EFFECT OF CORE CRUSH ON HONEYCOMB SANDWICH PANELS

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Abstract. *Nomex honeycomb is used as the predominate core material in aerospace standard sandwich structure. To provide aerospace standard composite face sheets it is necessary to cure the sandwich structure in an autoclave at elevated pressure. The honeycomb material is capable of withstanding the forces experienced through its thickness, but the lateral forces applied by the elevated pressure cause a crushing effect on the cells of the material. To prevent this crushing a 'core stabilisation' technique is applied to the core, prior to the lay-up of the sandwich panel, which increases the rigidity of the material and protects the cells. The core stabilisation process is time consuming and therefore costly. The current work investigates the effect of core crush on the mechanical properties of sandwich beams, along with the success of eight core treatments to reduce core crush. Without stabilisation, the core crushed by almost 12%, and had a large detrimental effect on the mechanical properties of the beam. However, by curing in a conventional oven at vacuum pressure crushing was prevented and similar mechanical properties to the fully stabilised core were achieved. Finally, the effect of core crush on actual sandwich components is investigated by loaded representative panels on a specialist rig capable of applying representative pressure loads and measuring the stress distribution using full-field thermoelastic stress analysis (TSA).*

1 INTRODUCTION

The use of honeycomb in aerospace sandwich structure remains a preferred option for many applications. Despite research into out-of-autoclave processing, e.g. [1], many of the composite sandwich components manufactured for aerospace applications require an autoclave cure at elevated pressure. One of the most common types of honeycomb core used in aerospace applications is Nomex honeycomb [2]. Nomex fibres are versatile, heat and flame resistant fibres that can be used to produce a wide variety of fabrics for high temperature and fire proof applications such as fire fighter bunker suits and flash hoods [2]. Its inherent flame resistance makes it an ideal candidate for the aerospace passenger transportation industry. The honeycomb is produced by using Nomex in a paper form, with adhesive applied so that the stack can be expanded to form hexagonal cells. Once expanded it is then dipped in a phenolic resin to form an open honeycomb structure, suitable for use as a core in the production of sandwich panels. Due to the relatively 'delicate' nature of the bare honeycomb core it is necessary to perform an extra processing step defined as 'core stabilisation' to avoid deformation of the core during autoclave cure, known as 'core crush'. During the autoclave cure the resin matrix becomes less viscous so that the resin can fully impregnate the face sheet fibre and attain the necessary material stiffness and strength. It is during this part of the process that the core crush occurs, the applied pressure from the autoclave and the loss of the tackiness of the resin allows slippage between the fibre layers [3]. Therefore, when a force is applied to the fibres, as a result of the autoclave pressure on the core, the fibres slip and the core is crushed. To avoid this, a core stabilisation process is used where a foaming adhesive is applied to fill the cells around the perimeter of the core, along with a film adhesive that encapsulates the entire core. The core stabilisation produces a more rigid structure without a significant increase in weight. However, it has been shown [1] that the requirement for the extra process of the core stabilisation increases the manufacture time significantly and therefore the cost of manufacture.

Previous work [3] has discussed avoiding core crush for honeycomb cores by altering the face sheet fibre tow shape so that the bundles of fibres would interlock and interfere with the sliding action associated with the crush. It was also suggested in [3] that ‘tie down plies in contact with the core’ could be used to hold the fibres straight, to prevent the sliding action and restraining the core to eliminate the crush. However, both these options require a large amount of extra investment in the design stage of the prepregs. An alternative is suggested in [4] where all the cells are filled with friable low density polyurethane or polyisocyanurate foam. The process has the added advantage of increasing the thermal insulation properties of the core but still requires an extra process in the manufacture procedure.

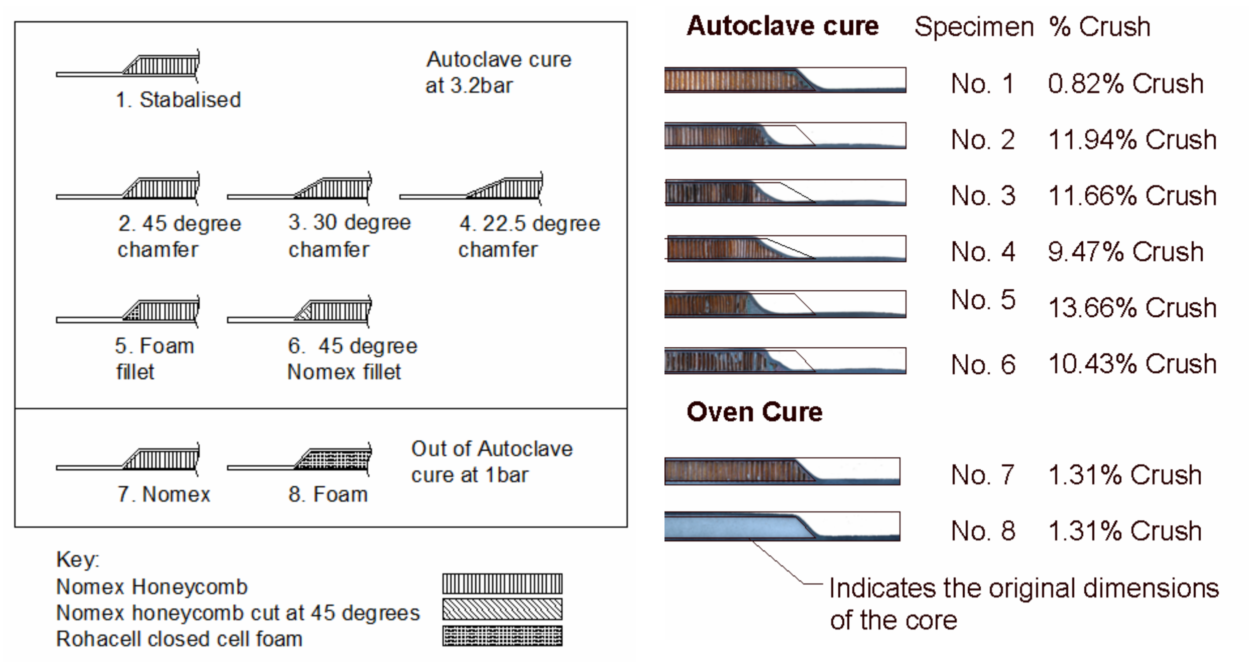
In this paper techniques for reducing core crush are investigated using simple inserts and materials that are readily available, where no additional processing steps are required. The paper also experimentally investigates the effect of core crush on the flexural properties of sandwich structure. Eight core treatments are described along with a brief discussion of their merits. The eight core treatments are used to produce sandwich beam specimens and the percentage of crush is established from measurements of each beam with each core treatment. The mechanical performance of each core treatment is assessed using four point bend tests. The effect of core crush in a realistic panel is also established by examining the effect of using unstabilsed core in and autoclave cure. Sandwich panels were produced using a generic design [1], which is representative of secondary wing structure and tested on a specialist rig capable of applying representative pressure loads [5]. This full-scale testing allows an investigation of the effect of core crush on the mechanical performance of actual components. Thermoelastic stress analysis (TSA) [6] is applied to provide full-field data that can be directly related to the stresses. Finally, the full-field data from TSA on the full-scale panels is compared to FE models of both the fully stabilised and unstabilised panel.

2 APPROACHES TO CORE TREATMENT

Sandwich panels were manufactured to be 600 mm long and 290 mm wide with an initial core length of 500 mm. The face sheets of the sandwich panels were produced from two types of carbon fibre epoxy prepreg. The autoclave cured panels used Hexcel’s 8552S/37%/AGP280C a five harness satin weave prepreg, whilst the out-of-autoclave cured panels used Hexcel’s DLS1726/40%/285T2/AS4C-6K a two by two twill woven side-preg. The face sheets were designed with a quasi-isotropic lay up, i.e. [0, 45, 0, 45, 0, 45, core, 45, 0, 45, 0, 45, 0], which is symmetric and balanced about the core. These two materials were selected to produce similar face sheets, although the fabrics have different weaves they have similar fibre weights. Tensile and flexural characterisation tests performed in [1] proved the two materials offered similar properties. Therefore the difference in face sheet material should not have an effect on the performance assessment. The core dimension was 500 x 290 mm and was chamfered on two opposite sides to represent the chamfer used in an actual panel (See Figure 1 (a)). Parallel with the chamfered edge of the core a stiffened flange is introduced by bringing together the two face sheets.

Eight different core treatments were selected in an attempt to reduce core crush without the need for the expensive stabilisation process. Two core materials were used: Hexcel's Nomex honeycomb HRH-10-1/8-3.0 and a high temperature, Polymethacryllmide-PMI, closed cell foam Rohacell 71IG. Figure 1 (a) summarises the eight core treatments. The first core treatment was the full stabilisation typically used for honeycomb sandwich panels [1] to be used as a control against which the other core treatments are compared. The stabilization process used Cytec's FM410-1CS foaming adhesive, in film form, to support the chamfered edges. Strips of uncured adhesive slightly wider than the chamfered region of the core were placed on to the honeycomb core. The entire core was also enveloped in a film adhesive, 3M AF163-2K 060, to provide some overall rigidity. The adhesives were cured in an oven at 107 °C for 90 minutes prior to the lay-up and cure of the sandwich panel. The following six treatments used unstabilised (bare) core. Treatments two to four were used to assess the affect of altering the chamfer angle. Three angles were selected 45°, 30° and 22.5° representing treatments two, three and four respectively. It was expected that the use of a shallower chamfer angle would reduce the severity of the core crush. Treatments five and six were designed to strengthen the chamfered region of the core, in a similar manner to the foaming adhesive applied in the full stabilisation. In treatment five a separate piece of PMI high temperature closed cell foam was used as the chamfered perimeter. Treatment six used a separate section of Nomex honeycomb core at 45° to the main section. The aim of treatment six was to ensure that the pressure of the autoclave cure was always applied in the most resistant direction of the honeycomb structure. Treatment six used a separate section of PMI foam core as the chamfered region. Finally, treatments seven and eight relied upon curing the sandwich panel out-of-autoclave consolidating only with the pressure of the vacuum applied in the vacuum bag. Treatment seven used an unstablised (bare) honeycomb core, whilst treatment eight utilized PMI high temperature closed cell foam as the core material.

After consolidation the severity of the core crush was established, this is summarised in Figure 1 (b). Figure 1 (b) shows the profile of a sandwich beam that is indicative of each of the eight core treatments both before and after cure. The length of the core after cure is estimated from these images and compared to the length before cure to provide the crush percentage. It should be noted that the cores do not crush in the same way for each type of panel and this is evident in the images. The panel with treatment one, crushed by only 0.82 %. However, the unstabilised core of treatment two crushed by almost 12 %, indicating current full stabilisation process is necessary to prevent such a large change in core shape during cure. Altering the chamfer angle of the core between 45° and 22.5°, treatments two to four, did provide a reduction in crush percentage, although only to just below 10 % at 9.47 %. This is obviously still a significant change in the shape of the core during cure and would not be acceptable for use practical applications. The chamfer strengthening methods, treatments five and six, do not provide any significant advantage over the unstabilised core, and the addition of a piece of foam as the chamfer increases the crush percentage to over 13 %. Finally, by replacing the autoclave cure with an oven vacuum only cure the crush is reduced to only 1.31 % for both the honeycomb and foam cores.



(a) (b)

Figure 1: (a) Summary of the eight core treatments (b) Relative crush for each treatment

3 SANDWICH BEAM TESTS

Sandwich beams of 50 mm width were cut from the larger panels constructed using each of the eight core treatments described above. These were tested using a four point bending rig to provide an initial assessment of the effect of core crush on the mechanical performance of the sandwich construction. The beam flexure tests followed ASTM C393-62 standard test method for flexural properties of flat sandwich constructions [7]. The experimental set-up used for the sandwich beam tests is illustrated in Figure 2. The beam tests were performed as a four point bend with the outer supports positioned 530 mm apart, outside of the core chamfer, such that the entire core stiffened region (including any core crush) is tested. In this way, the mechanical properties measured during the test provide an indication of the effect of any core crush. The full details of the bend test setup are presented in Figure 2. The beams were tested in a servo-hydraulic Instron 8032 test machine with a 100 kN load cell fitted and the data was recorded using ‘Dasylab’ software. The load was applied to each sample under displacement control at a rate of 1 mm/minute to a maximum actuator displacement of 1.75 mm. Two LVDT displacement transducers were used to record the deformation of the beams at points W_1 and W_3 in Figure 2. The recorded displacement and load data were used to calculate the flexural stiffness, shear stiffness, shear modulus and flexural strength of each of the beams using the following equations [3]:

$$\text{Flexural stiffness, } D = \frac{PL^3}{256(W_4 - W_2)} \quad (1)$$

where P is the load applied, L is the full span, W_4 is the full mid span deflection and W_2 is the crosshead deflection.

$$\text{Shear stiffness, } N = \frac{3PL}{8(11W_2 - 8W_4)} \quad (2)$$

Shear modulus, $$G_c = \frac{3PL}{8(t+t_c)B(11W_2 - 8W_4)} \quad (3)$$

where t is the sandwich thickness, t_c is the thickness of the core and B is the beam width.

Flexural strength, $$\tau_c = \frac{P}{(t+t_c)B} \quad (4)$$

Table 1 lists the average flexural stiffness, shear stiffness, shear modulus and flexural strength for the three beams with each of the eight core treatments alongside the standard deviation. For ease of comparison the average for each value is normalised against that for core treatment one and plotted on a bar chart in Figure 3. The mechanical properties of the beam with treatment two, using an unstabilised core (which crushed by almost 12 %), demonstrates that the core crush has had a profound effect. The flexural stiffness of beam two, a measure of the effectiveness of the entire sandwich construction, is 16 % lower than that for treatment one. The core dominated properties of shear stiffness and modulus are both reduced further by almost 50 %, which would cause a concern for the ability of the 'damaged' core to act in a satisfactory manner. Finally, the flexural strength of beam two is increased by 11 % over the stabilised treatment. Core treatments three and four, where the chamfer angle is changed, undergo a similar reduction in flexural stiffness and shear stiffness and modulus to that measured for treatment two. Despite the aforementioned improvement in core crush percentage by reducing the chamfer angle, no improvement in mechanical properties is evident. The attempt to increase the resilience of the chamfer section by using additional pieces of honeycomb or foam in treatments five and six has had a catastrophic effect on the mechanical properties of the sandwich beam. Whilst the flexural stiffness has only reduced by a similar amount to treatments two, three and four, the shear properties have shown significant further reduction. The addition of a separate section of core has a marked deleterious effect on the performance of sandwich beam. The removal of the autoclave cure for an oven vacuum only cure in treatment seven has produced sandwich beams with similar properties to the fully stabilised approach. This is an encouraging result for the use of out-of-autoclave cured sandwich panels without core stabilisation. Finally, by curing out-of-autoclave and replacing the core material for the PMI closed cell foam the mechanical properties of the sandwich beams have been noticeably improved. The flexural stiffness is increased by 18 %, the shear properties by over 50 % and the flexural strength by over 80 % over the baseline autoclave cured stabilised core beam. The sandwich beam tests have shown a reduction in flexural and shear properties when the core is not correctly stabilised and crush results.

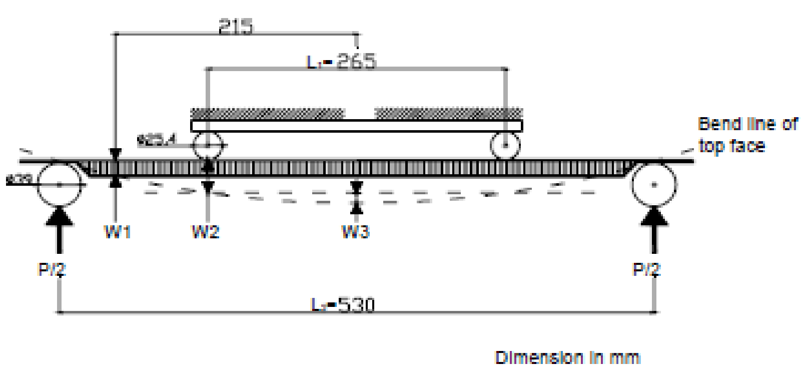


Figure 2: Experimental set-up for four point bend test on sandwich beam

Table 1: Mechanical properties of the sandwich beams

Treatment number	1	2	3	4	5	6	7	8
Flexural stiffness, D (Nm^2)	**411.5**	**347.7**	**322.5**	**337.1**	**363.6**	**348.9**	**399.2**	**485.1**
Standard dev	*61.6*	*23.9*	*7.5*	*18.3*	*48.0*	*12.8*	*18.3*	*7.2*
Shear stiffness, N (kN)	**22.73**	**12.81**	**11.95**	**14.18**	**9.07**	**15.25**	**24.84**	**36.39**
Standard dev	*5.82*	*0.60*	*0.31*	*1.39*	*1.53*	*2.31*	*2.31*	*1.21*
Shear modulus, G_c (MN/m^2)	**33.20**	**18.38**	**18.18**	**21.68**	**13.20**	**11.38**	**35.69**	**50.94**
Standard dev	*8.50*	*8.55*	*4.76*	*2.13*	*2.23*	*0.71*	*3.32*	*1.69*
Flexural strength, T_c (MN/m^2)	**0.79**	**0.88**	**0.90**	**0.92**	**0.93**	**0.86**	**0.86**	**1.44**
Standard dev (x 10^{-3})	*6.55*	*8.02*	*62.42*	*12.47*	*28.06*	*8.54*	*10.38*	*7.60*

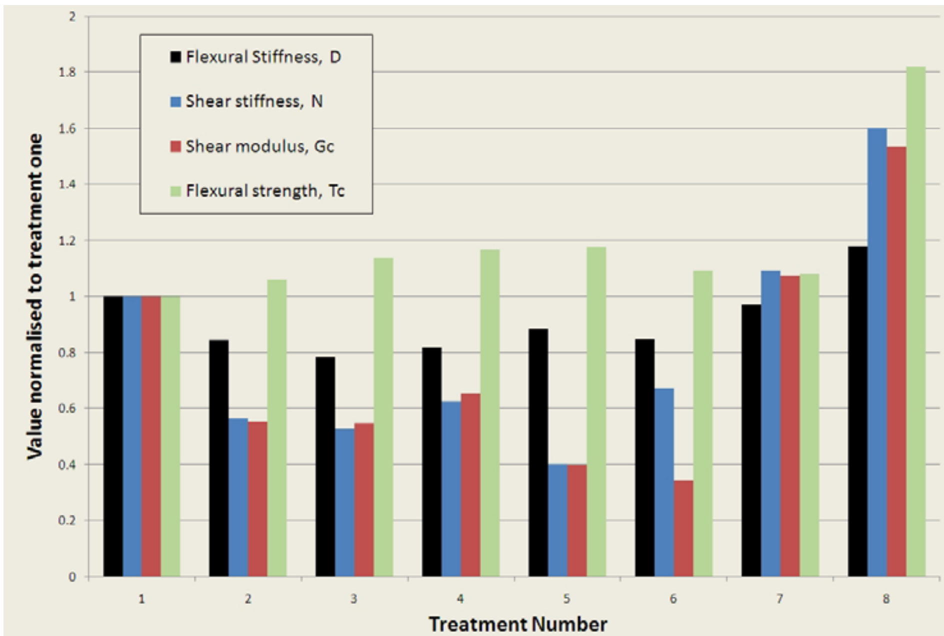


Figure 3: Normalised mechanical properties of the sandwich beams

4 FULL-SCALE TESTING

In previous work [5], generic sandwich panels were designed to capture some of the features representative of composite sandwich secondary wing structure (see Figure 4). A custom designed rig (see Figure 5) was used to apply a pressure load, representative of aerodynamic loading, to the sandwich panel. The rig uses the movement of an actuator in an Instron servo-hydraulic test machine to pull the sandwich panel over a water filled pressure cushion that is fully constrained by the rig and the panel. The rig has been designed to allow uninterrupted optical access to the top surface of the sandwich panel, thereby enabling the use of optical measurement techniques. It has been shown [5] that the stress distribution in the top face sheet of the sandwich panel can be obtained by using thermoelastic stress analysis (TSA). The panels are loaded cyclically at 1 Hz with a mean pressure of 10 kPa (1.5 psi) and an amplitude of 5 kPa (0.75 psi), thereby imparting a pressure range of 10 kPa (1.5 psi). It was vital to load the panels cyclically to allow the use of TSA. Two generic panels were manufactured using Hexcel's 914C-TS-5-34% prepreg tape as the face sheet material, producing quasi-isotropic sheets [0°, 45°, -45°, 90°, 0°, 45°, -45°, 90°, 0°, 45°, -45°, 90°]$_s$ about the core. The core material was the same Nomex honeycomb used for the sandwich beam specimens. One panel used the full core stabilisation process labelled treatment one (see section 2) and the other had a bare unstabilised core, i.e. treatment two. Both panels were cured in an autoclave and therefore the panel with core treatment two was expected to experience some core crush. The two generic panels were loaded using the pressure rig, and the temperature change on the surface measured (full-field) using TSA. The temperature change data was processed to provide a measure of the stress distribution using a calibration approach described in [5]. To obtain some deflection data a linear variable differential transformer (LVDT) displacement transducer was used to measure the out-of-plane movement of the panel at the point of maximum deflection.

An FE model of the generic panel was used, in addition to the experiments, to assess the effect of core crush on the mechanical performance of the sandwich structure. The model was constructed using Ansys 11.0. Briefly, the model treated the face sheets as homogenous blocks with experimentally measured material properties [1] meshed using element Shell181. Whilst, the honeycomb core was modelled using brick element Solid185. The pressure load was modelled by applying an individual force on the nodes on the bottom surface of the model. Full details of the construction of the model are provided in [5]. The generic panel with the core crush was modelled by reducing the core area by a similar amount to that on the actual unstabilised panel.

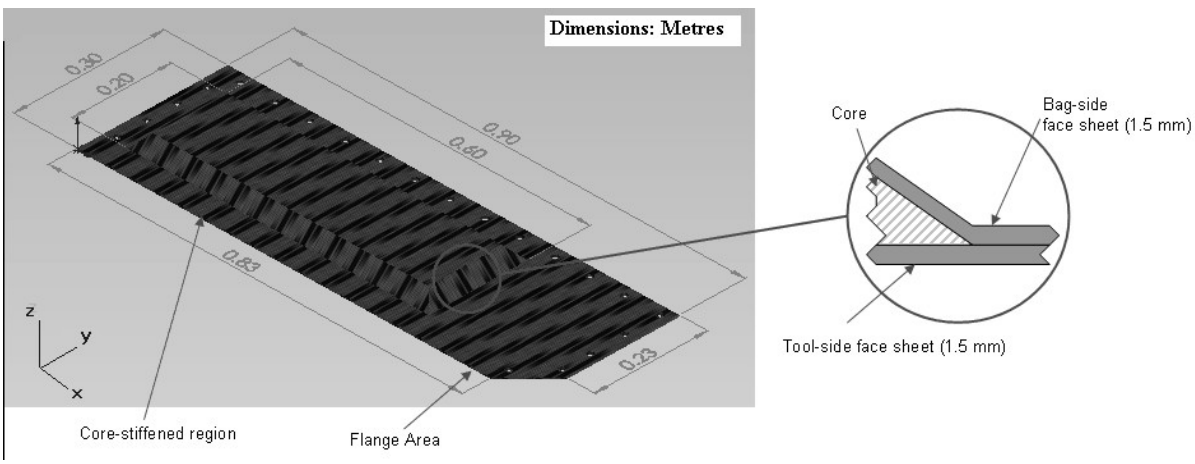


Figure 4: Design for generic sandwich panel [1]

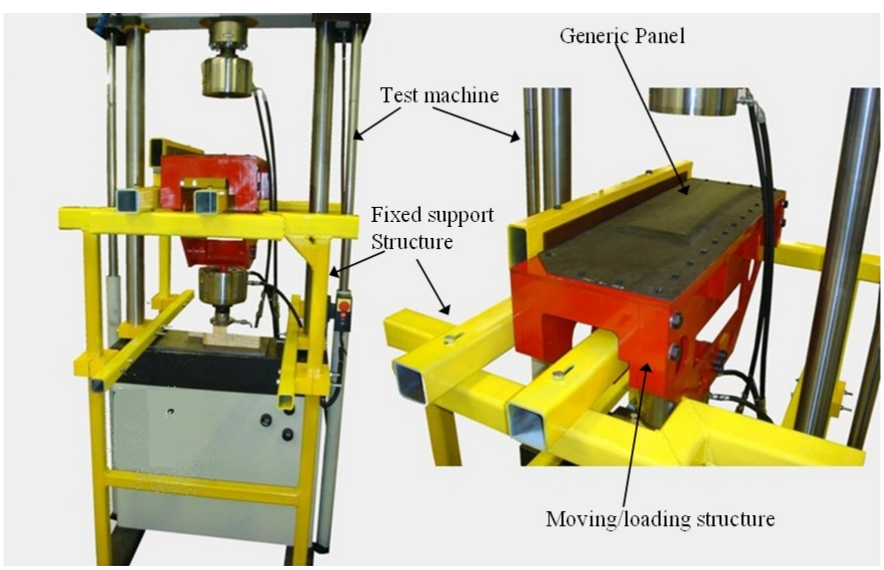
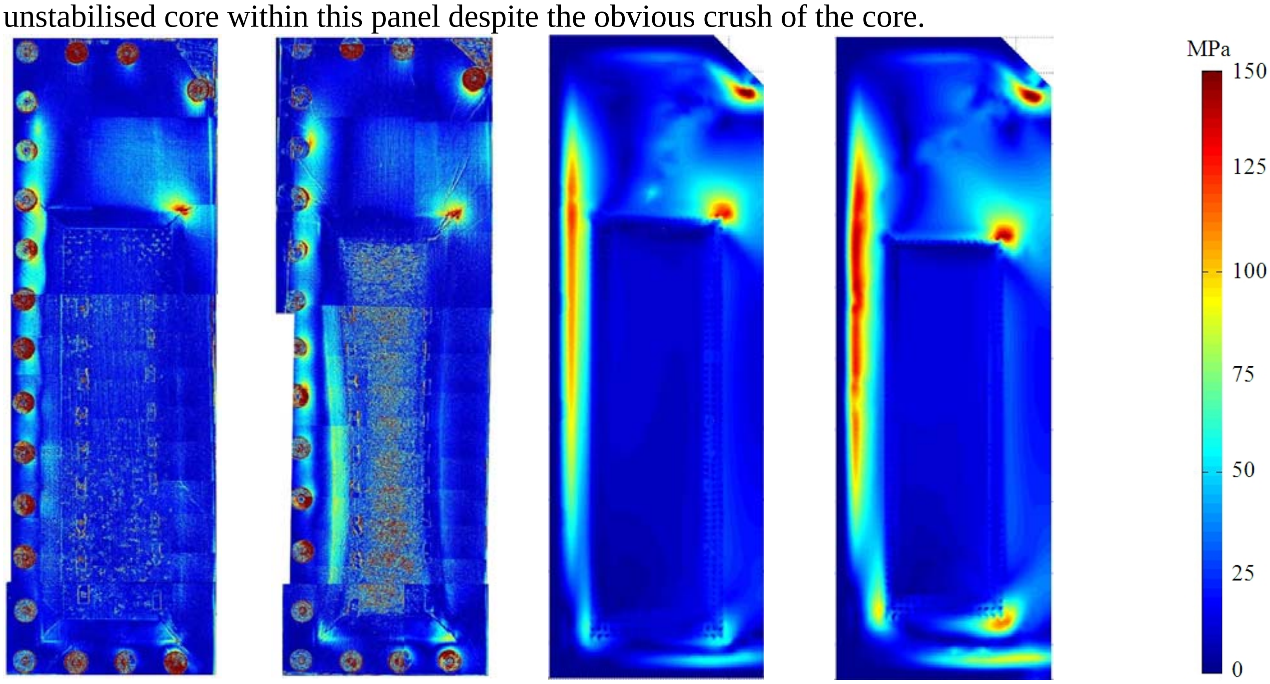


Figure 5: Pressure test rig mounted in an Instron test machine [5]

Figure 6 (a) and (b) show the full-field calibrated TSA data from the fully stabilised and unstabilised core panels respectively. In the images, the circles around the perimeter are the response from the washers used around the attachment bolts, whilst the numbered rectangles on the top of the core region were used during the experiments to assist with Joining an number of TSA images. In both figures the outline of the core is clear, the fully stabilised core in Figure 6 (a) has retained its rectangular shape and, as expected, there is no evidence of crush. The outline of the core in the unstabilised core panel, Figure 6 (b), demonstrates the extent of the core crush caused by the autoclave cure. Unlike the sandwich beams that crushed in a linear manner, with the entire ends of the core crushing inwards, the generic panel has crushed in a '2D' manner. The corners of the core appear to have remained in the correct position, therefore forming curved sides to the core as the crush is largest at the centre of each of the side of the core. Using image analysis of the core area, the crush can be measured as a reduction in area of approximately 20 % compared to the fully stabilised (non-crushed core). The fully stabilised panel deflected by 6.33 mm, whilst the unstabilised panel deflected by 6.72 mm a small increase in maximum deflection of only 6 %. Comparing the stress distribution plots for the two panels (see Figure 6 (a) and (b)), the apparent stress concentration formed by the top right corner of the core appears similar. Away from here there are some differences in the stress distribution between the panels, there is increased stress along the left and right sides of the cores and increased stress concentrations on the two bottom corners of the core. To analyse the magnitude of the stresses in more depth a vertical line of data was taken through the stress concentration at the top right corner of the core (see Figure 7 (a)). The line plots for the two panels are very similar, and the peak stresses are 168 MPa for the stabilised core panel and 165 MPa for the unstabilised core panel. It is evident from the TSA data and the maximum deflection data that although there is some re-distribution of the stress there is little difference between the mechanical performance of the stabilised and unstabilised core within this panel despite the obvious crush of the core.



(a) (b) (c) (d)

Figure 6: Full-field calibrated stress sum data from (a) TSA stabilised panel, (b) TSA unstabilised panel, (c) FE normal core, (d) FE reduced area core

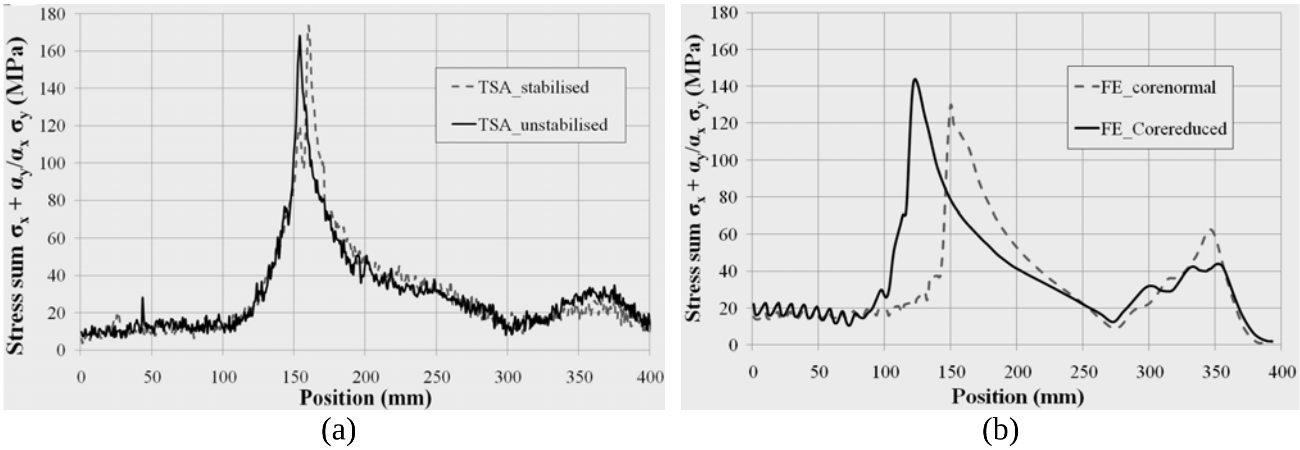


Figure 7: Line of calibrated stress sum data through top right corner of core for (a) the TSA data and (b) the FE data

Figure 6 (c) and (d) present the stress sum distribution for the FE model of the standard generic panel, and the panel with the reduced core respectively. The stress distribution for the standard model, Figure 6 (c), compares favourably with that seen in the measured image for the stabilised core panel, Figure 6 (a). Figure 6 (d) shows that by reducing the area of the core the stress distribution is altered in a similar way to that found from the experimental data in Figure 6 (b); there is increased stress on the left and right side of the core and stress concentrations at the two bottom corners of the core. The maximum deflection was predicted to be 7.7 mm for the standard generic panel, and 9.8 mm for the reduced core panel. This is a large decrease of overall stiffness in the panel of almost 30 % and indicates that modelling the core crush as a simple linear reduction of the core area does not adequately model the actual component. Further evidence of this is given by the vertical line of stress plotted in Figure 7 (b). The FE model predicts an increase of approximately 10 % in the peak calibrated stress sum at the core corner when the core is reduced in area by 20 %. This is not the case in the experimental data presented in Figure 7 (a).

The result of the full-scale sandwich panel tests demonstrates that the effect of core crush measured in the sandwich beam tests is not representative of that for actual components. The more complex '2D' crushing identified in the unstabilised core panel has a different effect on performance than the linear crushing observed in the sandwich beams. There is a proviso however, as the generic panel design has an unstiffened flange region, the stress distribution and maximum deflection are less a function of the rigidity of the core.

5 CONCLUSIONS

The paper has described the investigation of the effect of core crush on the mechanical performance of sandwich structure using Nomex honeycomb as the core material. Eight core treatments were used to produce sandwich beams that underwent four point bend tests to measure the flexural properties. The sandwich beam with a fully stabilised core (using a standard process in use in industry) performed as expected and had minimal core crush. The unstabilised core produced a sandwich beam that crushed by as much as 12%, and had significant reductions in flexural properties. The effect of a reduction of the angle of the core chamfer was investigated, and it was found that there was a small improvement, with a sandwich beam with a chamfer angle of 22.5° crushing by almost 10%. However, as with the first unstabilised core there was a large reduction in flexural properties over the fully stabilised core.

An attempt was made to strengthen the chamfered area of the core by attaching separate sections of other materials. These core treatments provided sandwich beams with the largest crush percentage and lowest flexural properties and should therefore be abandoned. Finally beams with honeycomb and foam cores, both cured out-of-autoclave, performed the best. The unstabilised honeycomb core cured out-of-autoclave matched the fully stabilised autoclave cured beam, whilst the foam core provided a beam with vastly improved flexural properties. However, honeycomb will remain the preferred material until issues associated with the detection of damage after impact of sandwich panels made using closed cell foam have been resolved.

To assess the effect of core crush on the mechanical performance of actual sandwich components, two full-scale panels produced to a generic design [1] were tested on a custom designed test rig [5] that allows pressure loading. By using TSA to provide full-field stress information it was possible to compare the stress distribution within these two panels. There was some redistribution of the stress field within the panel with core crush, but the peak stress remained largely unchanged. It was noticed that unlike the sandwich beams which were subjected to a linear crush, the core of the full-scale panel crushed in a much more complex and '2D' manner.

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