THROUG-THICKNESS SHEAR TESTING OF DIVINYCELL H130 FOAM

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ABSTRACT

Three different experimental techniques for measuring through-thickness shear stiffness and shear strength of foam core materials are compared through experiments with a 30 mm thick PVC foam core (Divinycell H130).

With the direct shear method (ASTM C 273) a prismatic core specimen is loaded along a diagonal plane by steel adherents adhesively bonded to the core. Thin adherents lead to high peel stresses, and thick adherents are not practical to handle during bonding. An approach is thus proposed, where thin adherents are bonded to the core and subsequently attached to thick adherents with bolts. Box beams of 100 mm by 100 mm and 8 mm flanges combined with 17 mm adherents proved adequate to measure both stiffness and strength.

A nearly pure shear stress is obtained in a region between two 90° notches of the Iosipescu specimen from the v-notched beam method (ASTM D 5379) and of the specimen from the V-notched rail shear method (ASTM D 7078). Iosipescu specimens can be cut directly from a 30 mm thick core but require tabs. The V-notched rail specimens were bonded from three parts arranged in two different configurations. An optical approach was used to measure the shear strain field. The Iosipescu specimen and one of the V-notched rail specimen configurations were found adequate to measure strength, whereas the optical approach needs refinement to reduce the scatter in the measured stiffness.

1. INTRODUCTION

Sandwich structures with thin, strong skin layers on both sides of a thick, compliant and light core combine low weight, high bending stiffness, high strength and high buckling resistance. These structures find use in many applications such as aircraft, marine applications and wind turbine blades. When used for wind turbine blades the sandwich structures are mainly made from FRP laminate skins and foam or balsa core. The shear properties of such sandwich shells are important design parameters.

The shear stiffness of the core influences the deflections of the shell and the shear strength of the core may be limiting for the bending strength of the sandwich. The through-thickness shear stiffness and strength of a core material can be measured in bending, in direct shear or shear of a V-notched specimen. The bending test involves 3- or 4-point-bending of a sandwich beam, where the span and the skin configuration are chosen in a way to ensure shear failure of the core.

With the direct shear test a core or a sandwich structure is adhesively bonded to two steel adherents loaded in tension. The adherents should be sufficiently stiff in order to obtain a stress state of (nearly) pure shear in the core. According to ASTM C 273 an adherent bending stiffness of at least 2.67 MN per mm thickness of the core is recommended. For a 30 mm thick core for example the steel adherent thickness should thus be at least 17 mm. For high density foams the ASTM lower stiffness limit of 2.67 MN per mm thickness is too low to get adequate results as reported by Olsson and Lönnö [1]. Instead they used 50 mm thick steel adherents for 25 mm thick foam specimens.

The V-notched specimens are loaded either at the top and bottom or at the sides in order to achieve a stress state of (nearly) pure shear in a volume between the notches.

One type of V-notched specimen has been used in the Arcan fixture to test PVC foam as reported by Deshpande and Fleck [2] as well as Gdoutos et al. [3]. In one case [2] the shear strains were obtained from a strain gauge rosette glued onto the foam specimen. It was suspected that the strain gauge stiffened the (Divinycell H100) foam locally resulting in artificially high stiffness measurement. The Iosipescu specimen is commonly used for fiber composite materials with the V-notched beam method (ASTM D 5379) and features a relatively low distance of 12 mm between the notches. The V-notched rail shear method (ASTM D 7078) uses a larger specimen with a distance between the notches of 31 mm.

In the present study the influence from direct shear adherent design on shear stiffness and strength is investigated for 30 mm thick Divinycell H130 PVC foam and a number of adherent configurations. The direct shear results in terms of G modulus, shear strength and failure mode are an extension of previous work [4], and are compared to results on H130 obtained from Iosipescu specimens as well as V-notched rail shear specimens.

The need for sufficiently stiff adherents [1] may lead to heavy parts that are impractical to handle during bonding. One way to overcome this [4] is to bond relatively thin 17 mm steel adherents to both sides of the foam specimen and subsequently bolt the 17 mm adherents to two 50 mm adherents.

The bonding procedure was improved compared to the previous work [4] and (new) results are presented for: 17 mm adherents, 50 mm adherents and 50+17 mm adherents. Results are also presented for adherents consisting of a relatively light and very stiff box beams bolted to 17 mm adherents (box+17 mm).

The V-notched beam method and the V-notched rail shear method have the potential of measuring the shear stiffness and strength with much smaller specimens and lighter fixtures. Iosipescu specimens can be cut directly from a 30 mm thick core but require tabs. The V-notched rail specimens were bonded from three parts arranged in two different configurations. An optical approach was used to measure the shear strain field.

2. EXPERIMENTS

30 mm thick Divinycell H130 foam (nominal density 130 kg/m^3) was tested with four different direct shear configurations, one Iosipescu configuration and two V-notched shear configurations. Two different H130 plates were used – the first plate (density around 126 kg/m^3) was used for the direct shear specimens and the Iosipescu specimens and the second plate (density around 113 kg/m^3) was used for the V-notched rail shear specimens.

2.1 Direct shear

The four different direct shear configurations (17 mm, 50 mm, 50+17 mm and box+17 mm) are shown in Figure 1 (centre and right). The 17 mm and 50 mm steel adherents had a width of 80 mm and the length of the different parts of the adherents is seen from Figure 1 (centre). The steel box beams were 500 mm long, 100 mm by 100 mm in cross-section and with a flange thickness of 8 mm.

Before bonding the steel parts were ground by hand with grit 60 paper and wiped with acetone (in the previous work [4] the steel parts were sand blasted with glass particles and subsequently wiped with ethanol). The epoxy adhesive 3M ™ 2216 B/A Grey Scotch-Weld™ was used for bonding of the steel adherents to the foam and cured at 40° C for 16 hours.

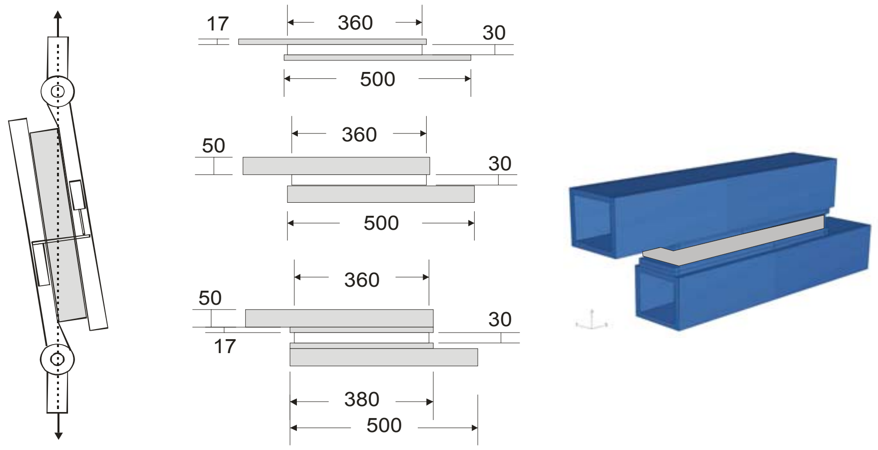

Figure 1: Direct shear through the diagonal (left) was performed with different solid adherent geometries (centre) as well as with box+17 mm steel adherents (right). From top to bottom the 17 mm, the 50 mm and the 50+17 mm adherents are shown (centre).

Each 17 mm steel plate of the 50+17 mm and the box+17 mm adherents was bolted to a 50 mm plate and a box beam, respectively, with 11 bolts (M12) with a tightening torque of 100 Nm. The adherents were fixed to the test machine with L-shaped steel parts and eyebolts (M24×2 with a spherical Ø25 bearing.) as seen from Figure 2.

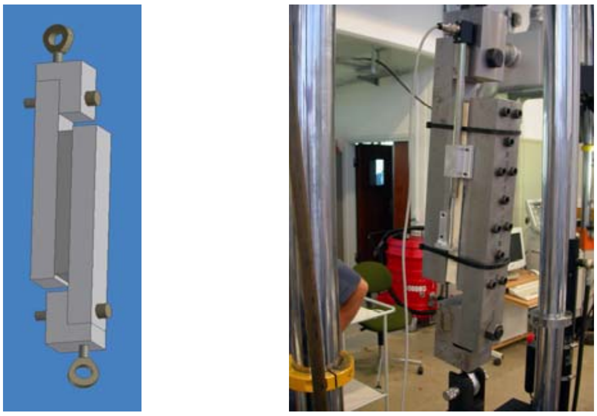

Figure 2: The experimental set-ups: (left) the 17 mm adherents; (right) the 51+17 mm combined adherents joined with 11 bolts and instrumented with an LVDT. The plastic strips hold the lower part of the fixture in place in case of separation of core or adhesive.

The tensile testing was performed on a servo-hydraulic testing machine (Instron 8842) with a ±100 kN load cell (UK054).The testing machine was operated in displacement control at 2 mm/min with a data acquisition rate of 10 Hz. The displacement of the (inner) adherents was measured by an LVDT (Figure 1 (left) and Figure 2 (right)).

2.2 Iosipescu shear

The Iosipescu specimen dimensions are shown in Figure 3 together with the loading rig. The glass/epoxy tabs were bonded with cyano acrylate adhesive to both major sides of the specimen.

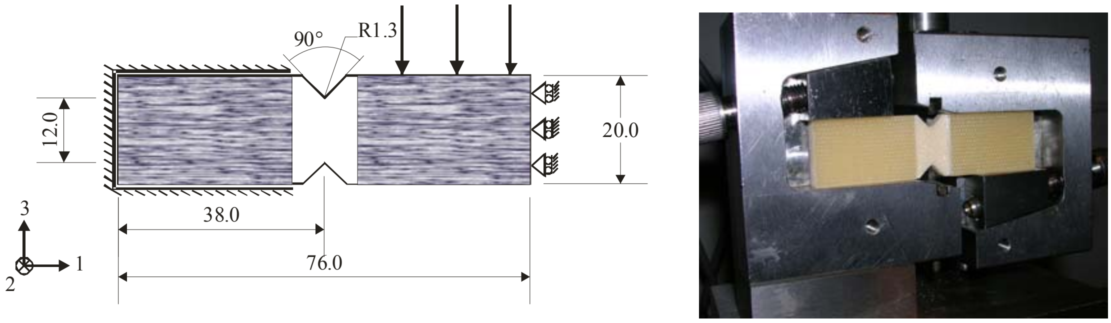

Figure 3: V-notched beam (Iosipescu) specimen with 2 mm thick glass/epoxy tabs: dimension (left) and loading rig (right).

Eight specimens were tested in all: three without strain measurement, one with a ±45° strain gauge (HBM 1-XY21-1.5/350) mounted at the centre of the major faces (front and back) and four were prepared for optical strain measurement.

The strain gauges mounted on the fourth specimen measured unrealistically low strain values. It was concluded that the high stiffness of the strain gauge adhesive influences the stiffness locally similar to the observations made by Deshpande and Fleck [2].

The last four specimens were ground with grit 320 paper on both major sides before bonding of tabs. Subsequently white paint and then black paint was sprayed on the front side of the foam to create black dots on a white background.

All specimens were tested by compression of the loading rig performed on testing machines with a 500 N load cell and operated in displacement control at 1 mm/min with a data acquisition rate of 10 Hz.

For the optical strain measurements a Nikon D200 (10 mega pixels) camera was used with a 60 mm macro lens positioned 185 mm from the specimen. During loading photographs were taken with 3 s intervals, and since the specimens did not fail, they were loaded until the right-hand part of the specimen made hard contact with the stationary (left-hand) part of the fixture.

2.3 V-notched rail shear

The initial designs for the V-notched rail specimens are seen in Figure 4. In order to attach the foam specimens to the loading fixture parts two 8 mm steel adherents are bonded to the ends of the specimen. Since the foam specimen is 60 mm by 56 mm a through-thickness specimen can not be cut out in one piece of a 30 mm thick foam plate. To overcome this problem three foam pieces (length 70 mm, width 40 mm and thickness 30 mm) were bonded top to bottom with an epoxy adhesive (3M™ DP-460 Off-White Scotch-Weld™). This assembly can be oriented in two ways: with the adhesive bonds parallel to the loading direction (Figure 4 (centre)) or with the adhesive bonds perpendicular to the loading direction (Figure 4 (right)). The thickness direction of the foam plate is indicated by the 3-direction in the coordinate systems of Figure 4.

An initial test revealed a problem with the intended design of the V-notched rail shear fixture. As seen from Figure 5 the specimen failed by propagation of a crack starting at the lower right corner. This corner (as well as the upper left corner) will “open up” during loading and give rise to high peel stresses at the foam/steel bonds near these corners.

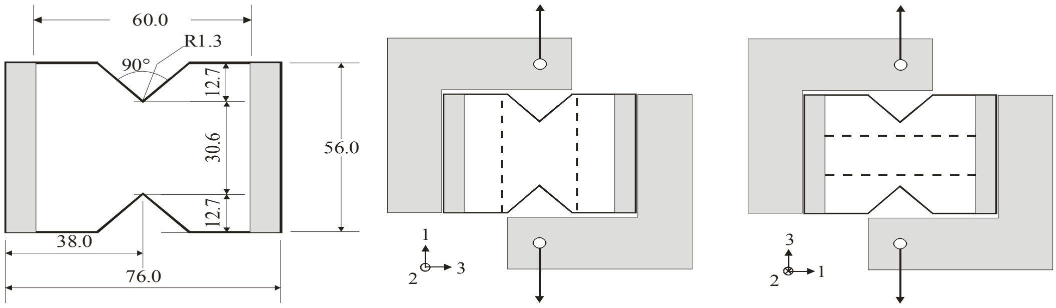

Figure 4: Geometry of V-notched rail shear specimen consisting of a foam part with two steel adherents bonded to the ends (left). The foam part is made by bonding (dotted lines) of three layers of foam. The centre version and the right-hand versions have the foam/foam adhesive layers parallel (||) and perpendicular (⊤) to the loading direction, respectively.

Figure 5: Initial tested V-notched rail shear specimen fractured at one of the corners (bottom right) with high peel stresses.

Before bonding of the L-shaped adherents the specimens were ground on the major faces with grit 320 paper. Subsequently white paint and then black paint was sprayed on one of the major sides to create black dots on a white background. Four specimens of type || and ⊤ (Figure 4) were prepared.

The specimens were attached to the fixture shown in Figure 5 with M8 bolts (Figure 6). The fixture was in turn attached to the testing machine with two M16×2 eyebolts with spherical Ø12 bearings (Figure 5).

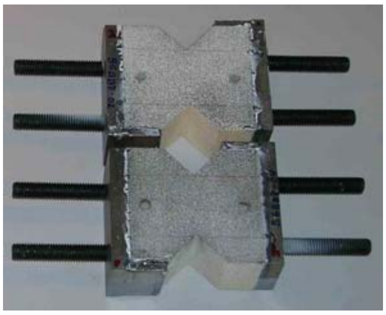

Figure 6: Two specimens with L-shaped adherents and bolts (M8) for attachment to the fixture. Two holes were made in each specimen in order to clamp the bonded foam assembly and machine all edges in one operation.

The tensile loading of the fixture was performed on an Instron 8874 with a 10 kN load cell operated in displacement control at 2 mm/min with a data acquisition rate of 10 Hz. A Nikon D200 was used during loading to take photographs of the sprayed area with 3 s intervals. The start of loading was synchronized with the start of the photograph recordings. The camera was equipped with an 18-200 mm zoom lens (set to 135 mm) positioned 280 mm from the specimen. The specimens were loaded to failure.

2.4 Optical strain measurements

The images taken during the testing with the Nikon D200 camera were analysed with the software package ARAMIS v.6.0.2-6 from GOM mbH (Germany). The analysis was performed for 2D images without calibration. The missing calibration of the distances in the images is not a problem for the computation of strains. The facet size was chosen to 40 pixels by 40 pixels with a facet step of 38 pixels – i.e. 2 pixels overlap between facets.

The shear strains were computed along 3 lines (sections) connecting the two notches of the specimens. Examples of sections are given for the Iosipescu specimens in Figure 7 and for the V- notched rail shear specimens in Figure 8. The strain data for each image is exported from the ARAMIS software to be analysed together with the time and load data obtained from the test machine data acquisition.

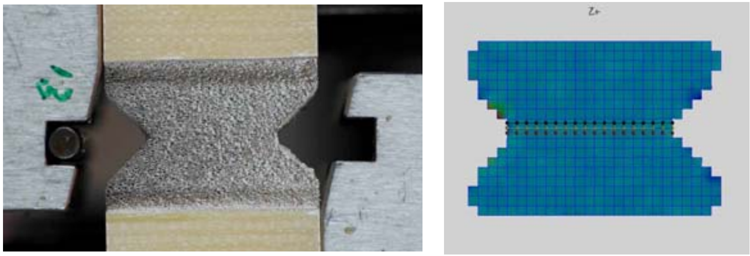

Figure 7: Iosipescu specimen: specimen with black dots (left), and ARAMIS sections defined (right).

3. RESULTS AND DISCUSSION

3.1 Data reduction

The strains reported are the engineering shear strains.

For the direct shear tests, the shear stress, τ, was calculated as the load divided by the cross-section area of the foam specimen (L×W), and the shear strain, γ, was calculated as the displacement of the adherents divided by the thickness of the foam specimen. The shear modulus, G, was calculated as the slope of the least square fit line of the (γ , τ) curve between 0.1 and 0.6% strain.

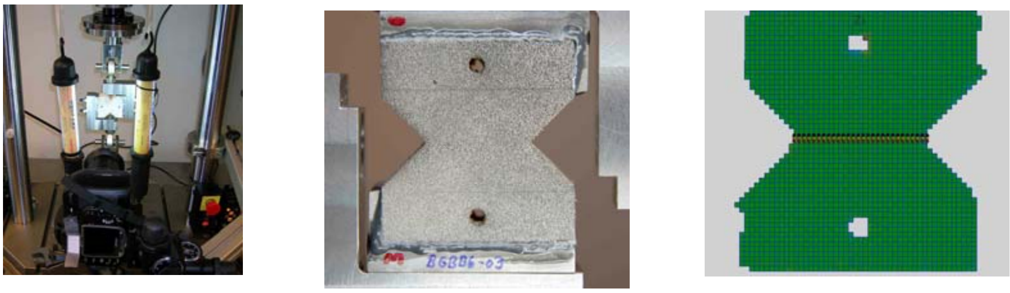

Figure 8: V-notched rail shear specimen: experimental set-up (left), specimen with black dots (centre), and ARAMIS sections defined (right).

For the Iosipescu and the V-notched rail tests, the shear strain was calculated from the image analysis as the average for the three sections of all strains along the centre part (between the quarterpoints) between the notches. For each image a shear strain was calculated and paired with the shear stress recorded at the same point in time by the test machine data acquisition. The shear stress was calculated as the load divided by the cross-section area of the foam specimen between the notches (W× T). The shear modulus, G, was calculated as the slope of the least square fit line of the (γ, τ) curve between 0.1 and 0.7% strain. The reason for the larger interval compared with the direct shear tests is that too few sets of time and strain are recorded below 0.6% strain in order to calculate the G modulus with the used combination of cross-head velocity and image frequency.

The ultimate stress (τ^u) and the ultimate strain (γ^u) were calculated as the stress and the strain, respectively, at fracture – both for the direct shear specimens and the notched specimens.

3.2 Results

The stress-strain curves of the four direct shear configurations are given in Figure 9. A low scatter is noticed for the box+17 mm and for the three valid curves for 50 mm. For the notched specimens the stress-strain curves based on image analysis are given in Figure 10. One typical curve is plotted in Figure 11 for each direct shear configuration and for each type of notched specimen.

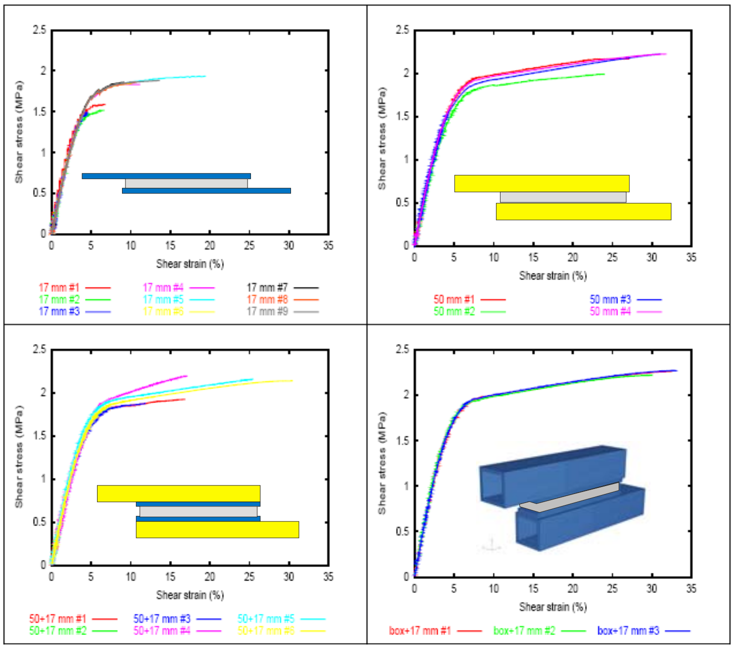

Figure 9: Shear stress versus shear strain for the direct shear configurations 17 mm (upper left), 50 mm (upper right), 50+17 mm (lower left) and box+17 mm (lower right).

Table 1 lists the results for all specimen types in terms of average ± one standard deviation for the foam density, the G modulus, the shear stress at peak load and the shear strain at peak load. The last two lines (Source DIAB) quote the datasheet values for H100 and H130.

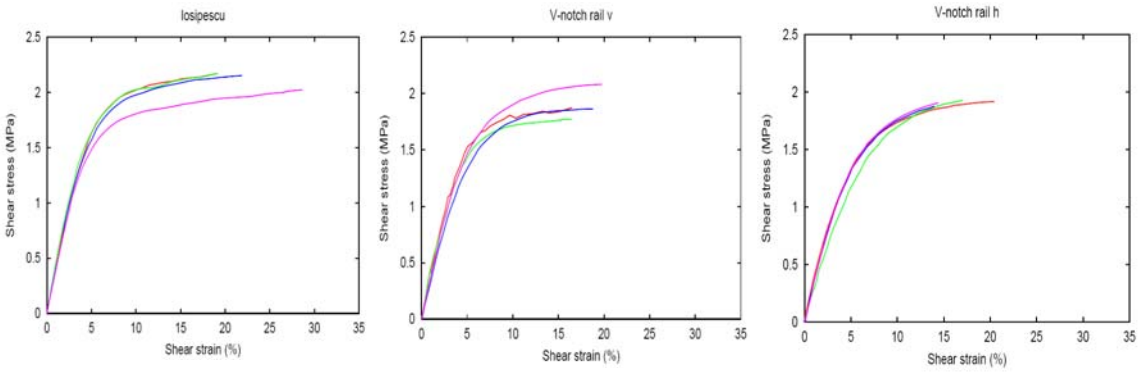

Figure 10: Shear stress-strain curves based on strain from image analysis for Iosipescu specimens (left) and for V-notched rail shear specimens of type || (centre) and ┬ (right).

The stress at peak load for the Iosipescu specimens is based exclusively on the four specimens without strain measurements, which failed during loading. The G modulus, on the other hand, is based exclusively on the four last specimens with image analysis.

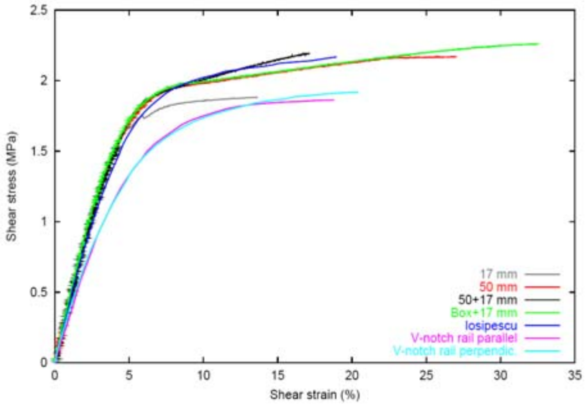

Figure 11: Comparison between typical stress-strain curves for the different direct shear configurations, Iosipescu and the V-notched rail types || and ┬.

Typical failure modes are shown in Figure 12 for the direct shear, Iosipescu and V-notched rail specimens. All failure modes are acceptable except for the V-notched rail shear specimens with a crack starting outside the gauge area at the short end of one of the L-shaped adherents.

Table 1. Results for all tested specimens in terms of average ± one standard deviation. The results are based on the number of specimens quoted in parenthesis under Source.

Source	Adherent thickness (mm)	Density (kg/m^3)	G * 0.1-0.6 % (MPa)	Stress at peak load (MPa)	Strain at peak load (%)
Direct shear (6)	17	126 ± 1	47.1 ± 0.6	1.87 ± 0.04	12 ± 4
Direct shear (3)	50	126 ± 1	45.2 ± 1.8	2.21 ± 0.03	30 ± 3
Direct shear (3)	50+17	125 ± 1	48.0 ± 5.9	2.16 ± 0.03	25 ± 7
Direct shear (3)	box+17	125 ± 1	47.2 ± 1.1	2.25 ± 0.03	32 ± 2
Iosipescu (8)	-	127 ± 3	41.8 ± 4.4	2.32 ± 0.17	-
V-notch rail ‖ (4)	8	113 ± 3	44.0 ± 9.1	1.90 ± 0.13	18 ± 2
V-notch rail ┬ (4)	8	113 ± 3	35.8 ± 5.8	1.91 ± 0.02	17 ± 3
DIAB	-	100	35	1.6	40
DIAB	-	130	50	2.2	40

*) An interval of 0.1-0.7% was used for Iosipescu, V-notch rail ‖ and V-notch rail ┬.

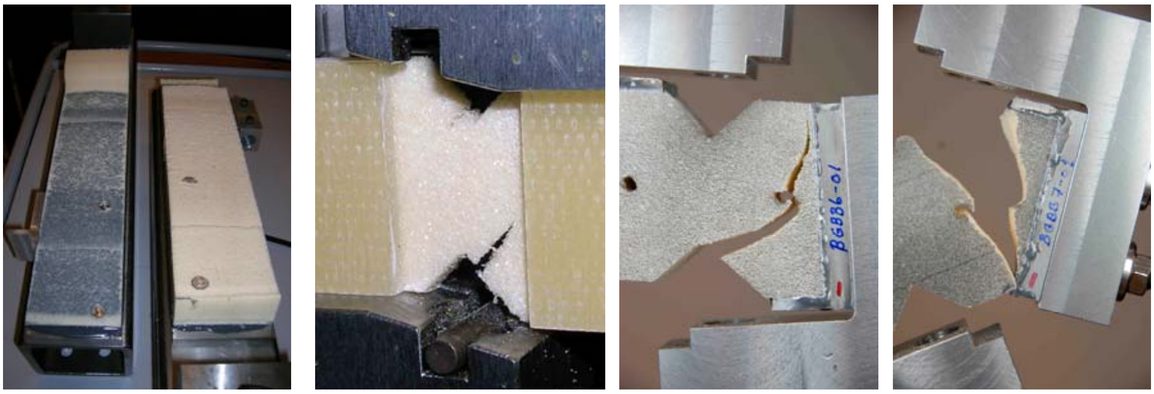

Figure 12: Typical failure modes (from left to right) of direct shear specimens with a crack running in the foam close to the adhesive layer, the Iosipescu cracks at the notches, the V-notched rail shear of type || with a crack from the notch and past a hole; and the notched rail shear of type ┬ with an unacceptable crack starting at the short end of one of the L- shaped adherents.

6. SUMMARY AND CONCLUSIONS

Direct shear

- 17 mm steel adherents are suited for stiffness measurements, but should not be used to measure strength.
- 50 mm steel adherents are suited for stiffness and strength measurements.
- Stiffness and strength can also be measured with combined adherents, where 17 mm adherents are bonded to the core specimen and subsequently joined to 50 mm adherents or 100 mm wide box beams. Here only 17 mm adherents need to be bonded (and subsequently cleaned) and only one set of heavy adherents is needed.

Notched specimens

- The V-notched rail shear specimens with adhesive bonds perpendicular to the loading direction fail in an unacceptable manner and need to be redesigned.
- Acceptable strength values and failure modes are obtained for the Iosipescu specimen and the V-notched rail shear specimens with adhesive bonds parallel to the loading direction.
- The measured shear stiffness for these two types of specimens has a somewhat high scatter, and the digital image correlation technique needs to be refined.

Final remarks

- Large specimens (length equal to 12 times thickness) are needed for direct shear together with heavy adherents.
- Stiffness and strength can be measured for large specimens by direct shear with very stiff adherents. Large specimens may be an advantage in cases where the specimens are not homogeneous and have a large-scale repeatable pattern.
- If the specimens are homogeneous such as H130 foam specimens smaller notched specimens can be used to measure the through-thickness shear strength. With an improved digital image correlation technique the notched specimens can also provide stiffness measurements.

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