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RESEARCH PAPER

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Behaviour of fibre composite sandwich structures under short and asymmetrical beam shear tests

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Abstract

The behaviour of structural fibre composite sandwich beams made up of glass fibre composite skins and phenolic core material was investigated under three-point short beam and asymmetrical beam shear tests. The effect of the shear span-to-depth ratio (a/D) on the strength and failure behaviour of the composite sandwich beams was examined. The results showed that with increasing a/D ratio, the failure load of the sandwich beam is decreasing. On the contrary, the coupling effect of flexural stresses increases with increasing a/D ratio. Noticeably, the fibre composite sandwich beams tested under asymmetrical beam shear exhibited higher failure load compared to beams tested under short beam shear. Analysis showed that the shear stress in the core is more dominant than flexural stress when the a/D ratio is 1 for the sandwich beams under short beam test and 1 to 3 for the sandwich beams tested under asymmetrical beams shear test. The proposed prediction equation which accounts for the combined effect of shear and flexural stresses due to the changing a/D ratio, presented a good agreement with the experimental results, showing that it can reasonably estimate the failure load of structural fibre composite sandwich beams.

Keywords: Fibre composites; sandwich beams; phenolic core; shear; short beam; asymmetrical beam.

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1. Introduction

Fibre composite sandwich structures are being increasingly used in applications requiring high bending stiffness and strength, combined with low weight. Sandwich structures generally consist of face sheets (skins) made of fibres which sandwiches the lightweight core material in the middle. In a sandwich structures, the strong and stiff skins carry most of the in-plane and bending loads while the core mainly bears the transverse shear and normal loads [1]. Fibre composite materials are now commonly used for the top and bottom skins due to their high mechanical performance and low density. On the other hand, the core keeps the skins apart from each other to provide a sandwich construction with high flexural stiffness and strength with a relatively lightweight structure. The material combination and geometry of composite sandwich structures vary depending on their intended applications, which results in different governing failure mechanisms [2]. Their usage is mainly in the aerospace, aircraft and marine industries because of their fuel efficiency in transportation vehicles, but at present, there is a strong interest in the development and applications of sandwich structures for civil and building material systems [3]. The light weight of this type of structure facilitates handling during assembly and reduces installation costs as well as transportation costs.

The large number of timber structures that need replacement in rural and regional Australia [4] has resulted in much research aimed towards the development of new and innovative fibre composites structures to address the need of the construction industry for a more durable and cost-effective infrastructure. Recently, a new generation composite sandwich panel made up of glass fibre composite skins and modified phenolic core has been developed in Australia [5]. Manalo *et al*. [6] have evaluated the flexural behaviour of these sandwich structures which indicates its strength has high potential for structural applications. Similarly, the higher in-plane shear strength of the sandwich structures due to the presence of vertical fibre composite skins showed that this composite material can be used for shear webs of a structural beam [7]. Furthermore, gluing these composite sandwich panels together resulted in a more stable and stronger section for structural glue-laminated fibre composite sandwich beam [8]. In another study, Fam and Sharaf [9] explored the feasibility of producing and evaluated the performance of sandwich panels made from polyurethane core and glass fibre reinforced polymer (GFRP) skins with ribs of various configurations. Results of their study showed that by integrating the GFRP ribs, the strength and stiffness of the sandwich panels increased by 44-140% depending on the configuration of the ribs compared to a panel without ribs. Moreover, the shear failure of the polyurethane foam core is minimised indicating that the potential use of the developed sandwich panel in structural engineering and construction applications. However, an accurate knowledge of the behaviour of fibre composite sandwich structures under different loading conditions is a fundamental requirement before they can be used effectively for construction and building applications.

In construction application, a thicker and stronger core is needed to efficiently transfer the bending stress between the top and the bottom skins than in automobile and marine applications [10]. It has been demonstrated that most sandwich construction fails due to shear failure of the core material [11]. In particular, the shear strength of the core is a critical parameter and is an important consideration when designing composite sandwich structures. The brittle nature of the core causes a sudden collapse and could become the limiting factor in designing such structures. These important aspects have to be addressed in order to advance the use of sandwich structures in civil engineering applications. Until recently, the failure mechanisms in thick composite sandwich structures were not well understood and very limited work has been reported on the shear behaviour of sandwich structures [12]. Similarly, there still exists a problem to describe accurately the true shear behaviour of composite sandwich structures due to lack of an accurate test method. Thus, a more in-depth understanding on the shear behaviour of fibre composite sandwich structures will help fill the knowledge gap that currently exists in civil infrastructure.

Several test methods were developed to determine the shear properties of fibre composite sandwich structures. The Iosipescu shear test was first developed for measuring the shear strength of metal rods [13]. In the early 80's, Walrath and Adams [14] developed a test fixture known as the 'modified Wyoming fixture', which was included in the ASTM standard D5379-93 [15] and is widely used in determining the shear properties of fibre composite materials. Although the Iospescu shear test is appropriate in determining the shear strength and modulus of fibre composite materials, the relatively small size of the fixture used in this test limits its application for a composite sandwich structures. Another is the V-notched rail shear test [16] which incorporates the attractive features of the existing Iosipescu and two-rail shear tests. This test method depends on the excellent gripping of the specimen on the test fixture however; it is very difficult to attain adequate gripping with standard fixture especially for high shear strength composite materials. Picture frame test on the other hand is regarded as the most accurate test giving the modulus of rigidity for a fibre composite sandwich panel [17] but this test method requires complex specimen preparations and special test fixtures. The ASTM C273-11 [18] suggested a standard test procedure for obtaining the shear properties of the sandwich core materials. In this test method, the core materials or the composite sandwich panel is adhesively bonded to two steel adherents loaded in tension. Generally, it was found that the usage of this test method was suitable for low shear modulus core but was not applicable for composite sandwich with high density core material. Delamination between the plies of fibres occurred during the test for composite sandwiches with modified phenolic core material while delamination between the glue line and the core material occurred using only the core material. Most of these test methods entails complex specimen preparation and have several difficulties in conducting the actual test which indicated the need for performing simple tests but can provide a reliable and accurate measurement for the shear behaviour of fibre composite sandwich structures.

In this paper, the shear behaviour of structural fibre composite sandwich beams was evaluated under two simple shear test methods, namely short beam and asymmetrical beam shear tests. The effects of the shear span-to-depth (a/D) ratio on the strength and failure behaviour of the sandwich beams were analysed. Simplified prediction method to calculate the failure load of the fibre composite sandwich beams accounting for the effect of a/D ratio was presented. The predicted failure load was then compared with the experimental results.

2. Experimental program

This section presents the materials and test methods to evaluate the shear behaviour of structural fibre composite sandwich beams.

2.1 Material properties

The structural composite sandwich panel used in this study is made up of glass fibre composite skins co-cured onto the modified phenolic core material using a toughened phenol formaldehyde resin [5]. The novel fibre composite sandwich panel has a nominal thickness of 20 mm. The sandwich panels are produced in limited thicknesses for reasons of cost effectiveness and efficiency as a sandwich structures with a thick phenolic core will result in a significantly long curing time. The fibre composite skin is made up of 2 plies of bi-axial (0/90) E-CR glass fibre fabrics with a chopped strand mat and has a total thickness of 3.0 mm. The modified phenolic foam core material is made primarily from natural plant products with a proprietary formulation of CarbonLOC Pty. Ltd., Australia. The effective mechanical properties of the skin and the core material of the fibre composite sandwich panel were determined from testing of coupon specimens following the ISO and ASTM test standards [15, 19-23] in earlier studies by Manalo *et al*. [6-8] and are listed in Table 1.

2.2 Test specimen

The sandwich beam specimens were cut directly from the composite sandwich panels provided by the manufacturer. All specimens have a nominal thickness or depth, *D* and width, *b* of 20 and 50 mm, respectively. As the main objective of the study is to investigate the shear behaviour of fibre composite sandwich structures, beams with a/D ratios of only 1 to 6 were examined. Six replicates for each specimen type and span were prepared and tested. The descriptions of the test specimens are listed in Table 2. In this table, *a* and L_T represent shear span and total length of the sandwich beam, respectively while SB and ABS corresponds to the specimens tested under short beam and asymmetrical beam shear, respectively. These shear test methods are described more in details in the following section. Due to the limitation of the test fixture, an a/D of 4 is not possible for ABS test hence 3.5 was instead performed.

2.3 Test set-up and procedure

There are a number of test methods developed to measure shear properties of fibre composite materials [24], however, until now very limited test methods can reliably evaluate the shear behaviour of structural fibre composite sandwich beams. In this study, two simple types of shear tests were performed to evaluate the shear behaviour of fibre composite sandwich structures, namely short beam shear and asymmetrical beam shear tests. In both test methods, the load was applied through a 100 kN electromechanical universal testing machine with a loading rate of 1.3 mm/min. An overhang length of 20 mm on both ends of the test specimens was provided to avoid slipping of the beam during testing. The loading pins and the supports had a diameter of 10 mm to prevent any indentation and crushing failure on the core of the fibre composite sandwich beams. All specimens were tested up to failure to determine the strength and failure mechanisms. The applied load and the crosshead displacement were measured and recorded using a material testing software TestWorks 4.

2.3.1 Short beam test

Three-point bending test using short beam specimen is suitable as a general method of evaluation for the shear properties in fibre-reinforced composites because of its simplicity [25]. This test method was performed in accordance with ASTM C393 standard [26] and involves loading a short sandwich beam under three-point bending (see Fig. 1a) to ensure shear failure of the core. The short beam (SB) test is considered as the simplest test method to evaluate the shear strength of materials. However, it provides a conservative estimate of the shear strength of composite sandwich materials as the beam is also subjected to a maximum bending stress in the location of maximum shear.

2.3.2 Asymmetrical beam shear test

The asymmetrical beam shear (ABS) test is proven effective in inducing shear failure and has provided a good estimation of the in-plane shear strength of fibre composite sandwich structures with high strength core material [7]. In this test method, the specimens were eccentrically loaded at two trisected points and the supports were applied at the remaining two points. This loading configuration generates a high shear stress and a nearly zero moment at the centre of the specimen. The test set-up for the asymmetrical beam shear test is illustrated in Fig. 1b. A steel spreader beam was used to transfer the single load applied by the loading machine to the specimen asymmetrically.

3. Evaluation of fibre composite sandwich beam behaviour

Approaches to estimate the stress in the core and skin of the composite sandwich beams under either shear or flexural load are presented in this section. These equations are used to evaluate the effect of a/D ratio on the behaviour of the sandwich beams tested under SB and ABS.

3.1 Approach to estimate shear strength

The average shear stress, τ of the composite sandwich beams can be estimated by dividing the shear force acting on the maximum shear region with the transformed area of the sandwich beam section and accounting for the different material properties of the skin and the core as given in Eq. (1). However, instead of transforming the composite sandwich section using the ratio of the modulus of elasticity of the materials as suggested by Triantafillou [27], all the materials were transformed into equivalent core using the ratio of the shear modulus of the skin and the core in the proposed prediction equation. This relationship is considered as the modulus of elasticity of the phenolic core is only 1/10 of that of the modulus of elasticity of the skin; however, its shear modulus is almost 2/10 of that of the skin. For the beams tested under SB and ABS methods, the maximum shear force acting on the sandwich beam section is equal to half that of the applied load P as indicated in Fig. 1.

$$\tau = \frac{P}{2\left[\left(c + 2t\frac{G_s}{G_c}\right)D\right]} \qquad (1)$$

where t and c are the thicknesses of the skin and core and the skin, respectively and G_s and G_c are the shear moduli of the skin and core, respectively. In this prediction equation, the failure of the sandwich beam will occur when the shear strength of the phenolic core, τ_c is reached.

3.2 Approach to estimate bending strength

Simple beam theory can be used to calculate the flexural stress in any layer of a fibre composite sandwich beam section. The maximum flexural stress, σ_s carried by the outermost fibres of the skin for a composite sandwich beam is calculated as Eq. (2) while the maximum flexural stress, σ_c carried by the core is given in Eq. (3). In these equations, the bending moment M is determined based on the loads applied to the sandwich beam.

$$\sigma_s = \frac{M(D/2)}{EI}E_s \qquad (2)$$

$$\sigma_c = \frac{M(c/2)}{EI}E_c \qquad (3)$$

where E_s and E_c are the moduli of elasticity of the skin and core, respectively while EI is the flexural stiffness. In the composite sandwich structures tested in this study, the contribution of the core and the skin were considered in the calculation of EI and is given as Eq. (4).

$$EI = \frac{bt^3}{6}E_s + \frac{bt(D-t)^2}{2}E_s + \frac{bc^3}{12}E_c \qquad (4)$$

4. Experimental results and observations

The results of the experimental evaluation of the behaviour of the fibre composite sandwich beams under SB and ABS test methods are discussed in this section.

4.1 Failure load

Table 3 summarises the mean maximum load carried by the sandwich beams tested under short beam and asymmetrical beam shear tests. For all the tested specimens, the maximum load corresponds to the failure load as the specimen failed immediately after the formation of the first shear crack in the core material. As expected, the failure load of the fibre composite sandwich beams with lower a/D ratio is higher than that of beams with larger a/D ratio. The results also show that the beams with the same a/D tested under ABS failed at a higher load than the specimens tested under SB. More importantly, the variability of the failure load for the tested specimen is less than 10% showing the consistency of the tested specimens and that the experimental procedures were conducted within acceptable error of margin.

4.2 Load and crosshead displacement behaviour

Fig. 2 shows the load and the displacement of the machine crosshead during the entire test regime for fibre composite sandwich beams with different a/D ratios tested under SB and ABS. As indicated in the figure, the failure in the sandwich beam specimens is represented with a load drop in the load-crosshead displacement relation curve. Generally, the load increased linearly with the displacement of the crosshead until final failure for most specimens except for some specimens where a slight decrease in stiffness was observed. This decrease in stiffness can be due to the initiation of flexural cracking in the core material. As expected, the longer beams deflected more than shorter beam specimens. A sudden load drop was observed which indicated the final failure of the beam. For composite sandwich beams tested under SB test and with a/D ratio higher than 4, there was a slight nonlinearity observed in the load-deflection curve before the final failure as shown in Fig. 2a. This is due to the initiation of the compression failure of the top composite skin. It can be clearly noticed from the figure that the specimens tested under ABS failed at a higher load compared to SB. For beams with an a/D ratio of 1, there was no significant different in the slope of the load-deflection curve between SB and ABS. This is due to the dominant contribution of shear deformation in the behaviour of the beams. However, for an a/D ratio of 2 to 6, the beams tested under SB deflected more than that of beams tested under ABS under the same level of applied load. This indicates the higher flexural stress experienced by the SB beams which resulted in a higher transverse displacement.

4.3 Failure behaviour

Figs. 3 and 4 show the typical failure behaviour of the fibre composite sandwich beams tested under SB and ABS methods, respectively. The experimental results show that the sandwich beam specimens failed after the formation of the first shear crack in the core. In this position, a diagonal shear crack propagates through the core material at the location of the maximum shear. In all the tests, shear cracks originates under the loading point and propagates towards the bottom of the sandwich beam. As indicated in the figures, the inclination of shear cracks is approximately 45 degrees. This failure is brittle and sudden which is accompanied by a loud noise after the appearance of the first shear crack.

In both test methods, the specimens with a/D ratio of 1 and 2 failed due to shear failure of the core with minor debonding failure between the skin and the core at the bottom part of the beam (Figs. 3a, 3b, 4a and 4b). For all the tested specimens, there was no observed indentation failure suggesting the suitability of 10 mm diameter roller for the loading points and supports. This can also be possible due to the presence of the stiff glass fibre composite skins which spreads out the compressive stresses under the loading area preventing any localised failure in the core. For beam specimens with a/D ratio of 3 to 6 and tested under SB (Figs. 3c to 3f), the debonding failure between the fibre composite skin and the core at the bottom of the sandwich beam extended up to the edge of the beam which preceded after the shear cracking of the core. On the other hand, the debonding failure of the sandwich beam tested under ABS is confined in the region of maximum shear as shown in Figs. 4c to 4f. For specimens tested under SB and with a/D ratios of 5 to 6, initiation of compressive failure of the top skin was observed (Figs. 3e to 3f). This beams exhibited a slight nonlinearity in the load and deflection curve before final failure as shown in Fig. 2a.

5. Discussions

The behaviour under SB and ABS tests and the effects of the a/D ratio on the shear strength and failure mechanisms of the fibre composite sandwich beams are discussed in this section.

5.1 Comparison of shear strength between short beam and asymmetrical beam specimens

Many researchers agreed that an appropriate test method should be adopted to evaluate the shear behaviour of sandwich structures. Sideridis and Papadopoulus [25] indicated that a good test method should require no special equipment for specimen preparation and be capable of being performed on readily available testing machines. These requirements were achieved using the two shear test methods as the specimen preparation for both tests involve only cutting the sandwich beam into required specimen dimension from a panel. Similarly, both these test methods use the same test equipment and fixtures. The only difference is that the specimen needed for ABS is longer than SB for the same a/D ratio as indicated in Table 1.

Another important consideration for a reliable shear test method is that a ‘nearly’ pure shear should be induced on the specimen and the test method should give reproducible results.

As shown in Fig. 1, the shear force existing on the sandwich beam are the same for both test methods at the same level of applied load. The results indicated a higher shear strength for fibre composite sandwich beam specimens tested under ABS than that of specimens tested under SB eventhough both test methods showed an almost failure behaviour for the same a/D ratio. The lower failure load for the specimens tested under SB can be explained by the coupling effects of flexural stresses experienced by the sandwich beams. As indicated in section 2.3.1, in addition to the maximum shear at the middle of the beam carried by the sandwich beam under SB, the specimen is also subjected to a maximum bending moment in this location. According to Chaterjee *et al*. [24], the failure of beams under SB often occurs due to a combination of flexural and shear stresses and most of the time is originated under the loading point. In fact, the maximum bending stress on the sandwich beam under SB is twice that of beam under ABS at the same level of applied load and with the same a/D ratio. This follows that the contribution of flexural stresses in the SB beams is higher than ABS beams.

5.2 Effect of a/D ratio on effective shear stress

Fig. 5 shows the average shear stress of the fibre composite sandwich beams calculated using Eq. (1). The results indicate that the a/D ratio has a significant effect on the shear stress of the composite sandwich beams. In all the a/D ratios, shear cracking of the core was observed on the fibre composite sandwich beams at the region of maximum shear. In both test methods, the average shear stress in the sandwich beam decreases as the a/D ratio increases. Similarly, Yoshihara and Furushima [28] pointed out that the shear stress of timber beams tends to increase with decreasing a/D ratio. In a composite sandwich structures, Dai and Thomas Hahn [29] and Awad et al. [30] indicated that shorter sandwich beams exhibited higher shear stress than beams with longer span. This is expected as the coupling effect of the flexural stress increases with increasing a/D ratio which contributes to the initiation of failure in the core.

Noticeably, the shear stress of the fibre composite sandwich beams tested under ABS is significantly higher than that of SB for the same a/D ratio. This is due to a higher bending moment existing on the specimens subjected to SB test than that of ABS specimens. As shown in Fig. 3, the maximum bending moment experienced by specimens with the same a/D ratio and tested under ABS is only half that of the SB specimens.

The maximum calculated average shear stress of the composite sandwich beams with a/D ratio of 1 tested under SB and ABS method is 5.3 and 7.2 MPa, respectively. This shear stress is 60% and 82% of the shear strength of the modified phenolic core material listed in Table 1. This decreases to 2.1 and 3.3 MPa for sandwich beams with a/D ratio of 6 tested under SB and ABS, respectively which are only 24% and 37% of the shear strength of the phenolic core material. While the two test methods are conducted to evaluate the shear strength of the sandwich beams, this result suggests that the flexural stress has played a major part in the overall behaviour of the fibre composite sandwich beams especially for beams with large a/D ratios. Thus, it is important that the contribution of bending stress in the sandwich beams should be considered in the analysis and prediction of the sandwich beam behaviour.

5.3 Effect of a/D ratio on bending stress

The bending stress in the skin and core of the fibre composite sandwich beams with different a/D ratios is shown in Fig. 6. These stresses are calculated using equations (2) and (3), respectively. As shown in the figure, the bending stresses in both the skin and the core increases with increasing a/D ratio. For sandwich beams tested under SB and with a/D ratio of greater than 5, it can be noted that the maximum bending stress in the skin and the core is around 188.8 MPa and 13.9 MPa, respectively. These stress values are almost comparable to the compressive strength of the skin and the flexural strength of the core determined from coupon test (listed in Table 1). This explains the reason why the initiation of compressive failure of the skin was observed for specimen with large a/D ratio. The results also indicated that even at an a/D ratio of 1, the specimen experiences bending moment which influences the failure mechanisms of the fibre composite sandwich beams. Because of the combined stress condition, it is more likely that the failure caused by the bending moment for SB specimens with larger a/D ratio precedes the shearing failure of the phenolic core which leads to the final failure of the sandwich beam. On the other hand, the maximum bending stress experienced by the skin and core of the specimens tested under ABS can be as low as 53.1 MPa and 3.9 MPa, respectively for an a/D ratio of 1 and are only 145 MPa and 10 MPa, respectively for an a/D ratio of 6. This result suggests that the sandwich beams tested under ABS are experiencing lower flexural stress that that of beams tested under SB. Consequently, this indicates that a more representative shear strength of a fibre composite sandwich structures can be determined using the ABS test method.

5.4 Effect of a/D ratio on failure mechanisms

It is important to examine the effect of a/D ratio on the failure mechanisms of fibre composite sandwich structures. The results of this study showed that the failure of the fibre composite sandwich beams tested either in SB or ABS occurred along the intended shear plane. As expected, the shear failure of the core for all the tested specimens was sudden and catastrophic. This can be explained by the brittle behaviour of the core wherein the shear failure occurred after the formation of the first shear crack. When shear failure of the core occurred, the sandwich beam lost its capacity to carry load instantly without any residual load-carrying capacity beyond the peak load. There was no observed indentation failure on all the tested specimens suggesting the high compressive strength of the core material and its suitability for civil engineering applications. This supports the observations by Sideridis and Papadopoulus [25] and Awad *et al*. [30] wherein they have indicated that composite beams are expected to fail in shear at small a/D ratios while the mode of failure becomes flexural at large a/D ratio. However, they also indicated that there is an intermediate a/D ratio for which the behaviour is transitional, and the mode of failure can either be shear or flexure or a combination of both. For the structural composite sandwich beams investigated, this intermediate a/D ratio was found to be around 5. For specimens with a/D ratio of 5 or greater, the initiation of the compressive failure of the top skin was observed. This preceded shear failure, and in some cases, initiated shear failure of the core. The initiation of the compressive failure of the top fibre composite skin also explains the slight non-linearity observed in the load-deflection relationship curve shown in Figure 2. Moreover, the shear stress in the core and the bending stress in the skin and the core for SB beams with a/D ratios of 5 and 6 are almost similar.

5.5 Effect of a/D ratio on shear crack angle

The angle of inclination of the shear crack developed in the sandwich beam was recorded and analysed. Figure 7 shows the inclination of shear crack developed on the tested fibre composite sandwich beams for different a/D ratios. The results showed that the a/D ratio has some effect on the shear crack angle on the core material. For short beams, the shear crack angle is between 40 and 50 degrees. However, the inclination of shear crack ranges from 40 to 60 degrees for larger a/D ratios. This is explained by the higher contribution of flexural stresses for longer beams which is characterised by a vertical crack in the core. The average value of all the measured inclination shear crack angles is around 46 degrees. This is very close to the expected inclination angle of crack due to shear which is approximately 45 degrees.

5.6 Effect of a/D ratio on combined shear and bending stresses

Fig. 8 shows the ratio shear stress to bending stress in the core, τ/σ_c for sandwich beams with different a/D ratios and tested under SB and ABS methods. The results shows that the τ/σ_c decreases as the a/D ratio increases. For specimens with a/D equal to 1, the τ/σ_c ratio is almost 1.8 for ABS but only 0.9 for SB while the τ/σ_c ratio for specimens with an a/D ratio of 6 is only 0.30 and 0.15 for ABS and SB, respectively. Yoshihara and Furushima [28] indicated that when the ratio of actual shear stress to bending stress is larger than the ratio of the allowable shear stress to the allowable bending stress, a timber specimen would easily fail by shearing. As the experimental results show that the specimens tested under ABS has almost double τ/σ_c ratio than that of specimens tested under SB, this suggests that the ABS test method is more effective in inducing shear failure on fibre composite sandwich structures than SB and can be used more reliably to evaluate the shear strength of sandwich beams. This is due to the lower bending moment experienced by the ABS than SB beams. As indicated in Figure 1, the bending moment for ABS specimens is only half that of SB.

Another important information that can be obtained from the τ/σ_c ratio is the possible type of failure that may occur on the sandwich structures. According to Sideridis and Papadopoulus [25], when the ratio of the allowable shear stress to that of allowable bending stress of the core is greater than τ/σ_c, shear failure is more likely to occur. On the other hand, the failure mechanism will more likely be dominated by flexural stress if this ratio is less than τ/σ_c. Using the material properties listed in Table 1, the ratio of the allowable shear stress to that of allowable flexural stress of the phenolic core is approximately 0.61. Referring to Fig. 8, this suggests that the failure of the fibre composite sandwich beams with a/D ratio of 1 tested under SB method and the sandwich beams with a/D ratio of 1 to 3 tested under ABS method is governed by shear failure of the core. This also follows that the flexural stress has a significant contribution on the failure behaviour of the fibre composite sandwich beams if the a/D ratio is greater than 1 for SB specimens and greater than 3 for ABS specimens.

6. Prediction of failure load for sandwich beams with different a/D ratios

The observed failure mode for fibre composite sandwich beams with short a/D ratio was a shear failure in the phenolic core material while for beams with higher a/D ratio was a combination of flexure and shear. Thus, the approach to estimate the failure load due to either shear or flexural failure only will not give reliable results. Awad *et al*. [30] highlighted that the available shear equations can be used only for sandwich beams with a/D less than 2 and the bending equation for beams with a/D greater than 4.5. However, there is still no reliable estimation method to predict the capacity of sandwich beams subjected to combined shear and bending or with a/D ratios between 2 and 4.5. In this section, simplified prediction equation to calculate the shear strength of the structural composite sandwich beams which accounts for the effect of a/D is proposed and comparison with the results of the experiments is conducted.

6.1 Proposed prediction equation

It is noted from experimental investigations that the failure of fibre composite sandwich beam tested under SB and ABS methods occurred under the loading point. In this location, the shear force and bending moment induced in the fibre composite sandwich beams are at their maximum values. Thus, although the shear stress is more dominant to cause failure, the flexural stress in the core is of considerable magnitude and should be accounted in the prediction of failure load. Under such condition, the phenolic core is subjected to a combined effect of the shear and flexural stresses. In this case, it may appear that a maximum stress criterion can be used in predicting failure of the fibre composite sandwich beam. In the proposed prediction equation, the failure of the composite sandwich beam is expected when the sum of the ratios of the actual shear and flexural stresses in the phenolic core material to that of the allowable stresses approaches unity and is given as Eq. (5). Similarly, a basic quadratic criterion approach of the interaction of the ratios of the actual to that of the allowable shear and bending stresses was considered as expressed in Eq. (6).

$$\frac{\tau_{act}}{\tau_{all}} + \frac{\sigma_{act}}{\sigma_{all}} = 1.0 \qquad (5)$$

$$\left(\frac{\tau_{act}}{\tau_{all}}\right)^2 + \left(\frac{\sigma_{act}}{\sigma_{all}}\right)^2 = 1.0 \qquad (6)$$

In these relations, τ_{act} and τ_{all} are the actual and allowable shear stresses of the phenolic core, respectively while the σ_{act} and σ_{all} are the actual and allowable bending stresses in the core, respectively. The allowable stresses of the phenolic core material are listed in Table 1 and the actual stresses τ_{act} and σ_{act} are calculated based on Eqs. (1) and (3), respectively. The predicted failure load of sandwich beams tested under SB and ABS methods which accounts for the combined effect of shear and flexural stresses are given in Eqs. (7) and (8), respectively for a linear prediction in Eq. (5) while the predicted failure load of the sandwich beams under SB and ABS methods for a quadratic criterion in Eq. (6) are given in Eqs. (9) and (10), respectively.

$$SB\_linear = \frac{1}{\left[\dfrac{1}{2D\tau_{all}\left(c+2t\, {G_s}/{G_c}\right)} + \dfrac{acE_c}{4EI\sigma_{all}}\right]} \tag{7}$$

$$ABS\_linear = \frac{1}{\left[\dfrac{1}{2D\tau_{all}\left(c+2t\, {G_s}/{G_c}\right)} + \dfrac{acE_c}{8EI\sigma_{all}}\right]} \tag{8}$$

$$SB\_quadratic = \sqrt{\frac{1}{\left[\left(\dfrac{1}{2D\tau_{all}\left(c+2t\, {G_s}/{G_c}\right)}\right)^2 + \left(\dfrac{acE_c}{4EI\sigma_{all}}\right)^2\right]}} \tag{9}$$

$$ABS\_quadratic = \sqrt{\frac{1}{\left[\left(\dfrac{1}{2D\tau_{all}\left(c+2t\, {G_s}/{G_c}\right)}\right)^2 + \left(\dfrac{acE_c}{8EI\sigma_{all}}\right)^2\right]}} \tag{10}$$

6.2 Predicted failure load and comparison with experiments

Table 4 summarises the predicted failure load of the fibre composite sandwich beams under SB and ABS methods and the percentage difference between the actual failure load is given in Table 3. Similarly, a comparison between the results of the theoretical prediction of the failure load of the structural fibre composite sandwich beams and the results of the experimental investigation are shown in Fig. 9. In the figure, *SB_exp* and *ABS_exp* correspond to the experimental failure load while *SB_linear*, *ABS_linear*, *SB_quadratic*, and *ABS_quadratic* correspond to the calculated failure load using Eqs. (7) to (10), respectively.

As can be seen from Table 4 and in Fig. 9a, a good agreement between the predicted failure load using the quadratic prediction given in Eq. (9) and that measured from the experiment was observed for sandwich beams tested under SB with a/D ratios of 2 to 6 but over predicts the failure load for sandwich beams with an a/D ratio of 1 by 28%. However, a good agreement between the predicted and the actual failure load for sandwich beams with an a/D ratio of 1 is attained using the linear relation in Eq. (7). For beams with a/D ratio of 2 to 6, using Eq. (7) conservatively predicts the failure load by 20 to 35%. This can be explained by the dominant stress existing in the sandwich beams which affects its failure mechanisms. As indicated in Section 5.6, the sandwich beam tested under SB and with an a/D ratio of 1 is more likely to fail by shear failure of the core as the ratio of the actual shear stress and bending stress is greater than the ratio of the allowable shear stress to that of allowable bending stress. On the other hand, the flexural stress is the more dominant stress to cause failure for sandwich beams with a/D ratios of 2 to 6. Thus, it can be concluded that a fibre composite sandwich beam tested under SB and fails in core shear can be accurately predicted using a linear interaction between the shear and bending stresses while the sandwich beam which is subjected to a higher bending stress than shear stress can be predicted reliably using a quadratic relation.

The predicted failure load based on the linear interaction of shear and bending stresses in Eq. (8) gives an only 5-11% lower than the actual failure load for sandwich beams tested under ABS method for all the investigated a/D ratios. On the other hand, the quadratic approach provides a far too high predicted load compared to the experimental values. Comparison showed that the difference between the predicted and actual failure load using Eq. (10) ranges from 13 to 26%. Fig. 9b further shows that the linear approach delivers a better fit of the experimental data than that of the quadratic relation of shear and bending stresses to specimens tested under ABS method.

The discrepancy between the predicted and actual failure load could be due to the actual dimensions of the sandwich beams and the material properties used in the prediction equation. In addition, the complex state of stress under the loading point where the failure initiated could not be accounted for in the proposed prediction equations. Moreover, the a/D ratios investigated in this study are considered by most researchers as the intermediate a/D ratios in which the behaviour is transitional, and the mode of failure can either be shear or flexure or a combination of both. Still the proposed prediction equations provided a conservative but reasonable estimation of the failure load of the fibre composite sandwich beams with different a/D ratios. The results further suggests that the shear strength of the fibre composite sandwich beam can be predicted accurately when all the materials in the beam section is converted into an equivalent core material using the shear moduli of the constituent materials. Similarly, the contribution of the shear and flexural stresses should be accounted for in the prediction of the failure load of the structural fibre composite sandwich beams.

7. Conclusions

The behaviour of structural fibre composite sandwich beams with different shear span-to-depth (a/D) ratios was evaluated using short beam (SB) and asymmetrical beams shear (ABS) test methods. The results showed that the shear strength of the fibre composite sandwich beams is affected strongly by the a/D ratios. The beams with lower a/D ratio failed at a higher load compare to the beams with larger a/D ratio. The shear strength of the sandwich beams decreases with increasing a/D ratios. On the contrary, the flexural stress increases with increasing a/D ratio. In general, the shear strength of the sandwich beams tested under ABS is significantly higher than that of the sandwich beams tested under SB for the same a/D ratio. The results also showed that the behaviour of the fibre composite sandwich beam is governed by the strength of the phenolic core material. In all the tested sandwich beams, the failure of the core occurred under the loading point where the shear force and bending moment are maximum. The fibre composite sandwich beams with lower a/D ratio failed due to shear failure of the core while the beams with a larger a/D ratio failed due to core shear with some initiation of compressive failure of the skin. Analysis showed that the shear stress in the core is more dominant than flexural stress when the a/D ratio is 1 for beams tested under SB and 1 to 3 for beams tested under ABS.

The proposed equation accounting for the combined effect of shear and flexural stresses in a sandwich beam section reasonably predicted the failure load of the fibre composite sandwich beams. Comparison showed that the predicted failure load agreed well with the experimental results. The predicted failure load is only 5-11% lower than the actual failure load for specimens tested under ABS method using the linear relationship between the shear and bending stresses. The proposed linear approach can also predict accurately the failure load of the sandwich beams tested under SB with a/D ratios of 1 and 2 but the quadratic interaction between the shear and bending stresses gives a better prediction of the failure load for beams with a/D ratio of 3 to 6. Further, the analysis showed that the shear strength of a structural composite sandwich beam can be reliably estimated when all the materials are transformed into an equivalent area based on the shear properties of the constituent materials. However, the results of this study can be limited only to fibre composite sandwich structures with a high strength core material. Further investigation is warranted for its practical applications in sandwich structures with other core material systems.

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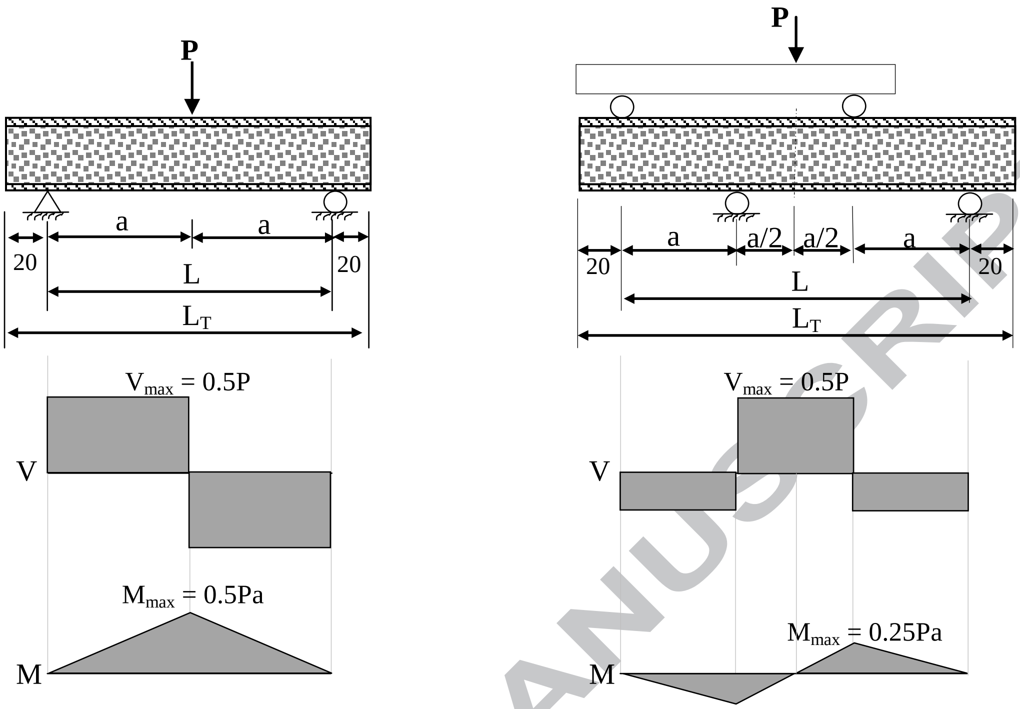
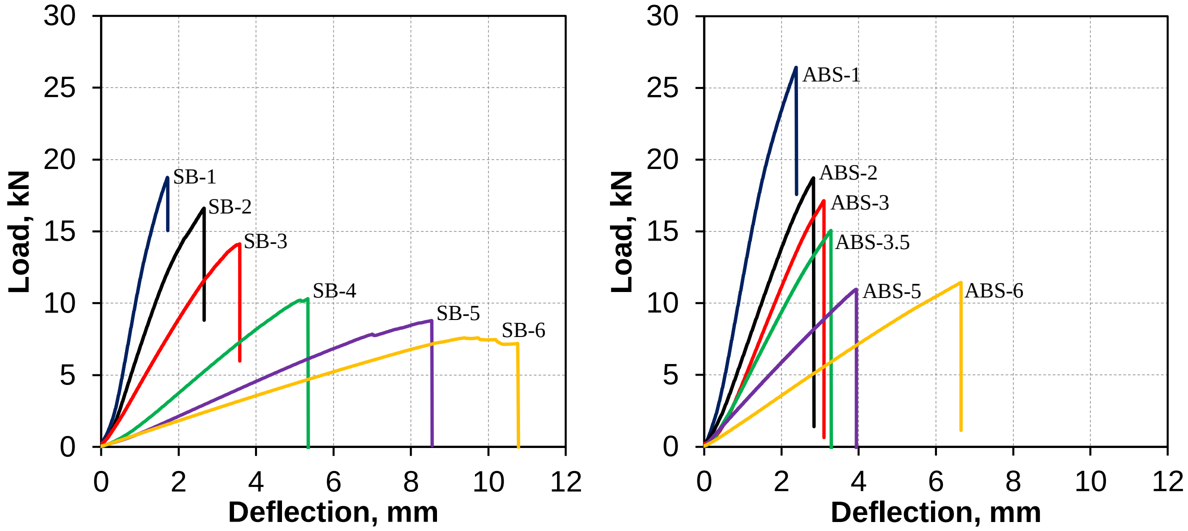


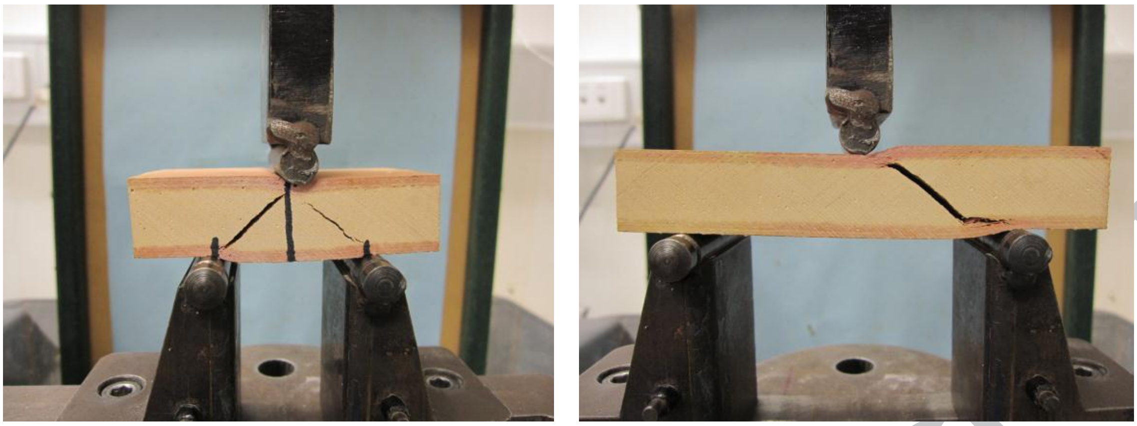
(a) SB test (b) ABS test

Figure 1. Test set-up, shear and moment diagrams

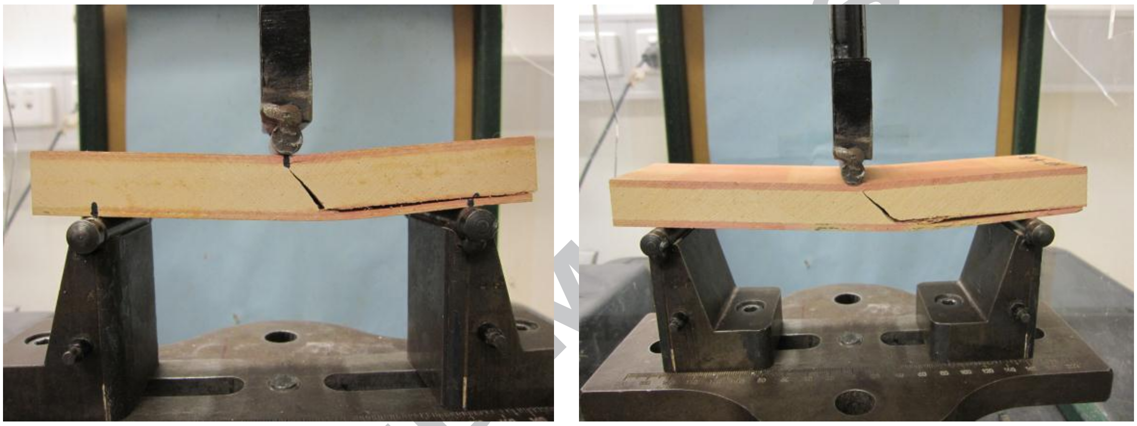


(a) SB (b) ABS

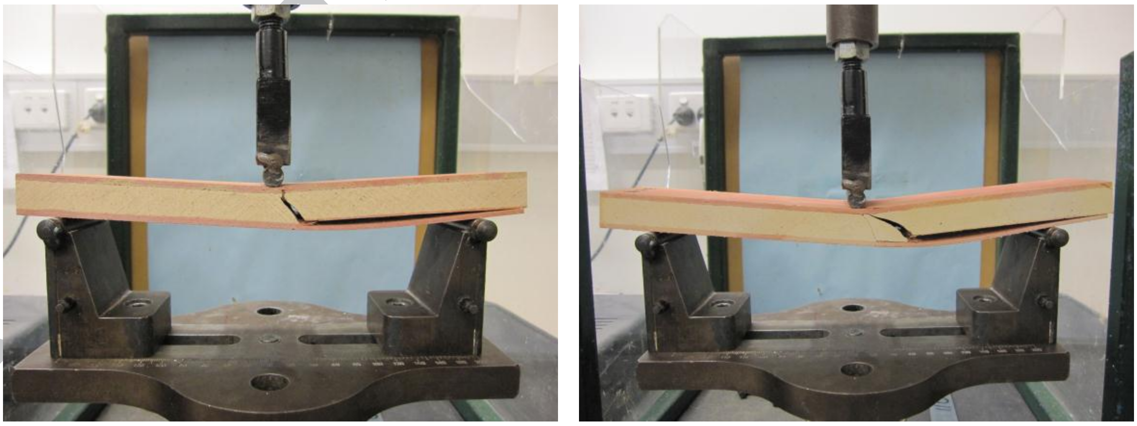
Figure 2. Load and crosshead relation curve of the sandwich beams



(a) a/D = 1 (b) a/D = 2

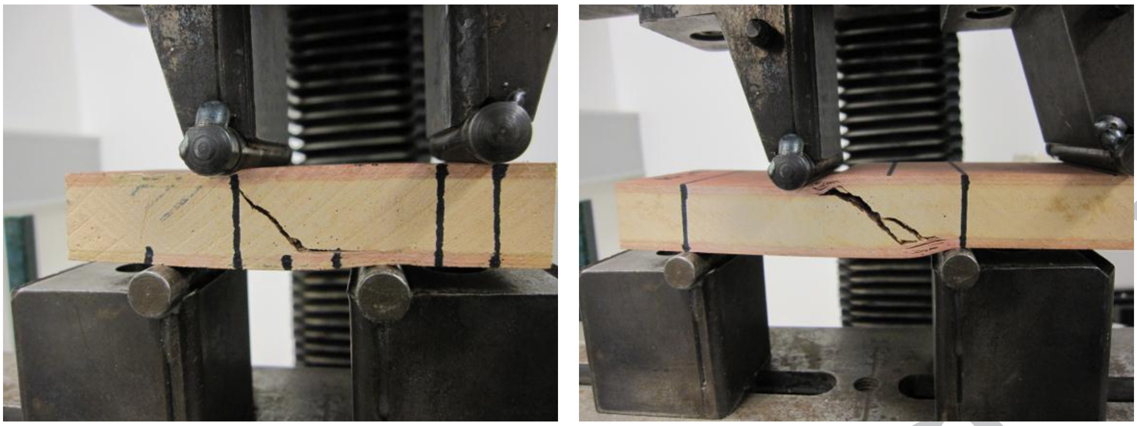


(c) a/D = 3 (d) a/D = 4



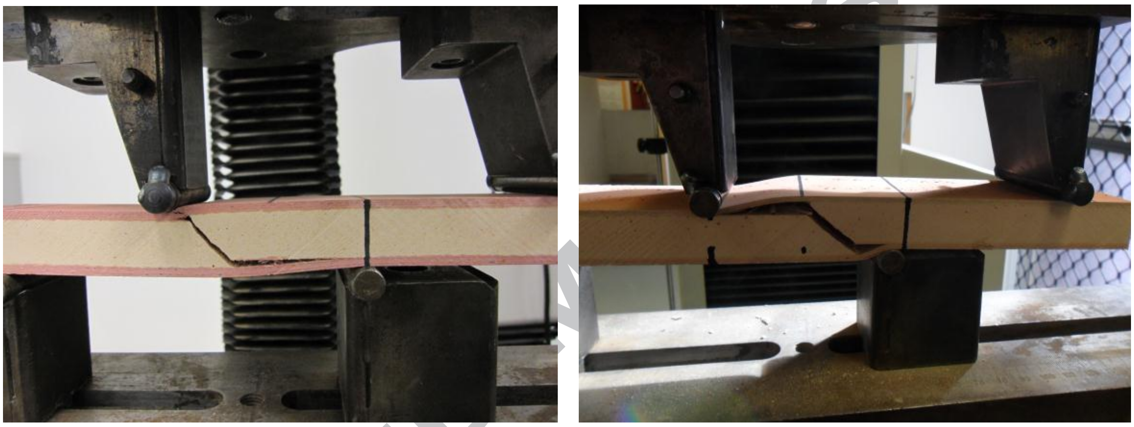
(e) a/D = 5 (f) a/D = 6

Figure 3. Failure behaviour of sandwich beams tested under SB method



(a) a/D = 1

(b) a/D = 2



(c) a/D = 3

(d) a/D = 3.5

(e) a/D = 5

(f) a/D = 6

Figure 4. Failure behaviour of sandwich beams tested under ABS method

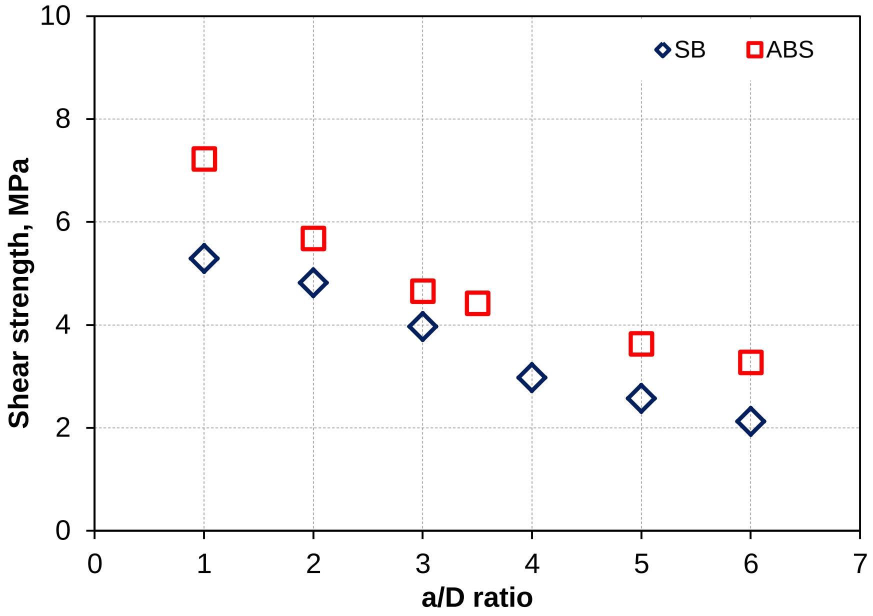
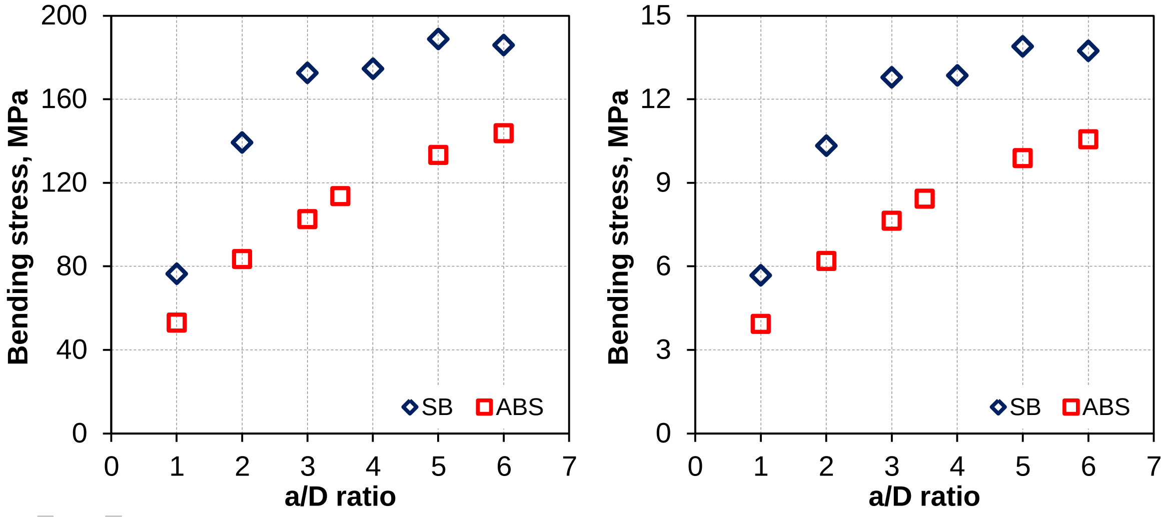


Figure 5. Average shear stress of the sandwich beam with different a/D ratios



(a) Skin

(b) core

Figure 6. Bending stress in the sandwich beams with different a/D ratios

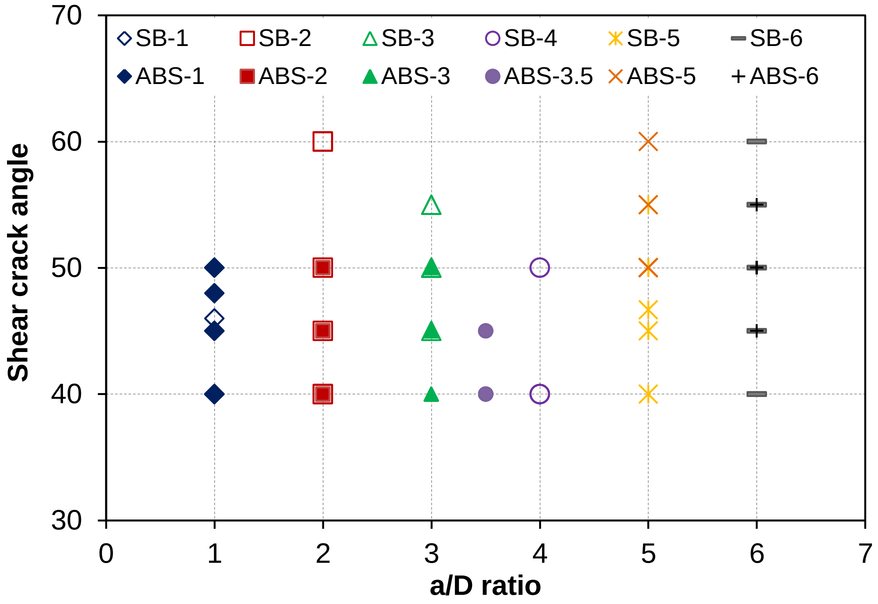


Figure 7. Shear crack angle on the core for different a/D ratios

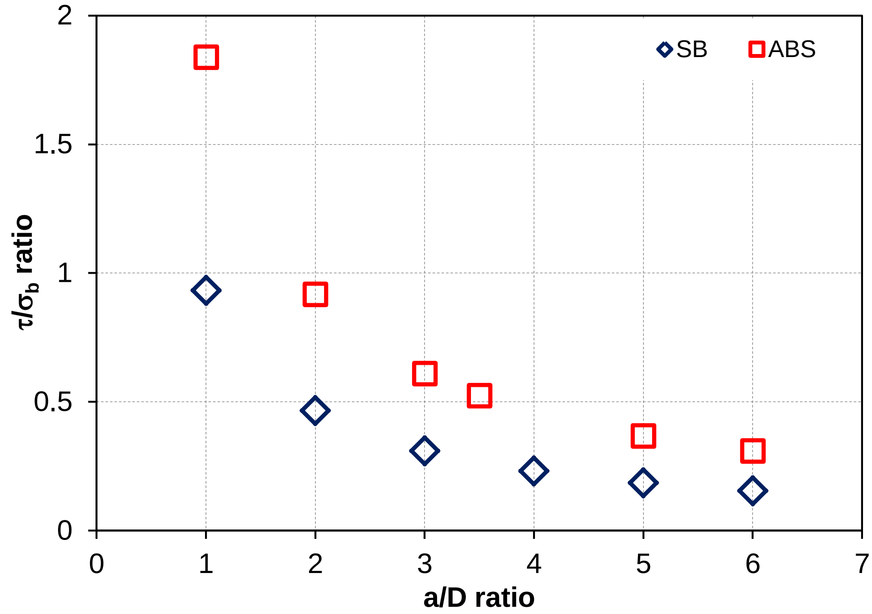
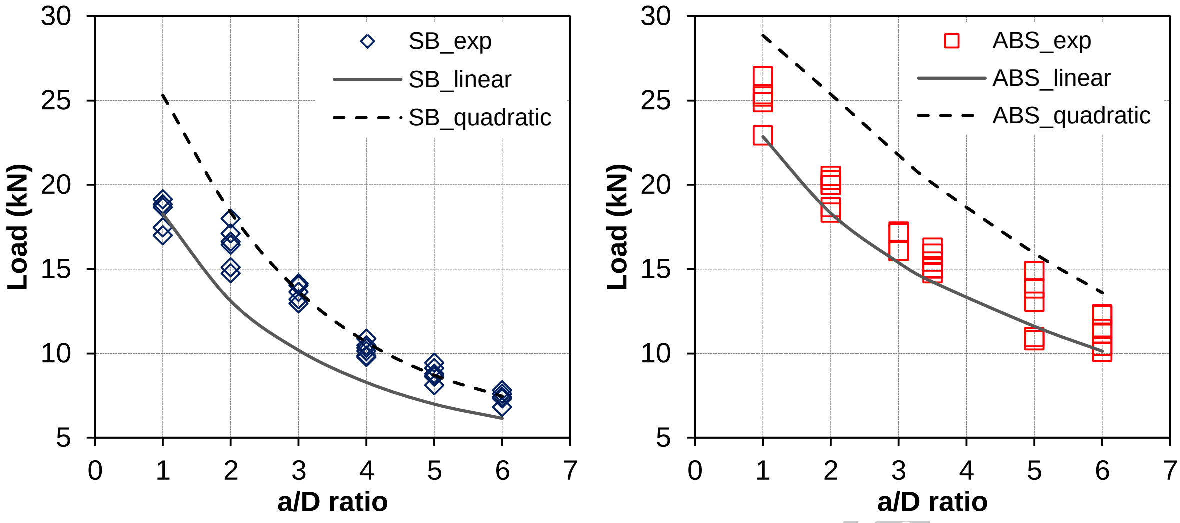


Figure 8. Ratio of shear stress to bending stress in the core with different a/D



(a) SB method (b) ABS method

Figure 9. Comparison of predicted and actual failure load

Table 1. Mechanical properties of the skin and core of the composite sandwich panel

Test	Test standard	Property	Skin	Core
Flexure	ISO 14125 [19]	Modulus (GPa)	12.82	1.32
		Peak stress (MPa)	317.37	14.32
Tensile	ISO 527-1 [20] - skin	Modulus (MPa)	15.38	1.03
	ASTM D638 [21] - core	Peak stress (MPa)	246.80	5.97
		Poisson's ratio	0.25	0.29
Compression	ISO 14126 [22] – skin	Modulus (MPa)	16.10	1.35
	ASTM C365 [23] - core	Peak stress (MPa)	194.77	22.99
Shear	ASTM5379 [15]	Modulus (MPa)	2.47	0.53
		Peak stress (MPa)	23.19	8.80

Table 2. Description of test specimens

Shear span-to-depth, a/D ratio	Shear span (a), mm	Total span (L_T), mm	
		SB	ABS
1	20	80	100
2	40	120	160
3	60	160	220
3.5	70	--	250
4	80	200	--
5	100	240	340
6	120	280	400

Table 3. Failure load of composite sandwich beams under SB and ABS test methods.

a/D ratio	SB (kN)		ABS (kN)	
	Peak load	Std. deviation	Peak load	Std. deviation
1	18.22	0.93	24.97	1.28
2	16.65	1.05	19.63	0.90
3	13.69	0.51	16.17	1.15
3.5	--	--	15.41	0.58
4	10.23	0.41	--	--
5	8.83	0.45	12.71	0.80
6	7.38	0.33	11.29	0.69

Table 4. Predicted failure load and difference with the actual failure load.

a/D ratio	SB (kN)				ABS (kN)			
	Eq. [7]	% diff.	Eq. [9]	% diff.	Eq. [8]	% diff.	Eq. [10]	% diff.
1	18.27	0.3	25.31	28.0	22.85	-9.2	28.86	13.5
2	13.11	-27.1	18.37	9.36	18.32	-7.1	25.37	22.6
3	10.19	-34.4	13.68	0.1	15.38	-5.1	21.57	25.7
3.5	--	--	--	--	14.24	-8.2	20.09	23.3
4	8.28	-23.6	10.67	4.0	--	--	--	--
5	6.99	-26.3	8.71	-1.4	11.61	-9.4	15.94	20.3
6	6.14	-20.1	7.46	1.1	10.13	-11.4	13.60	17.0