NEW FOUR-POINT BENDING BASED METHOD FOR IMPACT DAMAGE TOLERANCE ASSESSMENT OF SANDWICH PANELS

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ABSTRACT

When more and more load-bearing composite structures use sandwich construction, the need for a standardised test method to evaluate its compression-after-impact (CAI) strength becomes pressing. At present, there is no established standard CAI test method for sandwich panels. While a direct adaption of the end-loaded CAI method for monolithic laminates with up-scaled in-plane dimensions shows some promise, the sandwich material cost of such approach for generating CAI data could be prohibitive. This work intends to develop an alternative simple low-cost CAI test method via four-point bending (4PB) for as-received sandwich panels without the need for either panel ends machining or using a specific test jig.

An ultimate challenge of developing 4PB CAI test method is to find a balance between two contradictory requirements, namely, securing flexure failure in the compressive skin of sandwich panels and low overall cost. Such balance should encompass a wide range of combinations of intrinsic parameters for sandwich configurations. To this end, a total of 15 different sandwich configurations were constructed with two skin thicknesses, each in both cross ply and quasi-isotropic lay-ups, with three core densities, in both symmetrical and unsymmetrical constructions. In the majority of the configurations, skin laminates were made of carbon/epoxy but E-glass/epoxy was also used. A hole was drilled at the centre of selected specimens to simulate impact damage and a range of diameters was selected to offer a range of hole diameter-to-beam width ratios. These sandwich specimens were tested in 18 different set-ups. For the given support span-to-thickness ratios and loading arm, the combinations of core density and compressive skin thickness were found to be the most significant factor of influencing failure mechanisms. The 4PB CAI method worked well for beams with thin skin thickness and high-density core. It was found that having a weaker tensile skin in unsymmetrical beams proved to be better than a weaker compressive skin in failing the compressive skin due to their substantially reduced flexural rigidity and a lesser demand on the magnitude of the loading arms. On the contrary, beams with a core of 70 kg/m^3 density or less and 2 mm thick compressive skin were found to fail in the through-the-thickness shear, along with baseline beams.

1 INTRODUCTION

Advanced composite materials have been used extensively for load-bearing structural components in aircraft, helicopters, motor vehicles, ships and wind energy turbine blades. Many of these large structures are in sandwich construction. Regardless of structural form, they both are vulnerable to local impact damage. For monolithic laminates, the test methodologies for the evaluation of impact damage resistance and tolerance have already been established for some time [1-3] and the compression-after-impact (CAI) strengths of the impacted laminates are well known across the aerospace industry, as they dictate the design of the monolithic laminates. Specifically, the flat rectangular CAI panels with their ends being machined to parallel are end-loaded with the unloaded edges simply supported. For sandwich structures, however, the equivalent is not yet available. This is largely because the tolerance assessment of the impact damaged sandwich panels is much more complex and costly. Thus, at present there is no established industrial impact damage tolerance test methodology for sandwich construction. There is some indication [4] that this end-loaded CAI test method for monolithic laminates might be adapted for sandwich construction by up-scaling the dimensions of the rectangular sandwich test panels. Results of some experimental investigations using such approach are available in [5-8]. Nevertheless, such straightforward adaptation may be difficult to gain a wide industrial recognition, as the up-scaled sandwich panel dimensions in some cases [5-7] are so large, due to the inherent nature of the greater thickness of sandwich construction, that it could be economically unviable with potentially prohibitive costs involved, shall the CAI strength allowables of selected sandwich material systems have to be determined for structural design. This consideration provides a significant impetus to re-examine the test methodologies such as four-point bending (4PB) for the damage tolerance assessment of the impact damaged sandwich panels.

While the end-loaded CAI method for laminate panels is technically well established, it does have a few limitations, especially if adapted directly for sandwich panels. Firstly, it is extremely difficult to test baseline or control panels to establish valid reference values for in-plane compressive strengths when the panels are 4 mm in thickness or thicker [9]. The similar cases occurred in panels with low level of impact damage. With a typical thickness of over 10 mm for sandwich construction, it could be simply impossible for these sandwich panels with the up-scaled width-to-thickness and aspect ratios to fail around mid-section region. Secondly, for the similar reasoning to above, it could be very difficult to perform CAI tests for unsymmetrical sandwich panels, as demonstrated in [8]. Finally, the end-loaded CAI method could be very expensive in terms of amount of sandwich materials used in addition to end machining of each panel and requirement of specific test jig. A 4PB CAI method could overcome all the aforementioned limitations. In particular, it may offer a much better opportunity for an analytical model to be developed for predicting the CAI strengths of sandwich panels in future.

A viability of using the 4PB set-up to evaluate the damage tolerance of an impacted sandwich panel or wide beam depends on two critical but contradictory conditions. One is that the damaged sandwich beam must fail in flexure via the damaged compressive skin so that the obtained flexural strength of the beam could be equated to the residual in-plane compressive strength of the damaged sandwich beam. The width of the beams needed to be relatively large so that enough space was provided to accommodate a range of damage sizes. These sandwich beams are effectively panels but are continuously addressed as such for simplicity. The other is that the entire experimental procedure must deliver a substantially lower cost than that associated with the potentially up-scaled version of the end-loaded CAI test method for monolithic laminates. This 4PB concept for impact damage tolerance is not completely new and some of the early experimental attempts with long and wide unsymmetrical sandwich beams were reported in [10]. Recently, research work of using long and wide sandwich beams with a drilled hole in compression skin was reported [11-13], in which several different core materials were used in each beam. As could be seen from those investigations, achieving those two conditions in an ad hoc manner has proven to be very challenging, though the concept appears to be simple. This is largely because, among others, a stress analysis of the 4PB CAI test method for sandwich beams, albeit being essential to the development of the methodology, was not provided to address some of the crucial issues such as the effects of sandwich beam skin thickness, skin laminate lay-up, core density and beam width on failure modes before the experimentation. The addition usefulness of the 4PB CAI method is that it could conveniently be used for evaluating the load-restoration effectiveness in repair of sandwich structures [14]. This work intends to provide the initial development of the 4PB CAI method as a simple low-cost method for the damage tolerance assessment of pre-conditioned sandwich beams along with extensive experimental validations.

2 DEVELOPMENT OF FOUR-POINT BENDING METHOD FOR DAMAGE TOLERANCE

Since composite sandwich construction consists of at least two different materials, namely, two laminate skins and core, a multitude of damage or failure modes could thus occur, dependent on combinations of some of intrinsic material and structural parameters such as, among others, skin thickness, skin laminate lay-up, core density and core thickness in addition to testing conditions such as loader diameter, loading arm length and support span-to-thickness ratio. While the two skins are strong, stiff and relatively thin, the core is weak, soft and much thicker. Moreover, core can be made of either anisotropic honeycomb or homogeneous polymeric foam. Other types of cores include synthetic foam and end-grained balsa wood. In addition, the two laminate skins don't have to be identical so that unsymmetrical sandwich can be constructed. This characteristic of multiple damage mechanisms in sandwich construction presents a much greater challenge than what monolithic laminates ever faced.

A typical 4PB test set-up is shown in Fig. 1 and the longitudinal distributions of bending moment and through-the-thickness shear force between the two supports are shown in Fig. 2 for an intact beam. To develop such set-up into the 4PB CAI test method, details of specimen construction and testing conditions must be carefully considered and designed to ensure not only compressive skin failure but also a relatively low overall cost. In particular, those design considerations ought to aim at control or intact specimens. If proven to work, the present 4PB CAI test method should work for any of pre-conditioned sandwich beams. A real challenge in such development is that many of these design considerations are contradictory to one another so that in the end some balance would have to be achieved in terms of combinations of intrinsic parameters in sandwich construction.

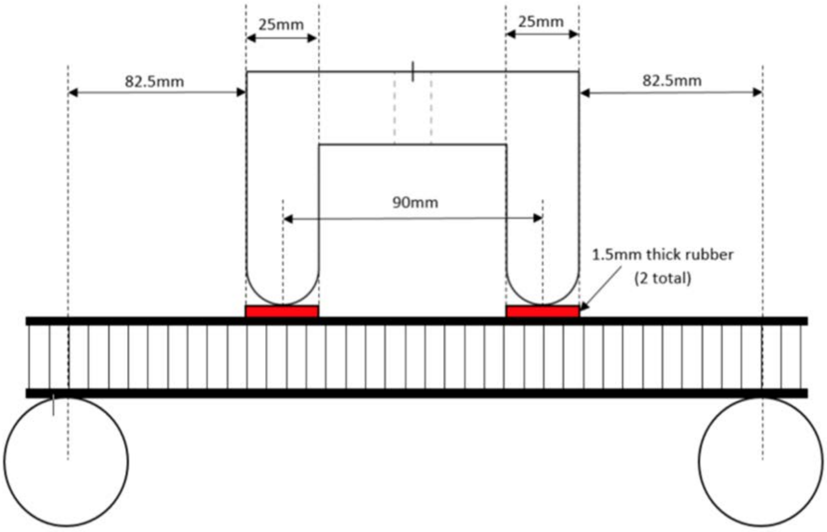

Fig. 1 An experimental set-up of four-point bending for sandwich beam

For a symmetrical sandwich beam in 4PB to fail in flexure, the compressive skin has to be relatively thin up to moderate in thickness, without having to require a large loading arm or support span-to-sandwich thickness ratio. Moreover, the skin laminate in a quasi-isotropic (QI) lay-up is easier to fail in flexure than the one in a cross ply (CP) lay-up. In addition, the skin laminates ought to be constructed to be symmetrical with respect to its own mid-plane, in order to minimise the effect of a potential bending-twisting coupling on the state of stresses. Alternatively, an unsymmetrical sandwich beam could be constructed with a weaker (i.e. thinner) compressive skin, like in [10-12]. In this way, intuitively, the likelihood of a compressive skin failure was enhanced. However, a bending stress analysis suggested that making the tensile skin slightly weaker could be just effective in failing the compressive skin due to the substantially reduced flexural rigidity of the unsymmetrical sandwich beam. There was also a strong argument for this case from a practical perspective, if the unsymmetrical sandwich construction had to be delivered. That is, the thicker skin of the sandwich was more likely to face practical impact threats and thereby get damaged. If the thicker skin gets damaged, the effect of a bending-twisting coupling on the state of stresses in the sandwich beams may be significantly less, as the bending performances of the two skins could 'even off' to some extent. Clearly, in the most of these scenarios, the sandwich beams intended for the damage tolerance assessment are pre-conditioned, containing damage of a varying severity, so that their likelihood to fail in the compressive skin is high. The thicknesses of skin laminates in this work ranged from 1 mm (8 plies) to 2 mm (16 plies) in both CP and QI lay-ups.

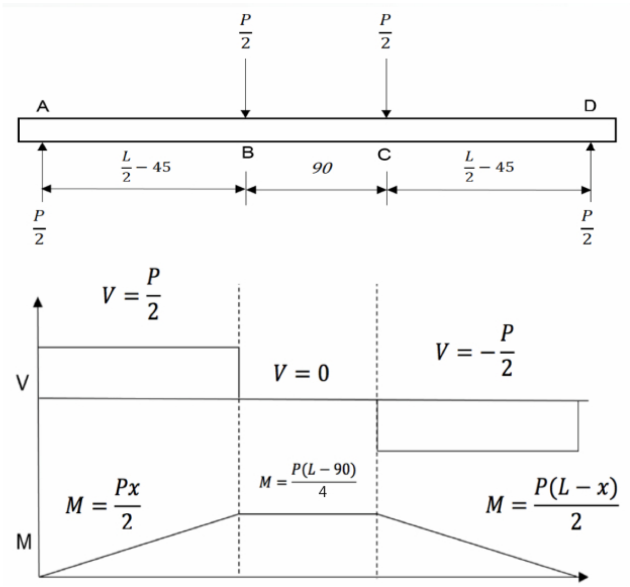

Fig. 2 Longitudinal distributions of bending moment and shear force in sandwich beam

A core density of the sandwich beams used in the development of the 4PB CAI test method was critical, as its through-the-thickness (TTT) shear strength had to be sufficiently high so that it did not fail in TTT shear in the loading arm region(s) before flexural failure of the compressive skin in the central region between the two loaders. A preliminary stress analysis suggested that the core density had to be at least 70 kg/m^3 or greater, without having to require a large loading arm or support span-to-sandwich thickness ratio. Densities of aluminium honeycomb core used in the present sandwich beams were 70, 110 and 135 kg/m^3, respectively. Furthermore, the core density in each sandwich beam remained constant without adding substantial manufacturing costs of featuring multiple core materials and densities in the different regions of the sandwich beams along the longitudinal direction. In addition, both the ribbon and width directions of aluminium honeycomb were examined in the construction of sandwich beams. A constant core thickness of 12.7 mm was selected in this investigation and thicker cores could increase flexural rigidities so much so that achieving flexural failure could be even more difficult. To demonstrate a capability of the 4PB CAI test method, focus of sandwich construction was deliberately put on some less favourable combinations of intrinsic parameters such as CP lay-up for skin laminate and ribbon direction of honeycomb cores aligned up in the width direction of some beams.

A relatively large support span-to-thickness ratio (L/h) was very desirable to promote flexural failure of the compressive skin. However, a larger L/h could also mean that the longer beams were needed so that the more sandwich materials would have to be used, which could make the present 4PB CAI method significantly less appealing. Therefore, a choice of L/h for this 4PB CAI method was guided by a consideration of specimen configurations, which directly impacted on the amount of sandwich materials used. In the current investigation, a minimum L/h was ensured to be greater than 16. As mentioned earlier in [8], the end-loaded CAI method adopted the in-plane panel dimensions of 200 mm by 150 mm. For the same planar area of 30000 mm^2 and hence the same amount of sandwich materials, an overall beam length of 300 mm was chosen with a width of 100 mm, which was considered to be sufficient to cover a substantial size of damage, though the narrower beam width was also examined.

For a given L/h, a larger loading arm for the outer regions was preferred to promote the bending moment and minimise the TTT shear in the core. On the contrary, again, that could also limit the (longitudinal) extent of the space required to accommodate a range of damage sizes, which was a key requirement in the 4PB CAI method.

The ultimate aim of all CAI methods is to provide a 'damage tolerance map', in which a reduction trend of residual in-plane compressive strengths with a variety of damage sizes is established for a design allowable to be established. Within the slightly limited space of less than 100 mm in the longitudinal direction, low-velocity impact tests are unlikely to deliver a range of expected damage areas in the width direction with a well-defined constant increment. Therefore, holes with a range of selected diameters were drilled through the compressive skins. Such simplified representation in place of impact damage offers a quick and low-cost preparation of pre-conditions. In particular, with hole, its effect on the non-uniform state of stress through the thickness of the compressive skin was much smaller than impact damage.

3 EXPERIMENTAL VALIDATIONS – PRELIMINARY RESULTS

3.1 Panel manufacturing and testing procedures

Sandwich panels were constructed with laminate skins and aluminium honeycomb core. The carbon/epoxy skin laminates were made of unidirectional (UD) 34-700/LTM45 prepreg with a nominal ply thickness of 0.128 mm in CP and QI lay-ups. The E-glass/epoxy skin laminates were made of UD PPG1062/LTM26 prepreg in a CP lay-up. They were laid up in the 300×300 mm panels and cured in an autoclave at 65^0C under a pressure of 0.62 MPa for 18 hours. The honeycomb core with a depth of 12.7 mm had a density of 70, 110 and 135 kg/m^3 with a constant cell size of 4.7625 mm. Adhesive VTA260 with built-in nylon mesh was used for skin-core bonding. Both skins were bonded individually to the core in an oven at 65^0C for 6 hours under a pressure of 0.1 MPa. The symmetrical panels with 8-ply skins are called 'thin' panels and the ones with 16-ply skins are called 'thick' panels. The unsymmetrical panels with 8/6 ply skin combination are also called 'thin' (unsymmetrical) panels, whereas the unsymmetrical panels with 16/12 ply skin combination are called 'thick' (unsymmetrical) panels. A nominal overall length of each specimen was 300 mm with two different nominal widths of 50 mm and 100 mm. A hole of a selected diameter was drilled through just the compressive skin at the centre of each specimen such that core underneath remained intact and a single strain gauge was mounted on the compressive surface at a hole-side on the mid-span 6 mm from a hole side on all occasions.

A total of 118 4PB tests in over 30 different groups were conducted at the fixed support span of 280 mm and the inner loader span of 90 mm, as illustrated in Fig. 1. Each of two double cylindrical line loaders had a diameter of 25 mm, whereas two cylindrical line supports had a diameter of 50 mm. Rubber shim strips of 1.5 mm thick were inserted under both loaders to ensure that core crushing would not occur. The overall test results are summarised in Tables 1-3. In each group, there were two to four tests executed, dependent on the availability of specimens, to ensure a repeatability and consistency of their results. On one occasion, there were 11 tests in a single (primary) group, as a testimony for the viability of the 4PB CAI method. The individual tests associated with single specific hole-to-width ratio in the tables were performed for a diagnostic purpose in the determination of a transition state between the two failure mechanisms. The parameters varied in the carbon/epoxy skinned sandwich beams for investigating the capability of the current 4PB CAI method include two skin laminate thickness of 1 mm and 2 mm, two different lay-ups, and three different densities of 70, 110 and 135 kg/m^3 for each lay-up in both symmetrical and unsymmetrical constructions. In the thin unsymmetrical sandwich beams, the 8 ply skin was drilled with a hole on the overwhelming majority of occasions whereas the intact 6 ply skin was used as the tensile skin. In the thick unsymmetrical sandwich beams, both the 12 ply and 16 ply skins were alternatively drilled with holes for different groups. The sandwich beams with the E-glass/epoxy skins had significantly less variations in their constructions, as it was intended to examine the effect of the different skin materials.

The thinnest sandwich construction was 14.75 mm thick and the thickest was 17.47 mm. They delivered the largest and smallest *L*/*h* ratios of 19 and 16, respectively. This variation in *L*/*h* ratio was reasonably close to each other so that it was considered that this difference might make only a small contribution to the bending and TTT shear behaviour of the sandwich beams.

3.2 Beam responses of and damage mechanisms in sandwich beams

Load-displacement response curves of the tested sandwich beams with or without a hole provide their global bending performances and in particular the pre-conditioned ones exhibit the dominant deformation mechanisms of the beams, as three selected examples show in Figs 3-5. It can be seen from these figures that the responses are initially linear, similar in all the cases, and are completely different, when the dominant failure mechanisms within the beams prevailed. When flexural failure occurred at the compressive skin of the beam across a hole of 54% width, the bending load dropped catastrophically in Fig. 4. A photograph of a typical specimen with flexural failure is shown in Fig. 6.

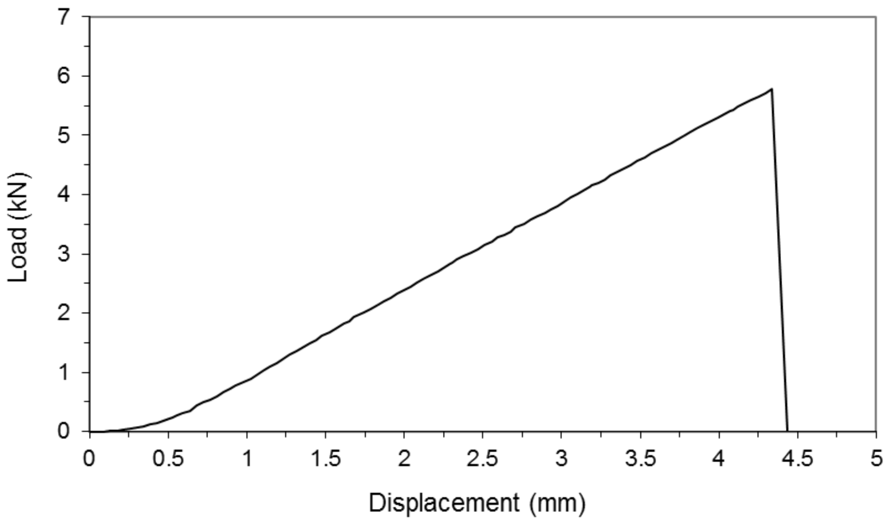

Fig. 3 A bending response of a thin sandwich beam in 8/8 CP skins and a core density of 110 kg/m^3 with flexural failure on the compressive skin

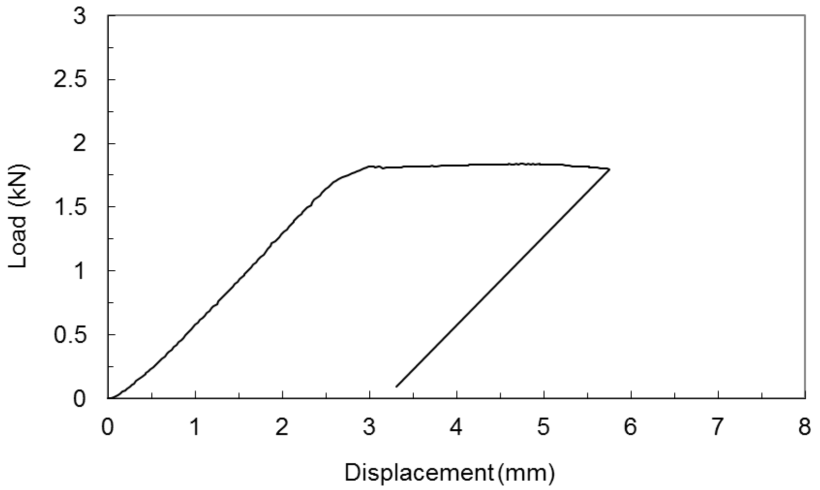

Fig. 4 A bending response of a thick sandwich beam in 16/16 CP skins and a core density of 70 kg/m^3 with core shear failure

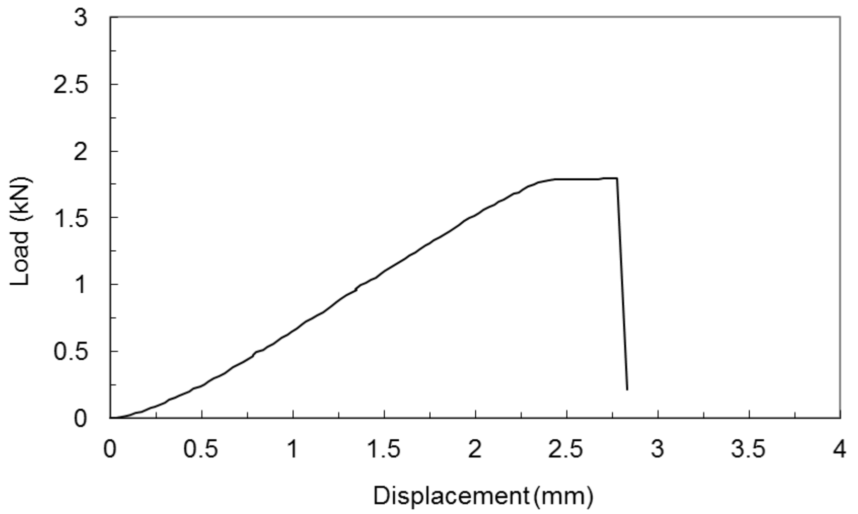

Fig. 5 A bending response of a thin sandwich beam in 16/16 QI skins and a core density of 70 kg/m^3 with flexural failure on the compressive skin

When the compressive skin of the sandwich beam was relatively strong, with a small hole of 27% width, the bending loads endured by the beams appear to level off, indicating a continued TTT shearing of core in the two loading arm regions, as shown in Fig. 4. This type of tests was terminated once TTT shear in core was observed. A photograph of such specimens with TTT core shear failure is shown in Fig. 7. Depending on combinations of sandwich construction, compressive skin thickness and core density, among others, a transition state between flexural skin failure and TTT core shear was fortuitously caught, as shown in Fig. 5, though this test was still categorised as flexure failure of the compressive skin. This implies that had the hole in the compressive skin been smaller, the magnitude of the core density been smaller, or even the lay-up of the compressive skin laminate been CP, the core of such beams could have been sheared through the thickness of the core, rather than been followed up by the flexural failure of the compressive skin. It appears that in every type of the sandwich constructions there was such transitional state with the increase in hole diameter and even in absolute value of the beam widths.

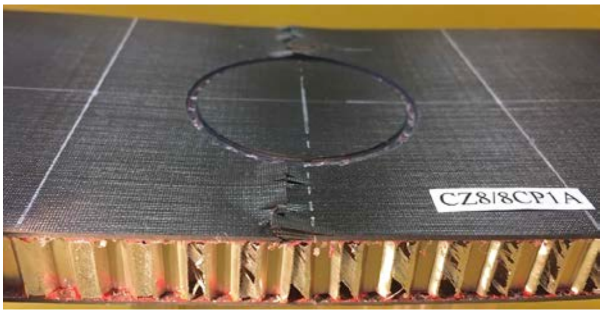

Fig. 6 Flexural failure of a thin carbon/epoxy sandwich beam in 8/8 CP skins with a hole of 54% width

Fig. 7 Core shear failure of a thick carbon/epoxy sandwich beam in 16/16 CP skins with a hole of 27% width

For the given support span and L/h ratio, we've found, as indicated in Tables 1-3, that core density and compressive skin thickness were the two most overriding parameters in the symmetrical sandwich construction in addition obviously to a diameter of hole or the ratio of hole diameter to beam width in dictating via which mechanism they failed. When a density of core was increased from 70 kg/m^3 up to 110 kg/m^3 and beyond, the beams with the denser cores failed in flexure, even when the hole-diameter-to-beam-width ratio was as low as 33%. For the symmetrical sandwich beams with a core density of 70 kg/m^3, doubling the skin thickness in these beams led to a lesser likelihood of flexure failure. While the thin beams required the hole-diameter-to-beam-width ratio to be around 50%, the thick beams failed in flexure only when the hole-diameter-to-beam-width ratio went up to 67%. The lay-up of the laminate skins also affected the likelihood of their failure mechanisms due to its contribution to the flexural rigidity of the beams with the skin laminate in a QI lay-up more likely to fail in flexure than CP lay-up. The use of the different skin materials shown in Table 3 did not show much of difference.

For the unsymmetrical sandwich beams, arranging the thinner or weaker skin to be on the compressive side of the beams in 4PB indeed could fail them in flexure, as shown in Table 2 from the thick unsymmetrical sandwich beams and also in [10-13,15]. As aforementioned, since it was less likely for the thinner skin of the unsymmetrical sandwich to meet impact threats in practice, it was thus considered to be advantageous to arrange the thicker skin to meet the compressive bending loads in the development of the 4PB CAI method. Such approach worked very well for the thin narrow unsymmetrical sandwich beams with the hole-diameter-to-beam-width ratio of around 50%. When the width of the beam was increased, a slightly greater hole-diameter-to-beam-width ratio of about 67% was required to fail the 'wide' beams in flexure. In addition, when the density of core was greater than 70 kg/m^3, the 4PB CAI method was readily proven to work.

The baseline sandwich beams with the compressive skin laminate being in a CP lay-up were proved to be much more difficult to fail in flexure, irrespective of core density, skin thickness and sandwich symmetry. It was slightly surprising that the narrow unsymmetrical sandwich beams with either 110 kg/m^3 or 135 kg/m^3 did not fail in flexure.

It was an important part of the present investigation for the development of the 4PB CAI method to examine the effect of combinations of intrinsic parameters in sandwich construction on transitional state from skin flexure failure to TTT core shear failure in terms of hole-diameter-to-beam-width ratio. While the transitional states were different for different sandwich constructions, they were from the groups of the specimens with identical sandwich constructions in addition to the same nominal hole-diameter-to-beam-width ratio, in which some test specimens failed in flexure, whereas the remaining failed in TTT shear. Interestingly, the majority of these transitional states were associated with a core density of 70 kg/m^3 with its ribbon direction in the beam width and with the thin skins in unsymmetrical construction, as shown in Table 1. The only other case is from the thick sandwich beams in symmetrical construction, as shown in Table 2. In the former, the results from the narrow beams seem to suggest that an average minimum hole-diameter-to-beam-width ratio of about 52% would be required to fail the beams in flexure. A further testing using the wide beams somewhat increased the minimum hole-diameter-to-beam-width ratio for flexure failure up to about 67%. For the latter, the minimum hole-diameter-to-beam-width ratio for flexure failure was also around 67%. Clearly, in both scenarios, the minimum hole-diameter-to-beam-width ratio of about 67% for flexure failure might be too large. This was especially so when the practice of using the end-loaded CAI method was considered. Nevertheless, it might be deduced that similar beams with the ribbon direction of core aligned in the longitudinal direction of the beams could all fail in flexure.

3.3 Residual strengths of pre-conditioned sandwich beams in 4PB CAI method

Current industrial practice with the 4PB CAI method is to use the bending stress out of elementary beam theory, as given in Eq. (1), to calculate the residual compressive strength σ_{max}. Although such practice could adequately account for the affected load resistance of impact-damaged beams, neither a stiffness degradation of the pre-conditioned compressive skin nor the degraded flexural rigidity of the sandwich beams is being considered, in addition to the shifted centroidal distance.

$$\sigma_{\max} = \frac{\overline{M}y}{I} \tag{1}$$

in which $\overline{M}$ is the maximum bending moment, y is the centroidal distance to the surface of the compressive skin and I is the second moment of area for rectangular cross section of the beam.

It is thus unclear at present that such usage of Eq. (1) underestimates or overestimates the residual compressive strength of the impact-damaged sandwich beams, though experimental results in [11] appears to show that the CAI strength values of the 4PB CAI method are less than those of the end-loaded CAI method for the given sizes of damage. For the 4PB CAI method to deliver the true and accurate residual compressive strength, Eq. (2) would have to be used, in which the degradation of both the longitudinal modulus of the compressive laminate skin and flexural rigidity of the sandwich beam has to be taken into account.

$$\sigma_{\max} = \frac{\overline{M}E_s y'}{D} = \frac{\overline{M}y'E_{s\,\mathrm{effect}}}{D_{\mathrm{effect}}} \tag{2}$$

where y' is the shifted centroidal distance to the surface of compressive skin, $E_{s\ effect}$ is the reduced longitudinal modulus of the compressive skin laminate of the sandwich beam and D_{effect} is the reduced flexural rigidity of the sandwich beam.

4 CLOSING REMARKS

The 4PB CAI method has demonstrated to provide a very simple and low-cost test set-up for as-received sandwich panels without the needs of either ends machining or using a specific test jig for the evaluation of the residual compressive strengths of the sandwich beams. The free longitudinal edges of the beam in the 4PB CAI method may not represent any realistic support conditions like in the end-loaded CAI method. The simulation of impact damage by a drilled hole is acceptable without having to perform a prior impact test. Its low cost potential was well demonstrated with the reasonable in-plane dimensions of the test specimens. In particular, pre-conditioned unsymmetrical sandwich panels could be tested without difficulty. It was found that having a weaker tensile skin in the unsymmetrical sandwich construction proved to be better than a weaker compressive skin in failing the compressive skin due to the substantially reduced flexural rigidity of the unsymmetrical sandwich beam and a lesser demand on the magnitude of the loading arms.

For the given support span-to-thickness ratios and loading arm, the combinations of core density and compressive skin thickness were found to be the most significant factor of influencing the failure mechanisms, irrespective of types of composite skin materials. Specifically, the sandwich configurations constructed with the moderately high core densities (110 kg/m^3 or greater) along with the relatively thin skin thicknesses promoted flexure failure well. Having a QI lay-up in the compressive skin laminate enhanced such tendency. On the contrary, the combinations of core density of 70 kg/m^3 or less and the compressive skin thickness of 2 mm thick or greater favoured TTT core shear failure, unless the ratios of hole diameter to beam width were very large. In particular, the narrow beams of about 50 mm wide were proven to work with the relatively small holes.

The baseline sandwich beams with the compressive skin laminate being in a CP lay-up were shown to be much more difficult to fail in flexure, irrespective of core density, skin thickness and sandwich symmetry. It was slightly surprising that the narrow unsymmetrical sandwich beams with either 110 kg/m^3 or 135 kg/m^3 did not fail in flexure. This aspect of the 4PB CAI method along with the more accurate calculation of the residual compressive strengths remains a challenge for further development in future.

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Table 1 Overall results of thin sandwich beams with 1 mm thick compressive carbon/epoxy skin at L/h of 19

Core density	Skin thickness arrangement*	Skin lay-up arrangement	Av. beam width (hole diameter)	Hole-to-width ratio	Failure mode	No of tests
kg/m^3	-	-	mm (mm)	%	-	-
70	8/8	CP/CP	89 (60)	67	Core shear	1
			42 (25)	60	Core shear	1
			49 (25)	51	Core shear	1
	8/8	QI/QI	46 (25)	54	Skin fracture	3
			45 (20)	44	Core shear	3
			46 (16)	35	Core shear	3
	8/6	CP/CP	76 (60)	79	Skin fracture	1
			86 (60)	70	Skin fracture	3
			93 (60)	65	Core shear	3
			94 (60)	64	Skin fracture	
			96 (60)	63	Core shear	
	8/6	QI/MD	85 (60)	71	Skin fracture	2
			96 (60)	63	Core shear	1
	6/8	CP/CP	84 (60)	71	Skin fracture	1
	8/6	CP/CP	49 (25)	51	Skin fracture	3
			49 (25)	51	Core shear	
			48 (25)	52	Skin fracture	
			41 (20)	49	Core shear	1
			46 (20)	44	Core shear	1
			47 (16)	34	Core shear	3
			48 (16)	33	Skin fracture	
			48 (16)	33	Skin fracture	
			42 (-)	0	Core shear	1
110	8/8	CP/CP	49 (25)	51	Skin fracture	3
			44 (20)	46	Skin fracture	1
			46 (16)	35	Skin fracture	3
			44 (-)	0	Core shear	1
	8/8	CP/CP	85 (51)	60	Skin fracture	1
			96 (51)	53	Skin fracture	11
	8/6	CP/CP	47 (25)	53	Skin fracture	3
			46 (20)	44	Skin fracture	1
			46 (16)	35	Skin fracture	3
			46 (-)	0	Core shear	1
135	8/8	CP/CP	38 (20)	53	Skin fracture	1
			47 (25)	50	Skin fracture	4
			43 (16)	37	Skin fracture	1
			48 (16)	33	Skin fracture	2
			38 (-)	0	Core shear	1
	8/6	CP/CP	37 (20)	55	Skin fracture	2
			49 (25)	51	Skin fracture	3
			39 (16)	41	Skin fracture	1
			49 (16)	33	Skin fracture	2
			37 (-)	0	Core shear	1

* The front ply number is for the compressive skin.

Table 2 Overall results of thick sandwich beams with a core density of 70 kg/m^3 and 2 mm thick compressive carbon/epoxy skin at the *L*/*h* of 17

Skin thickness arrangement*	Skin lay-up arrangement	Av. beam width (hole diameter)	Av. hole-to-width ratio	Failure mode	No of tests
-	-	mm (mm)	%	-	-
16/16	CP/CP	92 (25)	27	Core shear	2
16/16	QI/QI	41 (30)	73	Skin fracture	1
		44 (30)	68	Skin fracture	3
		45 (30)	67	Core shear	
		45 (30)	67	Skin fracture	
		48 (30)	64	Core shear	2
		50 (30)	60	Core shear	1
		47 (25)	54	Core shear	2
16/12	CP/CP	50 (30)	71	Skin fracture	2
		50 (25)	50	Core shear	2
16/12	QI/MD	82 (60)	73	Core shear	1
12/16	CP/CP	42 (30)	72	Skin fracture	2
		43 (30)	60	Skin fracture	2
		50 (25)	50	Skin fracture	1

Table 3 Overall results of sandwich beams with a core density of 70 kg/m^3 and compressive E-glass/epoxy skin

Skin thickness arrangement*	Skin lay-up arrangement	Av. beam width (hole diameter)	Av. hole-to-width ratio	Failure mode	No of tests
-	-	mm (mm)	%	-	-
8/8	CP/CP	44 (30)	68	Skin fracture	3
		45 (30)	67	Core shear	
		47 (30)	65	Core shear	
		54 (30)	57	Core shear	2
		53 (25)	47	Core shear	2
16/16	CP/CP	45 (30)	67	Core shear	3
		47 (30)	64	Core shear	1
		53 (30)	57	Core shear	1
		54 (25)	47	Core shear	2

* The front ply number is for the compressive skin.