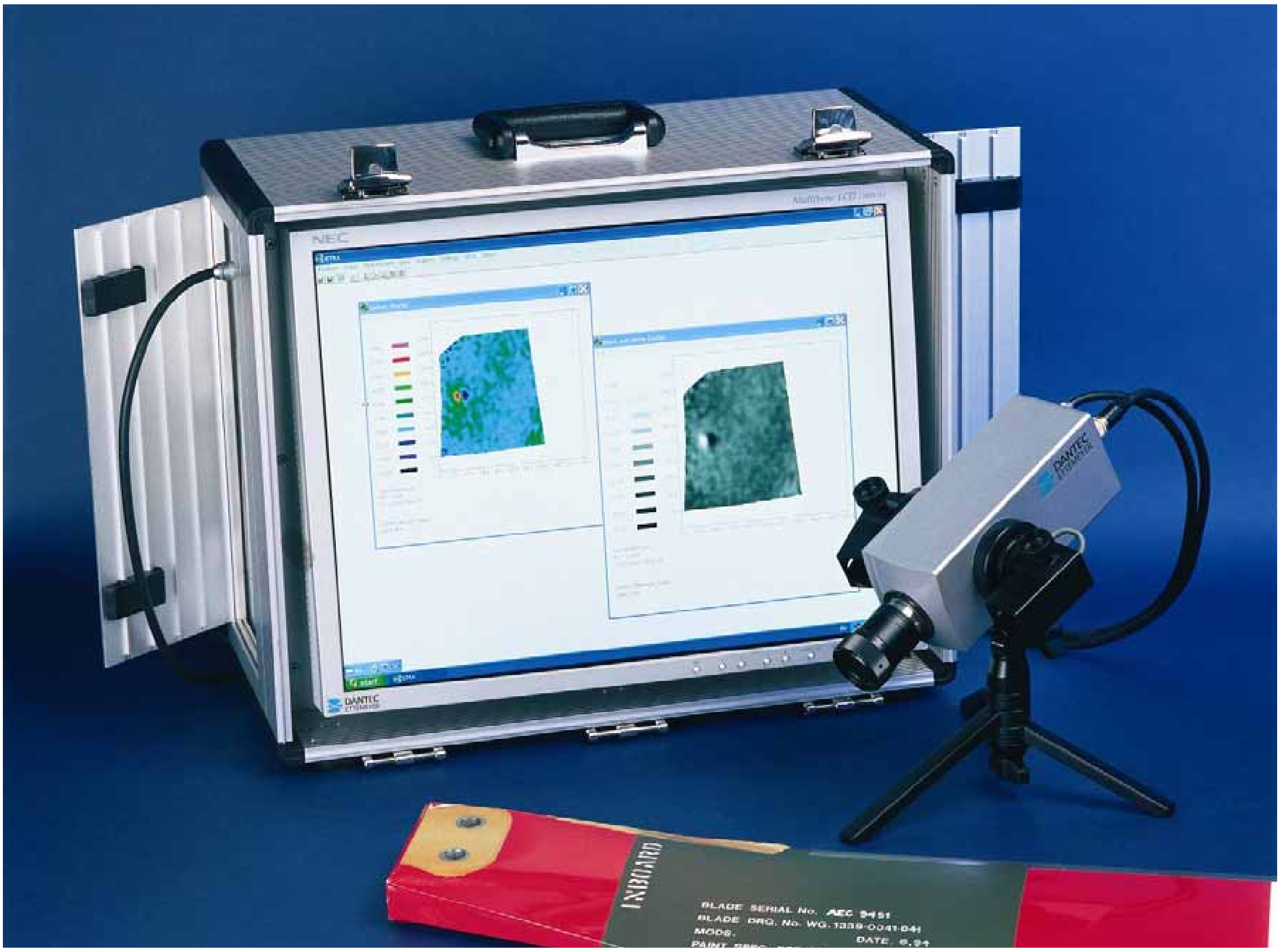
Non-Destructive-Inspection (NDI) on Bonded Sandwich Structures with Foam Cores and Stiff Skins – Shearography the answer?

Introduction

A NDT method for a structure with stiff stainless steel skins and low-density foam cores was to be found. Disbonds down to ∅ 25 mm should be detected. The defects may be positioned between skin and core or in the bondline between sheets in areas of multiple layers. The defects may be open to ambient air at the edges.

The following was considered at the application trials:
- Excitation method
- Geometry affect on results
- Inspectable areas (limitation of technique)
- Defect characterisation (sizing and depth position)



The investigation included literature studies, selection of feasible methods, evaluation of these methods and finally selection of a preferred NDT-method and application trials. Inspections on three typical structure areas were made for each method as a Round-Robin test. Only one method detected all defects in all structures during the Round-Robin test - Shearography.
The investigation continued with application of shearography on different structures.

Shearography was found to successfully detect and estimate depth position in relatively stiff areas. The toughest case where defects were detected was 3 mm skin + 2 mm doubler bonded to foam core of density 50 kg/m^3 with the defect between doubler and core, see figure 1.
The investigation will be continued by a project to establish the limits of shearography for this structure and to optimise testing with respect to speed.

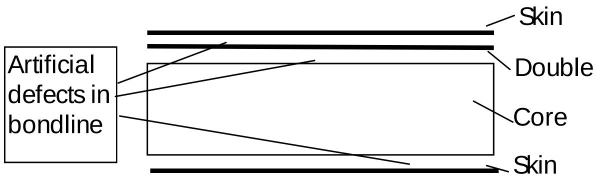


Fig.1: Typical structure with artificial defects

Background

A structure with stainless steel skins bonded to a foam core was interesting in an application for a customer to CSM Materialteknik. The work on NDT was focused on finding an inspection method fulfilling the following criteria:
Structure to be inspected: Skin 1 mm + doubler 1 mm both of stainless steel bonded to a 50 kg/ m3 foam core, see figure 1. Hollow areas (bonding to boxes) may be evident

Defects to be found: Disbonds of at least ∅ 50 in bondlines skin-to-doubler, skin and doubler-to-core and skin-to-core. The disbonds may be open to ambient air at edges.
Rational inspection due to large inspection areas on the full scale objects.
Preferable one NDT-method for all areas that is as user friendly as possible.
During the development the requirements have been slightly raised pushing the requirements on the NDT-method even further towards smaller defects and thicker structures.

Purpose

To identify and verify a cost effective inspection method for a stiff stainless steel skin sandwich construction with a low-density core.

Test samples

During the entire investigation artificial defects have been simulated to give the most realistic appearance without favouring any NDT-method. Three different ways of simulating the defects have been used, see figure 2.
Disbond type I: An area is left without adhesive. Around the "disbond" an O-ring or similar will be placed to prevent the surrounding adhesive to bond the skin to the core or beam. This will create a disbond (air gap) with a thickness equal to the bond line in the area.
Disbond type II: A plastic foil is taped to the skin. Adhesive will be put on the other part to be bonded in the area of the foil. This will create a very thin disbond (air gap) backed up by the plastic foil.
Disbond type III: A sharp tool is stuck into the core just below the adhesive. This will create a disbond-looking crack in the core. This is suitable to be used on real parts or test samples with access from sides, and will give defects open to ambient air.

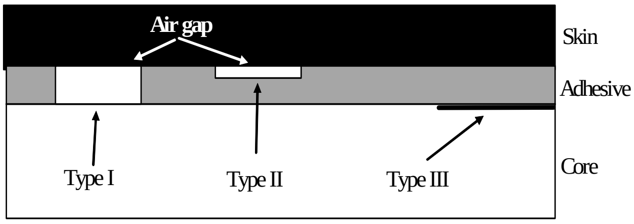


Fig. 2: Disbond type describtion.

Table 1 Panel design, ref. Figure 1. All panels have stainless steel sheets with Rohacell foam core (except NDT2) and Scotchweld 9323 B/A adhesive.

Panel	Core density and height	Skin [mm]	Doubler [mm]	Defect size [mm]	Remarks
A1	51 kg/m^3 - 30 mm	1	-	50x50	Defect type III + impact damages
A5	110 kg/m^3 – 45 mm	2	-	30x30 & 50x50	Defect type III + impact damages
A6	51 kg/m^3 – 50 mm	1,25	-	50x50	Defect type III + impact damages
A7	51 kg/m^3 – 50 mm	0,6	-	30x30 & 50x50	Defect type III + impact damages
NDT 1	51 kg/m^3 – 50 mm	1	-	Ø 50 mm	Defect type I and II
NDT 2	-	1	1	Ø 50	Defect type I and II
NDT 3	51 kg/m^3 – 50 mm	1	1	Ø 50	Defect type I and II
NDT 5	51 kg/m^3 – 50 mm	3	2	Ø 25 and Ø 50	Defect type II
R1	31 kg/m^3 – 40 mm	1	0,8	Ø 25 and Ø 50	Defect type II. The whole part has a radius of appr. 0,5 m

Investigation and results

The investigation consisted of two major parts a Round-Robin test and application trials with the chosen technique on realistic structures.
The investigation showed that within the round robin test, shearography was the only technique that managed to detect all defects. It was also possible to detect defects in areas with very stiff skins (up to 3 + 2 mm) with shearography if heat was used as excitation method. The depth position could be estimated from characterisation of the indications. More detailed results are given separately for the round robin test and the application trials.

Round robin test

Techniques to be used were chosen from previous knowledge and techniques described in (1). With regards to the critical criteria, see Background, the following inspection methods were chosen to be evaluated in the Round-Robin test:

1) Ultrasonic, resonance technique (described as spectroscopy in (1))
2) Mechanical Impedance technique (described in (1))
3) Pitch-and-catch technique (described as velocimetric method in (1))
4) Bondimeter technique
5) Shearography technique (described in (2))

The round robin tests were performed on test samples NDT1 through NDT3 only.
The inspections with the techniques 1) through 3) have all been performed with the Sonic Bond Master from Staveley. Specific information on that equipment can be found in Staveley operations handbook. In addition to the methods above radiographic inspection was used to verify some of the results. On test sample NDT1 through NDT3 were voids detected with radiography for all defects except the defect type II on sample NDT3.

Ultrasonic, resonance

For the resonance inspection three different probes and frequencies were used, 65 kHz, 110 kHz and 250 kHz.
On sample NDT2 (metal-to-metal bonding) both defect types (I and II) could be detected with the 65 kHz and 110 kHz probes. Sample NDT1 and NDT3 (skin-to-core bonding) was inspected but no reliable indications could be obtained from any of the two defect types.

Mechanical Impedance analyser

The probes S-MP-3 and S-MP-4 from Staveley were used. During the inspection the defects were indicated in sample NDT2 using the amplitude mode. A frequency of approximately 7 kHz gave the best signal to noise ratio for the amplitude mode. No reliable results could be obtained in the phase mode at any frequency.
No reliable results could be obtained from the defects in NDT1 and NDT3.

Pitch and catch technique

During the trials Staveley probe SPO-5699-8 was used.
No good results were obtained on samples NDT1 and NDT3.
The defect type I was detected on test sample NDT2 with the frequency range 37 to 43 kHz. Defect type II in NDT2 gave only vague indications that were not different to the general variation obtained in defect free areas.

Bondimeter technique

The Bondimeter technique uses vacuum to stress the part. A micrometer measuring skin surface deformation is fixed into the centre of a vacuum cup. In areas of disbond, the negative pressure will cause a surface deformation that can be picked up by the micrometer.
On sample NDT1 different surface deformation could be obtained at the defects. On sample NDT3, no difference in deformation was indicated for the defects.
Trials have also been made on the panels A1 through A7. Some positive results were achieved on the 50x50 mm defects, see table 2. As the defect type III is at the edges of the part the micrometer could not get closer than 45 mm to the edge due to the size of the vacuum cup (90 mm diameter). The 30x30 mm defects will therefore never affect the micrometer. Even for the 50x50 mm defects only the outer edges of the defect affected the micrometer. A disbond further away from the edges is expected to give stronger indications.
Uniform indications were obtained in areas without defects. At the 50x50 mm defects a noticeable increase in deformation was indicated.

Table 2 Bondimeter readings in defect areas. (Readings in 10^{-2} mm)

Panel and defect size	Initial value	Value over defect	Difference
A1 - 50x50 mm	30	36	6
A5 - 30x30 mm	28	28	0
A5 - 50x50 mm	27	32	5
A6 - 50x50 mm	32	35	3
A7 - 30x30 mm	32	33	1
A7 - 50x50 mm	31	44	13

The overall readings indicate that a fluctuation of the readings of 2 - 3x10-2 mm is normal.

Shearography

A Dantec Dynamics GmbH shearography system with a 50mW Diode laser (wavelength 780 nm) has been used at the investigations. The optics in the video camera was equipped with a daylight filter.
Positive results were obtained on the samples NDT 1 through NDT 3. All disbonds were indicated. At the inspections heat was used as the excitation force. In general the defect type I was easier to detect in all test samples. The defect type II needed more excitation to be detected. The heating has to be adapted to the defect that is hardest to detect.

Even on the sample NDT3, with skin and doubler, both 1 mm of steel, bonded to the core, the defects were indicated, see fig. 3. These defects were not detected by any other inspection method.

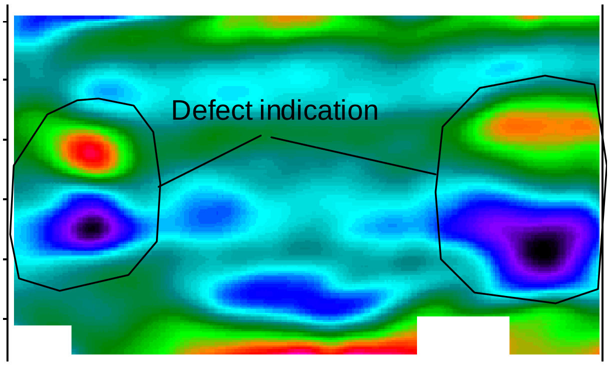


Fig. 3: Shearography results on NDT3.

Application trials

During the application trials different full scale related items were investigated that were not covered at the Round-Robin test. In addition to this the best way to apply shearography for this project was also studied.
Following items were investigated:

1) Excitation method
2) Geometry affect on results
3) Inspectable areas (limitation of technique)
4) Defect characterisation (sizing and depth position)

The application trials showed that heat was easier to implement directly to the structure than vacuum. Larger panels were actually easier to inspect than small test samples due to less full body movement and more rapid cooling in the large panels. Defects down to 50 mm could be detected in a bondline between core and doubler (2 mm) underneath a 3 mm skin, see fig. 4.

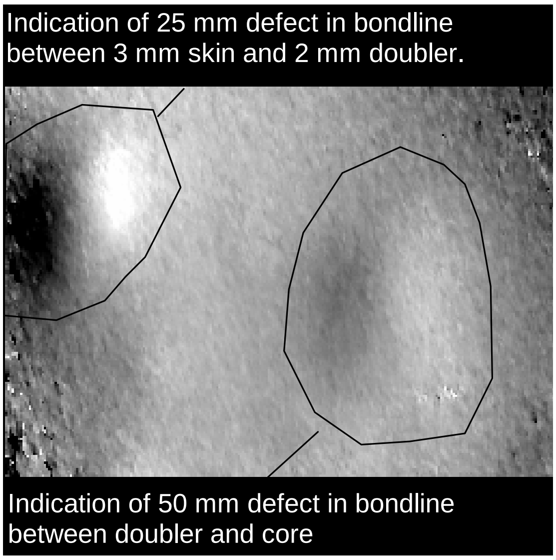


Fig. 4: Shearography results on NDT5.

Excitation method

Even though vacuum excitation is easier to control and repeat, there were a number of reasons to choose heat in favour of vacuum as excitation method:

1) Defects at the edges were open to ambient air thus making vacuum less useful
2) Heat was easier than vacuum to adopt to variation in geometry
3) The investment cost was higher for vacuum chamber or hood than for heat sources

Hence the work was concentrated to using heat as the excitation method.

Temperature change for different structures

For metal-to-metal bonds (NDT2) a temperature difference of ½ degree Celsius was enough to get clear defect indications. Higher temperatures resulted in larger deformations and slightly larger affected area (making the defects look bigger). Maximum temperature difference used was 10° C.
It was very difficult to get good results for skin to core disbonds on NDT1 and NDT3. Before any clear defect indications were obtained the whole part would bend which caused a disturbing deformation.
Inspections on panels A1 through A7 and R1 gave better results. Clear defect indications were easily obtained on these panels. A temperature difference of approximately 5° C was enough to get defect indications from 1 mm skin + 0,8 mm doubler to core disbonds. The conclusion was made that larger panels gave faster cooling and less full body bending which affected the inspection quality in a positive direction.

Initial temperature - How does it affect the inspection?

The temperature of the part compared to the ambient air was important. If the temperature difference between the part and the ambient air exceeded 10° C the measurements were disturbed. The laser fringes got very turbulent, probably due to air turbulence.
Within the 10° C temperature range the increase and decrease of temperature was not affected by the initial temperature of the part. The reference image can be taken before or after heating. The trials showed that a higher sensitivity was achieved with heating prior to taking the reference image.

Heating sources

Air guns and Halogen lamps were used as heating sources in the investigation. Halogen lamps have the advantage of being fast and easy to turn on and of without creating to much air turbulence. If high temperatures are to be achieved air guns are faster. As the investigation showed that temperature increases exceeding 10° C actually not are practically useful the halogen lamp was enough. A 500 W lamp at approximately 300 mm distance created a 5° C increase of the surface temperature in 20 seconds. More lamps and/or higher effects will reduce the heating time. The heat from the lamp itself created air turbulence in front of the lamp even after switching the light off. This made it necessary to screen the heating source after heating the part. Also it was not possible to make measurements while heating since the halogen lamp included wavelengths that were not filtered out by the optics which caused the video camera to saturate.

Optical filters and lamps with light outside the wavelength area of the laser may allow heating during measurements without saturating the video camera.

Surface geometry and inspectable areas

The affect of surface geometry on the shearography results was investigated on sample R1. Sample R1 have approximately a 0,5 m radius. No change in sensitivity was indicated in the curved area. The affect of impact damages was studied on panels A1 through A7. Even in areas with heavily deformed skins due to high impact energies, shearography could indicate the damages. Geometry changes did not affect the results significantly. Defects close to the edges and in some cases open to the edges were also indicated as good as in the middle of the panels.

Trials were made on thicker and thicker test sample to try to find the skin thickness limitation for shearography. For thicker skins larger temperature differences were necessary to detect defects. Indication from the Ø 50 defect was vaguely distinguished from the background noise on NDT5 with 3 mm skin + 2 mm doubler bonded to the foam core, see figure 4. The Ø 25 defect was detected in bondline between the 3 mm skin and 2 mm doubler, see figure 4. Each different combination of skin thickness and core density may give different results.

Defect Characterisation

When a defect has been indicated it is essential to know as much as possible about the defect. In the trials to find the skin thickness limitation it was evident that defects appeared at different excitation levels depending on the depth position. The part was heated and a reference image was taken as soon as possible heating. As the part cooled down measurements were made. Longer time between reference image and measurements resulted in higher excitation level (temperature difference). If measurements are made at different time intervals, different excitation levels are achieved. A typical inspection cycle consisted of:

1) 20 seconds of heating giving approximately 5° C temperature increase
2) Reference image immediately after heating
3) The first measurement approximately 2 seconds later
4) Second measurement approximately 10 seconds later
5) Third evaluated image another 10 seconds later and so on until no further change in temperature was achieved

Evaluation of when in time the indications were clearly visible gave information of the depths. Defects between skin and doubler were clearly indicated already in stage 3) or 4) above. Defects between core and 1 mm skin + 1 mm doubler were not clearly indicated until stage 4) or 5). Defects in bondline between doubler were not indicated until stage 5).

Several bondlines will require more exact control of the excitation (cooling) to enable depth estimations. As the cooling of the part depended on the size of the part and also ambient air temperature, it was difficult to get any absolute depth estimations. The estimations were always relative for each test sample type.

The size of a defect was measured directly in the software. If a very high excitation level was used the size of the indication got slightly larger than the defect. On the other hand the defect was not indicated or indicated as much smaller if a very low excitation level was used. The heating will therefore influence the size of the defect indication.

Conclusions

There are a number of methods (1) that traditionally are expected to be better fitted to inspect bonded structures with multilayered stiff skins and low-density than shearography**. This investigation shows that even for sandwich structures with stiff skins and low-density cores shearography can be the answer.** The use of heat and the temperature elongation of the sheets seems to take away some of the drawbacks related to shearography, like difficulties to detect defects open to ambient air or adopting excitation method to curved or irregular shapes.

Future prospects / ideas

The investigation will be continued by a project to establish the limits of shearography for this structure and to optimise testing with respect to speed.

References

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