EXAMINATION OF SANDWICH MATERIALS USING AIR-COUPLED ULTRASONICS

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Abstract: The air-coupled ultrasonic techniques have been improved drastically in recent years. Better equipment has made this technique much more useful.
This paper focuses on the examination of sandwich materials used in naval ships. It is more convenient to be able to make the measurements directly in atmospheric air instead of using immersion technique. The air-coupled techniques have been used in through-transmission mode using separate sender and receiver transducer. The frequency was either 50 kHz or 120 kHz. Laboratory tests on glass fibre/PVC foam core sandwich panels showed that debonds between core and skin laminate could be found by the air-coupled technique.
It was therefore decided to use this technique in-situ during mechanical testing of sandwich panels. These tests were done in order to verify a developed FEM code using interfacial fracture mechanics and illustrated on a superstructure/deck debond in a representative sandwich panel. The purpose of the ultrasonic scanning was to detect the actual crack front, which can be difficult to detect otherwise.
The described ultrasonic set-up has shown to be a reliable technique for measuring crack propagation and it has been successfully used in verifying the model for crack propagation. The techniques work best for core densities of 130 kg/m^3 and 200 kg/m^3. For 80 kg/m^3 the damping of the ultrasonic waves is higher resulting in less well-defined crack detection.

Introduction: The presented work in this paper follows as an extension to Berggreen et al. (2003), where a similar crack problem was studied using two independent numerical methods. Furthermore this work is performed within an international project called saNDI (Inspection and Repair of Sandwich Structures in Naval Ships). One of the aims in this project is to predict the residual strength in sandwich materials and to predict the damage tolerance.
For this purpose a series of beam tests were planned. During these tests a crack was initiated between the foam core and the glass fibre skin laminate. In order to follow the crack propagation the ultrasonic air-coupled scanning technique was applied.
The crack propagation can also be measured by visual inspection on the side of the panel, but the ultrasonic method is more reliable since it can be difficult to see the crack visually and the crack front is not necessarily a straight line.

Results: Specifications of the tested sandwich specimens: In total 10 specimens were produced using 3 core densities:

- H80 (80 kg/m^3): 4 specimens
- H130 (130 kg/m^3): 3 specimens
- H200 (200 kg/m^3): 3 specimens

The face consists of hand lay-up quadro-axial glass fibre mats of the type DBLT-1150 surrounded by two CSM450 chopped strand mats, similar to the configuration used in many naval vessels. The resin is polyester and the total thickness is about 4.5 mm.
The core thickness is 50 mm. The core material is Divinycell PVC structural foam.

Description of test procedure: The idea was to measure the crack front at different stages during the loading of the panels. Typically, a scanning was made each time the crack propagation increased approximately 50 mm. It is important to know the exact position of the scanner relative to the panel. Therefore, a reference scan was made for each panel test. This scan was made with an aluminium bar placed above the panel. The bar gives a clear indication on the ultrasonic scan and can be used as an absolute reference for measurements in the direction of the crack propagation.

<u>Description of ultrasonic equipment and setup:</u> The ultrasonic in-situ scanning system is based on the air-coupled system Airtech 2400 from Ingenieurburo Dr. Wolfgang Hillger in Germany. More information can be found in Hillger (2000). The main advantage of this equipment compared to conventional ultrasonic equipment is that it avoids the disadvantages of the coupling liquid or coupling gel and the time-consuming cleaning after the inspection. Therefore, the non-contact ultrasonic technique is very attractive for in-situ measurements in a mechanical testing machine. Sandwich composites are inhomogeneous and anisotropic materials with extremely high sound attenuation. Through-transmission technique with separate receiver and transmitter transducers on opposite sides of the component is often used for their testing.
Compared to immersion technique the amplitude difference between transmitter and receiver is –138 dB due to the high difference in the acoustic impedance between the piezoelectric material and air and also between sandwich material and air air (see Gundtoft et al. (1996) for a description of immersion technique).
To overcome the high damping of the ultrasound at the interface air/sandwich material a special high power transducer with integrated preamplifier was used. It consists of a composite system with impedance matching to air.
A special X-Y scanner was build for this purpose. In Figure 1 and 2 the fork-fixture for holding the transducers is shown. The ultimate resolution of the scanner is 10 micros, but in this case a resolution of 200 microns was sufficient to get a detailed picture.
Two pairs of transducers were used: 50 kHz and 120 kHz. The lower frequency gives a lower attenuation and consequently a better penetration is obtained but a lower frequency also gives a lower axial resolution. Therefore, a trade-off between penetration and axial resolution must be made. The 120 kHz transducers were best suited for this task because it has the best axial resolution and the penetration is sufficient for the present specimens. The diameter of the transducer is 19 millimetres. The distance from the transducer to the specimen was approximately 15 millimetres. The peak detector was setup to measure in a time-gate covering 200 –250 µs. The pulse repetition frequency is limited by the time-gate value since the time between the pulses must be higher than this value. The pulse repetition frequency is linearly proportional to the scanning time and the axial resolution. For an axial resolution of 0.3 mm the scanning speed is 20 mm/sec. and a typical scanning takes 10 minutes. For practical reasons ultrasonic scanning monitored only the left crack.
<u>Description of structural setup:</u> A test rig has been produced and can be seen schematically in Figure 1, and consists of a rigid overhanging beam-construction.
In order to assume a perfect clamping of the beam-ends, wood inserts have been introduced at the beam-ends, and the beam is then bolted with 4 bolts onto the test rig. 2 bolts are perfectly fitting bolts and go all the way through the beam end with the wood insert, and transfer the horizontal forces from mainly the bottom face into the test rig. The two remaining bolts only introduced a pressure force on the bottom face, and transfer the vertical forces into the test rig.
The arrangement around the middle of the beam on the de-bonding side consists of two plates on each side of the face bolted together to insure that the loading area remains straight all the time. For fitment of the plate on the core side of the face, a little part of the core has been removed, and the starter crack has been introduced with a razor blade extending 5 mm away from the plate on each side.
A similar arrangement is present at the opposite side of the de-bonding (the other side of the sandwich beam), except that no core has been removed and the plate is screwed onto the upper face. Furthermore adjusting screws have been inserted between the two metal plates, making it possible to adjust the distance between the beam and the test rig.

The complete test rig is finally hanging in a rod and connected to the top loading head of the testing machine. The connection between the rod and the test rig is done through a spherical bearing.
While carrying out the test, the force and vertical movement of the loading heads are monitored. Furthermore strain gauges have been placed on both beam-ends for verification purposes with the finite element calculations.
Both the strain gauge and the ultrasound transducers are schematically shown in Figure 1.

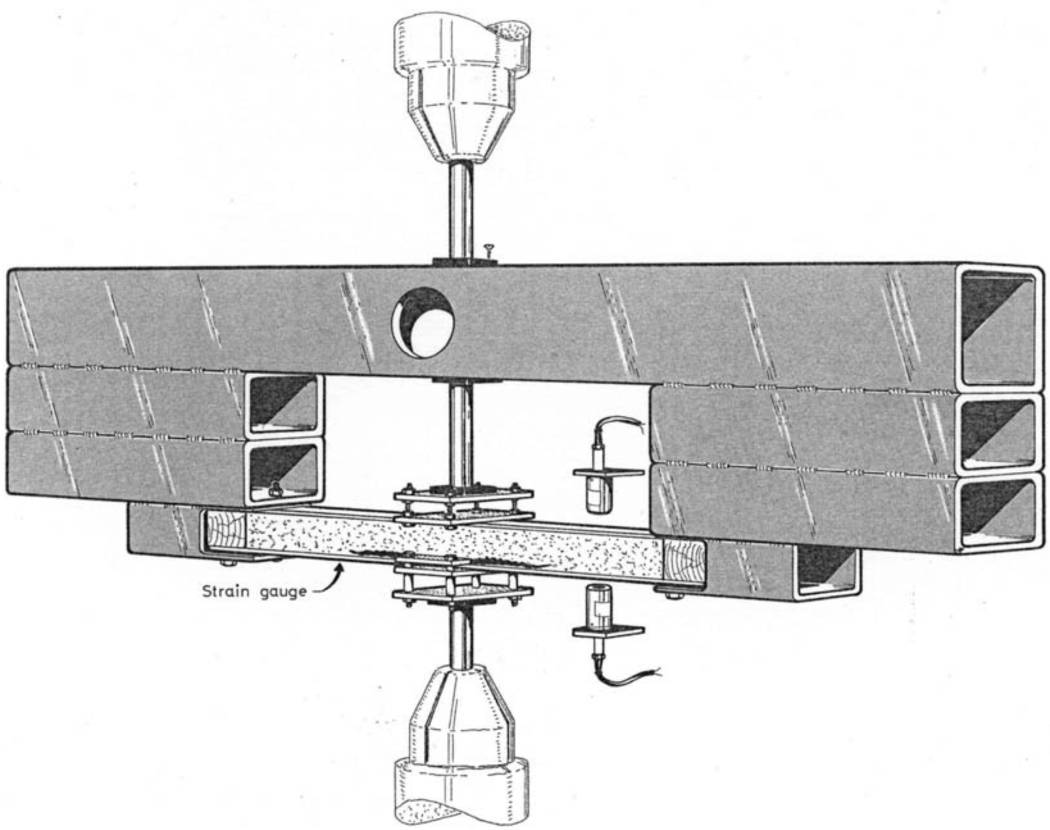

Figure 1. Structural test rig schematically illustrated. The transducer set-up can be seen to the right.

Figure 2. In-situ ultrasonic scanning system. To the right the two air-coupled transducers in through-transmission set-up are seen. The distance to the specimens is 15 millimetres

Results from experiments: The general observation from the experimental investigation was that, as expected, very different propagation patterns were seen between the different core densities. For the specimens with H80 cores the crack only propagates just beneath the glue interface on the core side, see Figure 3. On a micro scale the crack tip continues to seek up into the interface because of the negative mode-mixity, but the fracture toughness of the H80 core is so low that the crack never reaches into the interface, but instead is forced to continue to propagate just below the interface on the core side. Furthermore the propagation is very sudden, and happens in relatively large steps. This is believed to be due to dynamic effects when the crack propagates. The release of elastic energy, when the Griffith-energy reaches the fracture toughness and the crack is released in a split second, generates stress waves that makes the crack propagate even further, especially for small crack lengths, where nearly unstable crack growth is predicted by the theoretical models.

For the specimens with H130 and H200 cores a very different crack propagation behavior is seen. In the H130 specimens the propagation for small crack length is similar to the one seen in H80, but quickly fibre bridging is observed, see Figure 3. Fibre briding happens, when the fracture toughness for the H130 and H200 cores is sufficiently high that when the crack on a micro-scale continuously seeks up into the interface, again because of the mode-mixity, the crack prefers to kink into the glue layer and further into the interface between the glue layer and the chopped strand mat, located between the quadro-axial laminate and the core, and hereby pulling out fibres, which bridge between the crack flanks. These fibres will hereby restrict the crack from opening and shearing and hereby also carry a large portion of load.

For H200 the fibre bridging happens earlier, but the behavior thereafter is very similar to that observed for the H130 specimens.

During the mechanical testing of each specimen, 4-5 scans were made at different stages in the crack development.

In figure 4 examples of four scans are shown.

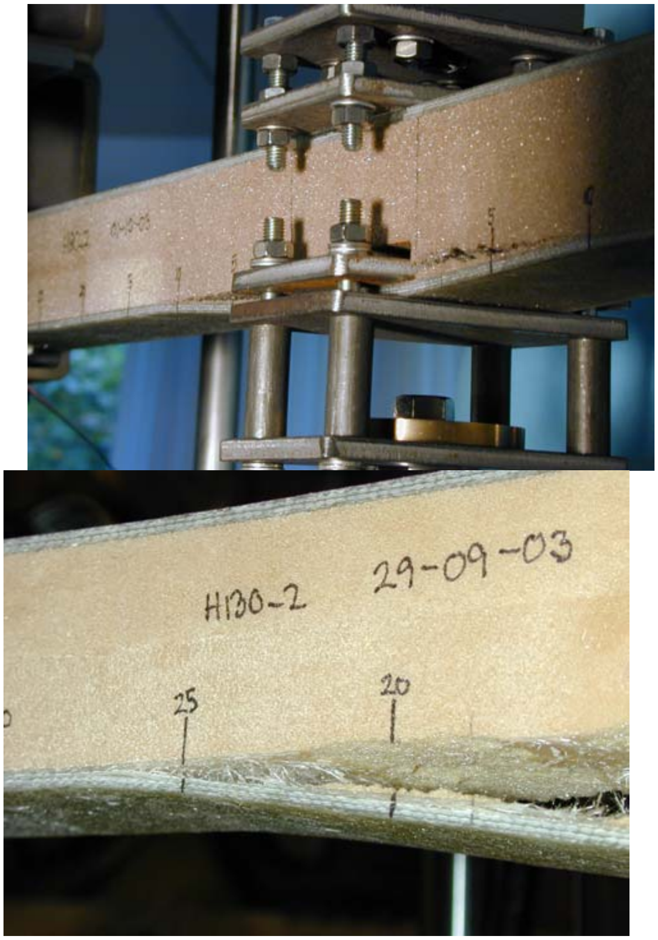

Figure 3. Sub-interface crack propagation in H80 specimen (left) and interface propagation with fibre bridging in H130 specimen (right)

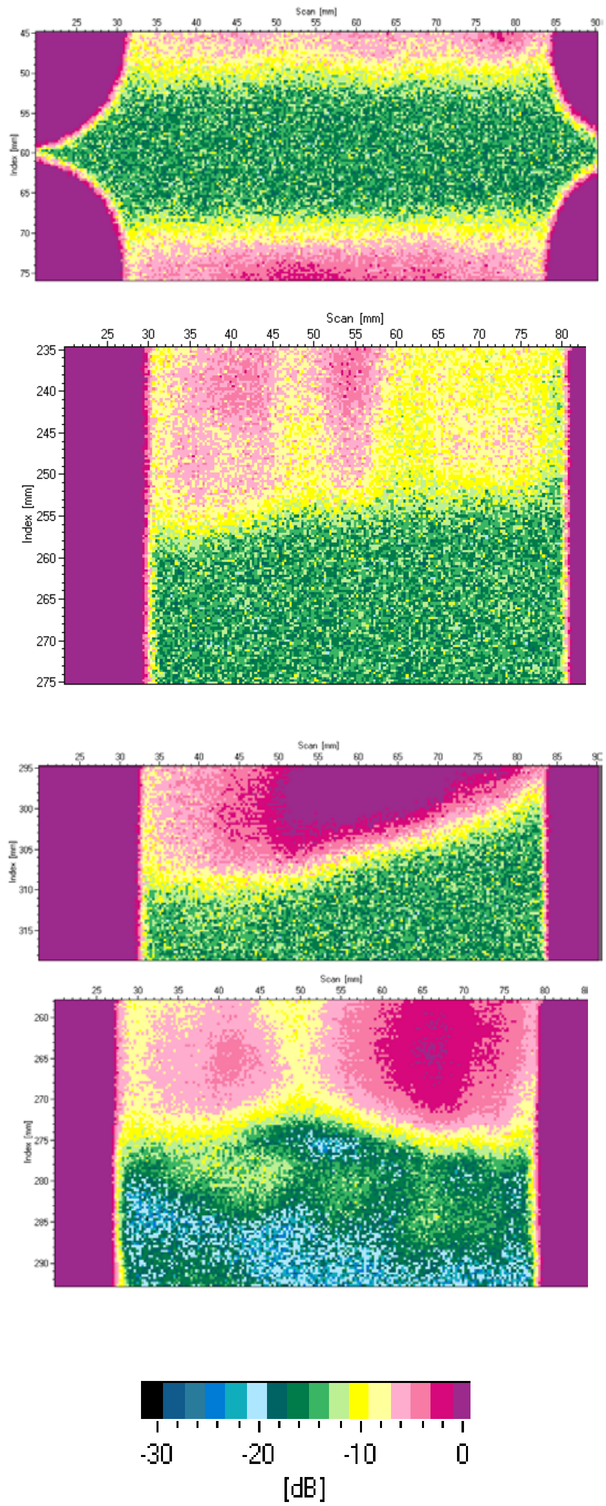

Figure 4. Ultrasonic scan results from in-situ scanning. Upper left picture shows the reference scan used for absolute position reference. The other three pictures show scans of panels with different core densities and different shapes of the crack front. The scale on the plots is in dB and the highest signal transmitted through the panel is on the right on the scale.

The quality of ultrasonic results is dependent on the core density. The sharpest picture of the crack front is obtained for the high-density cores. This is due to lower attenuation in the high-

density cores. For the H200 density panels there is a large amount of fibre-bridging, as mentioned above, which results in slower crack propagation.
In order to be able to use the scans in the structural evaluation of the crack propagation, the scan plots have to be post-processed. The post-processing is mainly focused on two factors: Extrapolation and linearization of the crack front, so that propagation distance on the front and back sides of the beam can be determined. Identification of the crack lengths is based on the initial reference position scanning. In figure 4 the crack propagation lengths based on the ultrasonic scans are shown as red lines on the scan plots.

Discussion (Comparison of NDI and visual inspection data): The crack front positions from the ultrasound scans and the visual inspections can be compared for the H80 specimens in Figure 6 and 7 (left side crack only). Furthermore it can be seen in Figure 6 and 7 that for both NDI and visual inspection there is an overall good agreement between the measured and calculated propagation lengths. In this connection it must be taken into account that the propagation for small crack lengths is very difficult to predict accurately with the finite element model. In this area the stiffness of the rather crude loading arrangement of the test rig and the blunt shape of the starter crack tip, have a large influence, and it cannot be expected that the initiation values will correlate between the theoretical model and the experimental results. Therefore, the initiation value observed is higher than the value predicted by the theoretical models.
By comparing the results in Figure 6 and Figure 7 it can also be seen, that there are a marginally better agreement between the measured and calculated results by using the NDI propagation lengths.
Similar graphs with similar conclusions have been made for the H130 and H200 results. When the amount of fibre bridging increases with the increasing core density, the theoretical estimations become highly unstable, because the validity of the fracture mechanics models is lost.

Both a 2D and 3D model have been used for the theoretical predictions, and can be seen in figure 5. More details about the modelling part can be found in Berggreen (2004) and Berggreen et al. (2003).

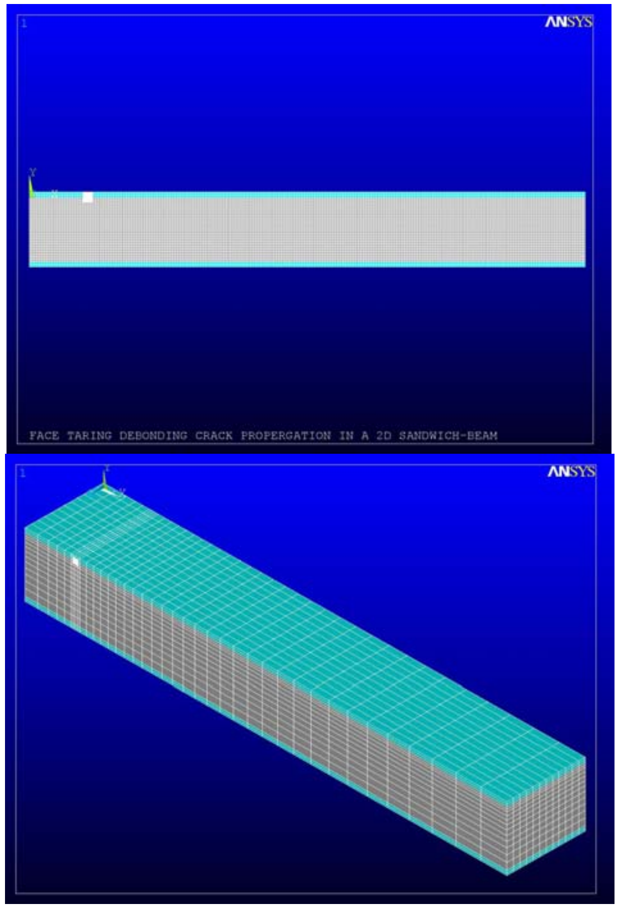

Figure 5. Finite element models used for crack length prediction. The 2D model (left) and the 3D model (right)

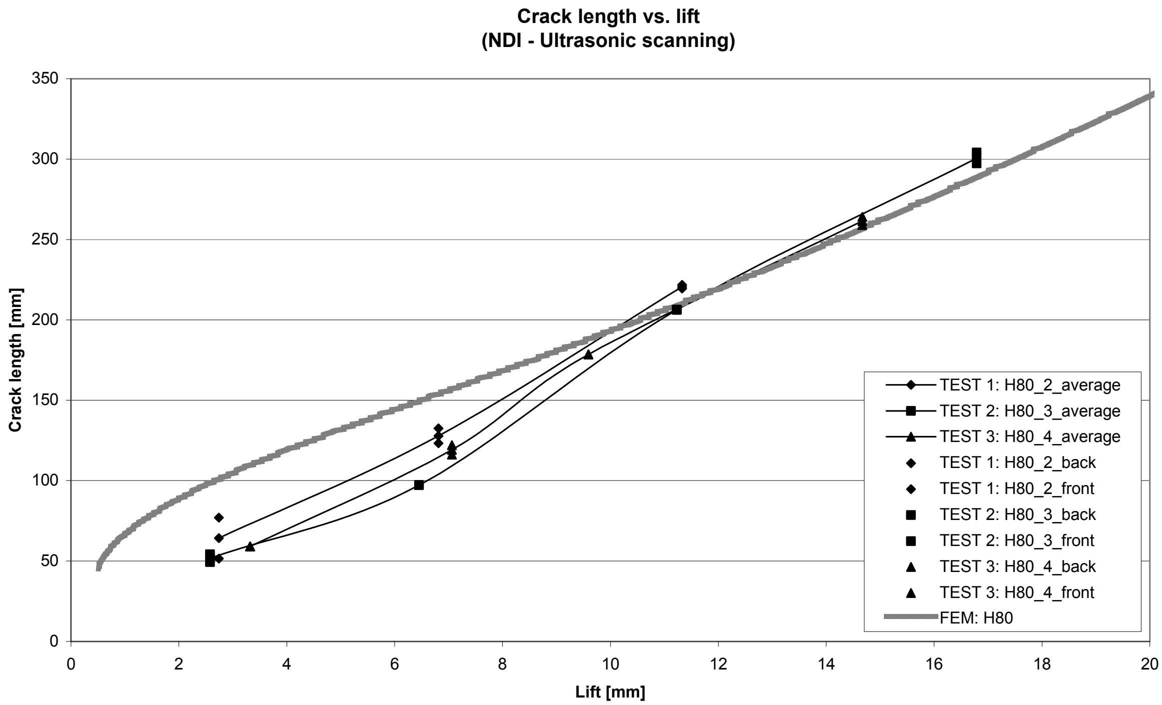

Figure 6. Correlation between the lift of the skin layer and crack length based on ultrasonic results.

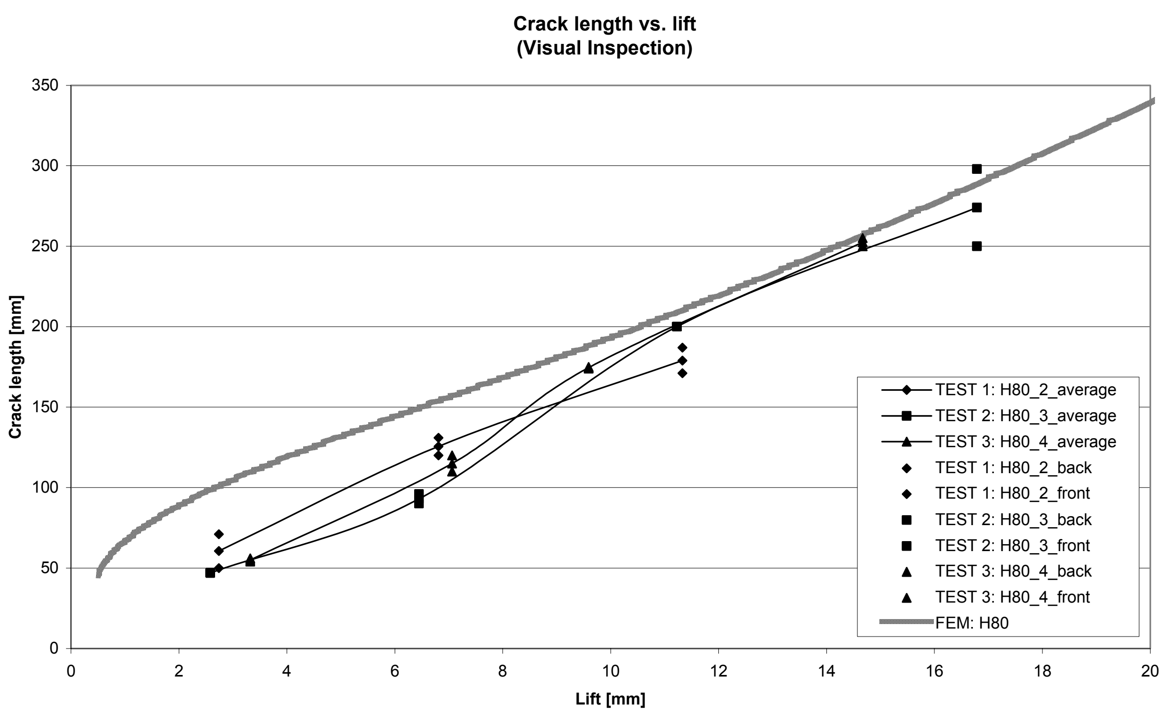

Figure 7. Correlation between the lift of the skin layer and crack length based on visual inspection.

Conclusion: It has been shown that the described air-coupled ultrasonic system can be used in-situ to monitor the crack propagation during crack test of sandwich panels. The air-coupled technique avoids the need for water coupling or contact measurements.
The described mechanical panel tests were done in order to verify the theoretical model for crack propagation between skin and core in glass-fibre/PVC foam core sandwich materials.
The in-situ ultrasonic air-coupled scans were made to experimentally measure the extent of the crack front propagation. It was shown that the crack front could be monitored with a resolution of a few millimetres. In addition, the crack front was measured by visual inspection of the side of the panel, but the crack propagation was difficult to observe because the crack front is not necessary always a straight line. Therefore, the in-situ ultrasonic method is a more reliable method to monitor crack propagation.
Although the visual measurements are more doubtful, the two methods of measuring the crack length gave results with little difference. However, the ultrasonic scan method was used to verify the model.
For the H80 core results are in good agreement with the model (see figure 6 and 7).
It has not been possible in the present project to take the bridging effect into account in the model.

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