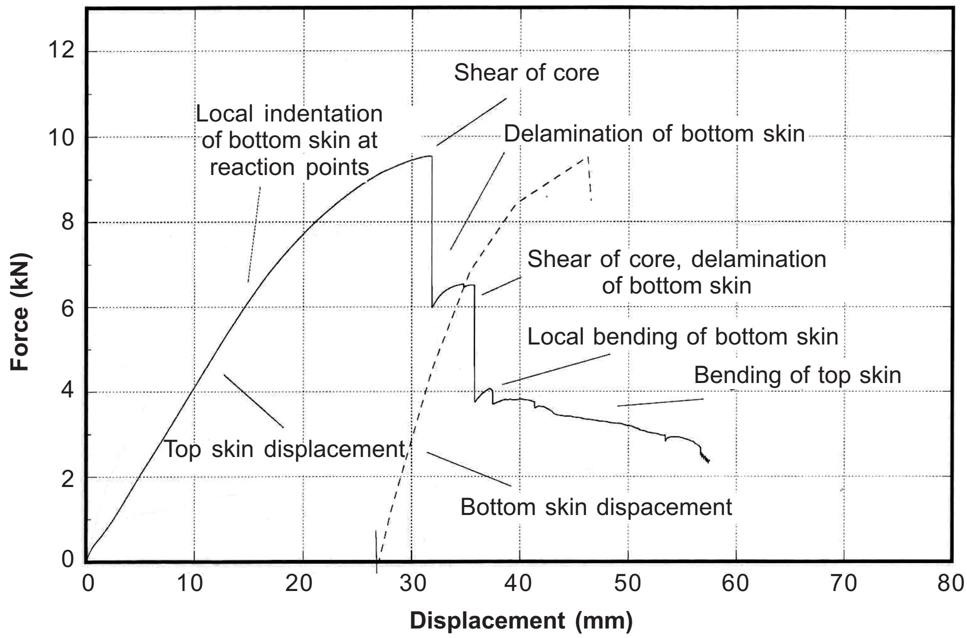

Figure 10 Result of static test on square R55 panel under hemispherical indenter

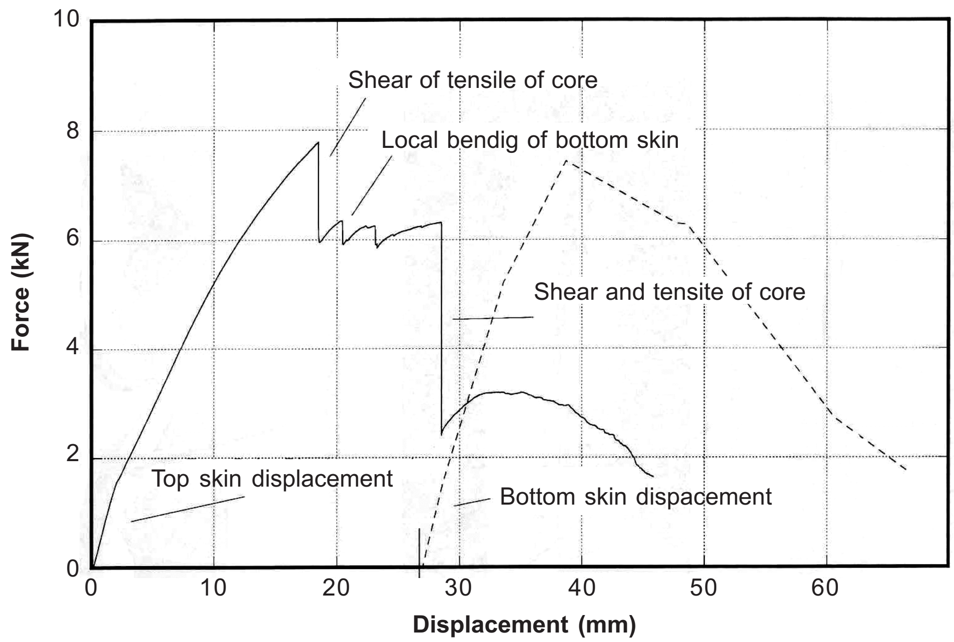

Figure 11 Result of static test on square R55 panel under flat indenter

Table 3 Data on Sandwich Panels Under Static Tests

Specimen	Core Material	Nose shape of indenter	Max load (kN)	Disp. at max load (mm)	Energy to max load (J)	Energy to top skin disp. of 40 mm (J)
S1-Sq	PU	Hemispherical	2.958	28.24	43.2	68.0
S2-Sq	PU	Flat	2.527	28.32	47.9	75.1
S3-Sq	R55	Hemispherical	10.046	31.76	184.8	226.1
S4-Sq	R55	Flat	7.749	18.51	84.4	180.8

Sq: Square

4.3 Failure Modes on Square Panels in Static Tests

The common failure modes observed during the static tests on square panels are:

(i) Shear of core
Usually this type of failure was associated with other types of failure modes such as tensile of core and delamination. This failure mode is shown in Figure 12.

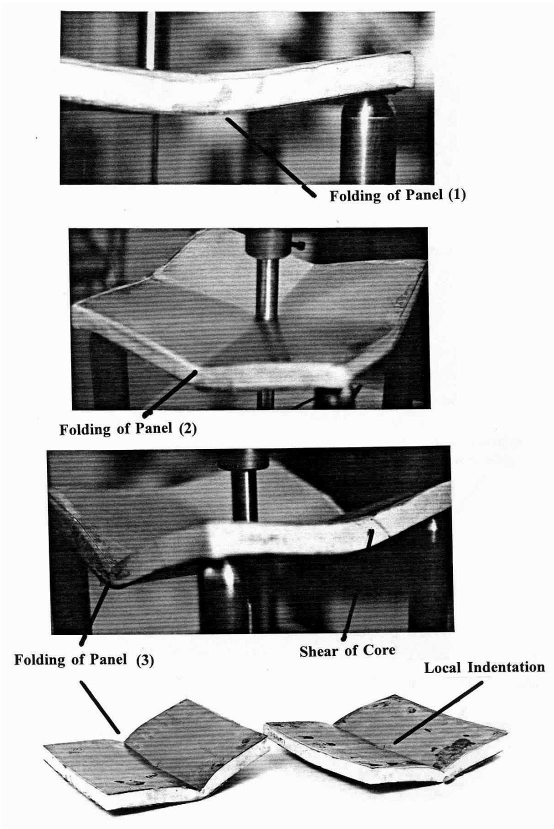

Figure 12 Failure modes on square PU panels under static tests

(ii) Tensile of core
Tensile of core was a failure on the core. The failure mode is shown in Figure 13. It looks very similar to delamination type of failure, but in actual it is not. Tensile failure happened on the core, while delamination happened between adhesive and skin. The line of failure was parallel to the face's plane of the panel.

(iii) Delamination
This type of failure was associated with the bonding failure between the skin and the adhesive. It usually happened at the top skin. The failure mode is shown in Figure 13.

(iv) Local indentation
This type of failure mode occurred at the point of loading at the top skin and the reactions from the support points at the bottom skin. This type of failure was accompanied by little crushing of core at that point. The failure mode is displayed in Figures 12-13.

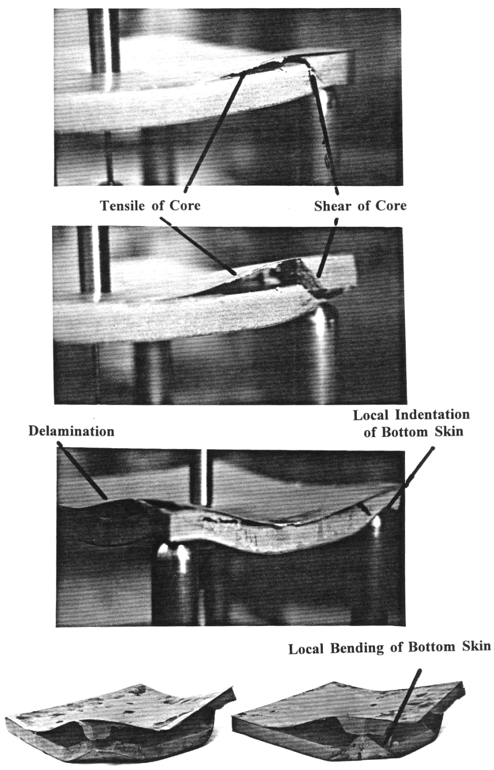

Figure 13 Failure modes on square R55 panels under static tests

(v) Local bending of bottom skin
This type of failure occurred around the reaction points at the bottom skin. The bending line usually was associated with the line of shear of core. The failure mode is shown in Figure 13.

(vi) Folding of panel
This type of failure was the last type of failure in square specimen. The panel started to fold and finally tended to form a 'V' shape canal. The failure mode is displayed in Figure 12.

5.0 DISCUSSION

5.1 Static Tests on Square Specimens

(i) Behaviour of single and double skins plates
The behaviours of single and double skins were quite similar to each other. As the indenter moved downward, the applied loads increased almost linearly and then started to stay at almost constant values until the end of the tests (see Figure 6). The maximum loads for the single and double skins were about 0.2 and 0.4 kN, respectively. One obvious failure mode that happened to the skin panels was the folding of the panels to form a 'V' canal shape (see Figure 7).

(ii) Behaviour of sandwich panels with PU foam under hemispherical and flat indenters
The load-displacement profiles of these panels were quite similar to that of monolithic plate. The applied load increased as the indenter moved downward. Shear of core occurred at some point before the maximum load values were reached (see Figures 8 and 9). It occurred at load of 2.2 kN for both panels under hemispherical and flat indenters, while the respective top skin displacements were 21 and 17 mm. After the shear of core failure occurred, the applied load increased until a maximum value was reached. That was the point where the 'folding' of the panels started. The folding process continued until the tests were stop with a decrease in skin's rolling direction, which resulted in a slightly different strength value. The load at the starting of the folding process was about 2.5 kN under hemispherical indenter and at about 2.4 kN under flat indenter. The displacement of the top skin under both indenter was quite the same at 30 mm.

(iii) Behaviour of sandwich panels with R55 core under hemispherical and flat indenters
The failure mode of R55 panel under hemispherical indenter started with local indentation at the reaction point at the bottom skin. This type of failure was

accompanied with the crushing of the core around the local indentation points. This failure was observed before the maximum point was reached (see Figure 10). Later, shear of core failure occurred at the maximum load with a sudden decrease in the load. This shear of core failure was always be succeeded by the tensile of core failure of delamination of skins and local bending of the bottom skin. Shear of core occurred at load of 9.5 kN and top skin displacement of 19 mm under flat indenter. The position of the local bending of the bottom skin was always associated with the shear of core's line. That happened because as shear occurred, there was less resistance to further deformation at that line.

5.2 Effect of Foam's Type on Sandwich Panels Performance

The higher density foam (R55) had a higher maximum load than that of the lower density foam (PU). The failure loads were also higher in R55 panels in all types of the common failure between the two foams panels. These behaviours were shown in both the circular and square panels under both hemispherical and flat indenters. The explanation was that, R55 panels had a higher modulus of rigidity (EI). The experimental value of compressive Youngs' modulus, E_c for R55 was 32.5 MPa while for PU, E_c = 3.08 MPa.

5.3 Effect of Type of Indenter

Tests under flat indenters had less value of maximum load than that of hemispherical indenters. The displacement at the respective maximum load was also less with the flat indenter. This was shown in all of the cases. This might be due to the effective area of contact during the tests. Flat indenter had a higher effective area of contact than that area and gave a lower effective load to get the same failure modes.

6.0 CONCLUSION

The behaviour of the sandwich panels under static loadings depends on the property of the core materials. The R55 permits more localized failure with higher energy while the failures on PU are spread out with less energy required. The common failure modes on square panels sandwich panel are local indentation, shear and tensile of cores, delamination of top or bottom skins, local bending of bottom skin and folding of panels. In the static test, panels with R55 core showed a better performance compared with panels with PU core. The use of polyester resin for bonding of the core and the skins was quite satisfactory. The test results can be used to determine behaviours in material models especially through using FEA packages.

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