NONDESTRUCTIVE INSPECTION AND EVALUATION METHODS FOR COMPOSITES USED IN THE MARINE INDUSTRY

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SUMMARY: The paper reports on a test and evaluation programme to compare different non-destructive inspection and evaluation methods for the inspection of single skin and sandwich panels and joints. As part of the benchmark test programme a number of T-joints and top hat stiffener specimens were built using single skin and sandwich construction. These specimens contained defects of various sizes which were located at different depths. The specimens were tested in the laboratory using ultrasonic and thermographic methods. In addition field tests on ship structures were carried out in ship yards to determine the performance of the ultrasound, infrared and automated coin tap methods in a production environment. These included tests on an old 2/3 scale section of a single-skin GRP minesweeper and a small ship section of sandwich construction which had been used in explosion trials. The paper summarises the results, comparing the different methods and showing their respective capabilities and limitations.

KEYWORDS: non-destructive evaluation (NDE), infrared thermography, ultrasonics, automated coin tap, field testing, joints

INTRODUCTION

A critical element of the technological infrastructure supporting large scale applications of composites in both naval and civilian vessels is the availability of reliable NDE/NDI techniques. Methods are needed for use in quality assurance during manufacture and also for through-life condition monitoring and inspection under in-service conditions. A comprehensive literature review preceded this study in order to find suitable NDE/NDI methods which included: infrared thermography, ultrasonic methods and mechanical methods (automated coin tap and impedance method).

Infrared thermography is now also a well-established NDE/NDI method as shown for example by Bar-Cohen [1], Vikström et al [2] and Vikström [3]. Equipment is readily available and the method can be used in the laboratory and in the field. An important aspect when using this method is to heat up the test specimen to a constant temperature. Different methods exist which can be used for this purpose such as lamps, electric blankets and ovens.

The ultrasound method is a well-established NDE/NDI method for a wide range of materials as shown for example by Parmar and Boyce [4] and Bar-Cohen [5]. Equipment is readily available in various degrees of sophistication. Fully automated C-scan equipment can be used for small components. Small portable units are available for field-testing. The portable units are the most interesting for inspecting large marine structures. The capabilities of the method depend mainly on the transducer and receiver that are used. It is important to realise that composites should be inspected with a frequency of about 1 MHz and fairly high energies are needed.

The manual coin tap method has been used successfully to quickly scan composite structures for defects. However, this method is dependent on the capability of the operator to hear changes in the sound of the structure being tapped against. Automated coin tap devices exist for the aerospace industry. These methods allow recording of the signal and documentation of a possible defect. The automated coin tap method and impedance method developed for the aerospace industry were investigated in the benchmark tests of this project without success. For the experimental programme described in this paper a new automated coin tap method developed specifically for marine application was used instead.

Another important result emerging from this review was that there is limited practical experience of using NDE/NDI methods on naval vessels. A large body of knowledge exists for aerospace applications. However, this cannot be easily transferred to ship building as usually much thicker laminates are used reinforced with glass fibres instead of carbon fibres. It was concluded that benchmark and field tests should be carried out to compare the capabilities of all methods to detect defects in both single-skin and sandwich structures. The present paper confines attention to the inspection of joints and the field testing. Detailed information about the benchmark programme can be found in References [6] and [7].

OUTLINE OF EXPERIMENTAL PROGRAMME

Materials used

T-joints and top hat stiffeners

Four specimens were built, two T-joints and two top hat stiffened plates (see also Figure 1).

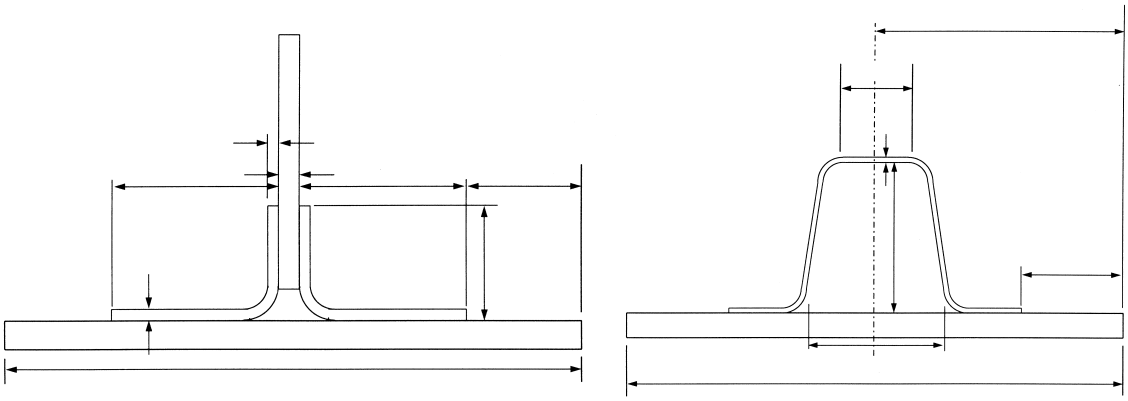

Figure 1 Schematic of T-joints and top hat stiffener specimens used in the study

Both the T-joints and top hat stiffeners have a base plate measuring 500mm x 500mm x 20mm. The laminate was made of woven roving (Vetrotex RC 830 2139 WR) and Synolite 3785 resin. To produce the T-joints an upright plate was bonded to the base plate with CRESTOMER 1152PA to the base plate. In addition 10 layers of Vetrotex RC 830 2139 WR were laminated to each side with Synolite 3785 resin. To produce the top hat specimens a polyurethane foam former was stuck to the base plate. 5 layers of Vetrotex RC 830 2139 WR were laminated on top of the former with Synolite 3785 resin. Artificial delaminations were introduced into the base plate, T-joint and top hat stiffener. These delaminations were modelled by inserting two PTFE sheets between the laminates. The sheets were sealed to prevent resin from penetrating between the two layers.

Field testing

In addition to the above tests, field tests on ship structures were carried out. These included tests on an old 2/3 scale section of a single-skin GRP minesweeper and a small ship section of sandwich construction which had been used in explosion trials. The sandwich structure consisted of a panel with a 60 mm thick PVC core, two bulkheads 2.3 m apart and two stiffeners with knees. The bulkheads and stiffeners were laminated onto the inside of the panel. The special load introduction of the support structure used in the explosion trials caused delaminations between the bulkhead and the panel. Figure 2 shows this structure.

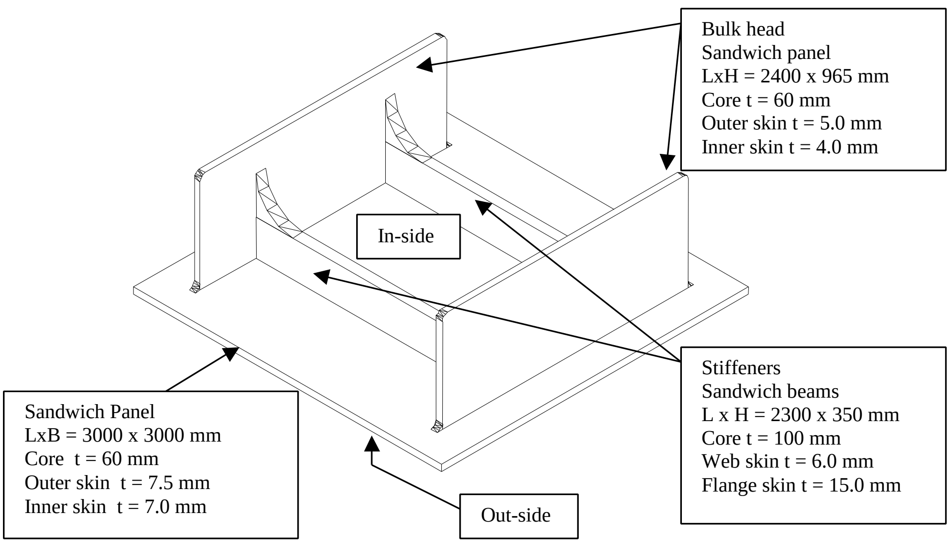

Figure 2 Sandwich test structure

Methods used

Throughout this investigation the ultrasonic pulse-echo method was applied. For inspecting the joints a C-scan system was used. This included a USIP12 ultrasonic flaw detector, digital thickness module and a number of different probes. In some instances it was necessary to use a specialised contact probe and a simple scanning frame together with a partial wet coupling system. In addition the portable Epoch III flaw detector (model 2300) together with a 1 MHz, highly damped contact probe type Panametrics V602, Videoscan was utilised.

The infrared thermography equipment comprised a infrared heating lamp with an electric power of 5000W and a 2x1m heating blanket with a heating power of 800 W/m^2. Data was recorded with an AGEMA 880 SWB infrared camera while the data was analysed using the PTR2 *Photo Thermal Radiometric* software package.

The smart hammer system developed in the U.S. by Smart Hammer Systems, Westerly, RI was used to inspect the sandwich test structure. This method is based on a fixture with a small hammer driven by pressurised air which produces a controlled reproducible knock against the surface. A microphone which is placed next to the fixture with the hammer records the sound from the tapping. The acoustic signal is subsequently sent to a portable computer where a frequency analyses of the signal is carried out to detect and document possible damage.

SUMMARY AND DISCUSSION OF RESULTS

Results obtained from inspecting the joints

Two methods were used to investigate the T-joints and top hat stiffeners: Infrared Thermography and Ultrasound.

Ultrasound

The components were examined both with the immersion and contact method together with the C-Scan equipment. Further detailed assessment was also made with the portable equipment. For all defects a clean defect signal was obtained with a corresponding loss of back wall echo, clearly suggesting that the defect is likely to be a delamination.

For the T-joints all defects in the base plate, on top of the base plate and in the fillet were detected. Only the defect in the stiffener away from the base plate was not found. All defects in the base plate and on top of the base plate were detected for the two top hat stiffener specimens. The only defects which were not found were those located either in the stiffener or at the fillet which is expected considering the inspection was restricted to only one side of the component.

Infrared Thermography

The results are not very good when the samples are heated with the electric blanket. This was mainly caused by the fact that the temperature could only be controlled to an accuracy of 5^{o}C while infrared thermography requires an accuracy of +/- 1^{o}C. For this reason an oven was used to heat the specimens. This ensured a more homogeneous temperature distribution and consequently better results. Defects were mainly detected in the base plate with only very few defects detected in the intersection of vertical plate or top hat stiffener with the base plate. The reason for this is that this region was difficult to observe with the camera because of the variable angle that modified the emissivity.

Results obtained from field testing - single skin composite material

Ultrasound measurements

Initial scans were carried out with a portable ultrasound device on a grid of 50 x 50 mm. More detailed assessments were made on any defects identified on the initial scan. The following observations were made:
- The central part of the stiffener is clearly identified.
- A clear signal is also obtained on either side of the Top-Hat stiffener.

- The most interesting region is the interface between the base and the flange of the Top-Hat stiffener. In areas with a good bond a high attenuation is observed due to the thicker composite. However, in areas with delaminations a high signal and lower thickness reading was recorded.
- Signals due to fibre and matrix crazing and fibre whitening were observed.
- Impact damage and surface voids resulting in a lower signal were observed.
- Furthermore a change in thickness was found.

A visual inspection of the test sections on the MCMV was carried out in addition. The measurements of the ultrasound method correlate very well with the observed defects. Other conclusions are that the ultrasound method requires little or no preparation of the surface. Furthermore the application of the method requires a minimum of external support or services. Only safe access has to be provided. It was also observed that the method used for the field trials achieved an inspection rate of about 1.5 to 2 m^2 per day. Significant improvements of the inspection rate can be expected by the adoption of automated scanning systems.

Infrared Thermography

Two different heating methods were used in these trials. A lamp and an electric blanket. It was found that the blanket was much more practical as the lamp required a carriage which made it difficult to get access to some parts of the test sections. The following conclusions were drawn from the inspection:
- Infrared thermography cannot detect defects close to stiffeners or bulkheads as the variation in thickness becomes the dominant effect.
- Some patches with lack of resin were found.

The set-up of the equipment took a long time because the equipment was heavy and bulky. A crane had to be used to lift the carriage onto the scaffolding. The test sections had to be painted prior to inspection. Furthermore, infrared thermography cannot be used in rainy weather, it requires dry surfaces. The test sections had therefore to be covered. An additional difficulty was the strong wind which cooled down the heated surfaces very fast. The electric blanket appeared to be more successful than the lamp and gave a significant increase in time available for thermal imaging and defect mapping. The overall inspection rate is 6 to 8 m^2 per day which is considerably faster than ultrasound.

Results obtained from field testing - sandwich composite material

Ultrasound measurements

The sandwich composite section was inspected with a portable ultrasound device. Initial scans were carried out on a grid of 50 x 50 mm. More detailed assessments were made on any defects identified on the initial scan. The following observations were made:
- It was not possible to obtain a backwall echo either from the core or the skin on the opposite side. Nor was it possible to obtain a clear signal from either side of the stiffeners.
- At the interface between the base and the flange of the Top-Hat stiffeners gross delaminations were detected.

No defects were found in the panel. It seems that this method does not work well on sandwich panels. The gross delaminations detected at the interface between the panel and the stiffeners were clearly visible by eye from the inside.

Infrared Thermography

Two different heating methods were used. A lamp and an electric blanket. However, since the surface of the test section was not very smooth the lamp produced a very inhomogeneous heat distribution. Hence this method of heating was abandoned. From the results obtained (see Figure 3) with the heating blanket it was found that:

- The method is very sensitive to thickness variations and surface roughness.
- Some possible areas with excess of resin and some skin delaminations were found.
- Close to or on stiffeners it could not detect any defects as the thickness of the laminate changes.
- Monitoring the intersection between flat panel and the vertical stiffeners with the camera is difficult
- Possible defects were mainly detected on the flat base plate.
- The heating of up to 2 m^2 takes about 30-45min.

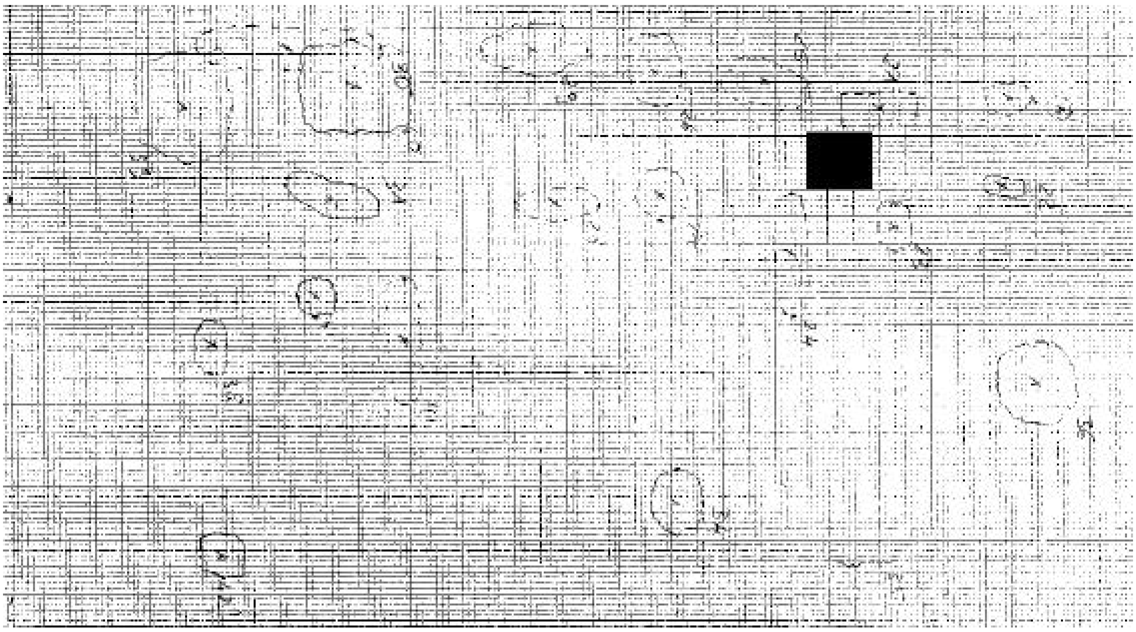

Figure 3 Possible defects detected with infrared thermography (measured from the inside; the black square is the cut out)

Smart hammer system

The sandwich composite section was inspected with the portable smart hammer system. Initial scans were carried out by just tapping the structure with a regular hammer and listening to possible defect locations. The structure was scanned systematically on both sides in-between the area of the stiffeners and also in the region outside the stiffeners. Figure 4 shows the location of the possible defects detected in the panel. The delaminations found next to the stiffeners are not shown in the figure. It was observed that:

- The method could easily detect the debonding areas between the main panel and the stiffeners. A few other defects were found outside the stiffener area.
- The inspection from the outside was more difficult. However, it seems that the method could distinguish the signal of an intact stiffener from a debonded stiffener by inspecting from the outside. All other methods were not capable to analyse the structure from the outside.

- For the inspection from the outside an inspection rate of 4 m^2 per hour with recording and 6-10 m^2 without recording was achieved.

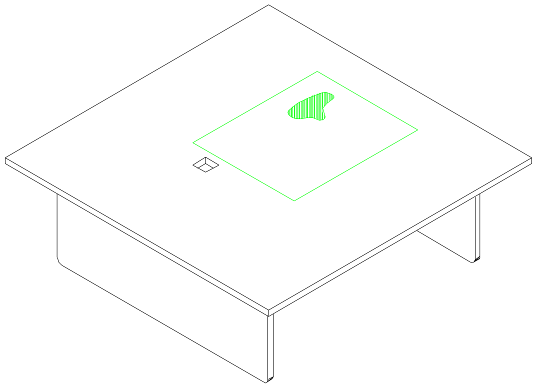

Figure 4 Possible defects detected by smart hammer system (delaminations near the stiffeners are not shown in the sketch)

Destructive testing

To verify the findings made with the three inspection methods a panel was removed from the test section and cut into narrow beams (see Figure 6). The beams are shown in Figure 5. They clearly show core damage, delamination and debonding. But there were no areas with excess or lack of resin. The observed defects are summarised in Figure 7. The results obtained with infrared thermography and the smart hammer seem to correlate quite well with the observation from the destructive testing. The main areas of core damage and debonding have been detected by both methods. In addition, infrared thermography found other possible defects which are not visible on the beams removed from the test section. Ultrasound did not find any defects in the panel, only the delaminations of the stiffeners.

Figure 5 Damage in panel

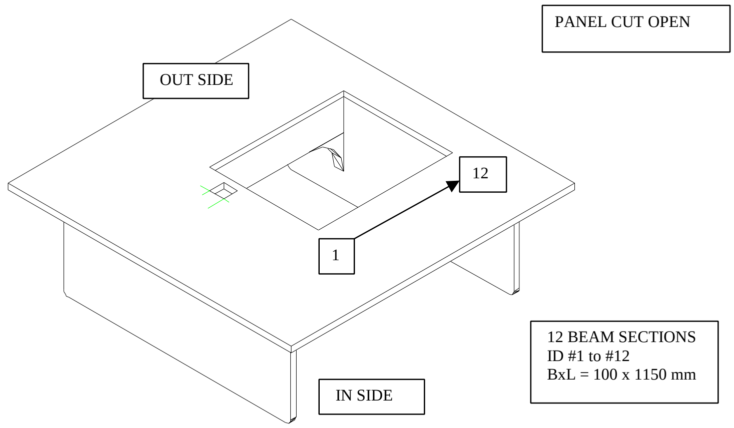

Figure 6 Test structure with panel removed and showing the beam numbering

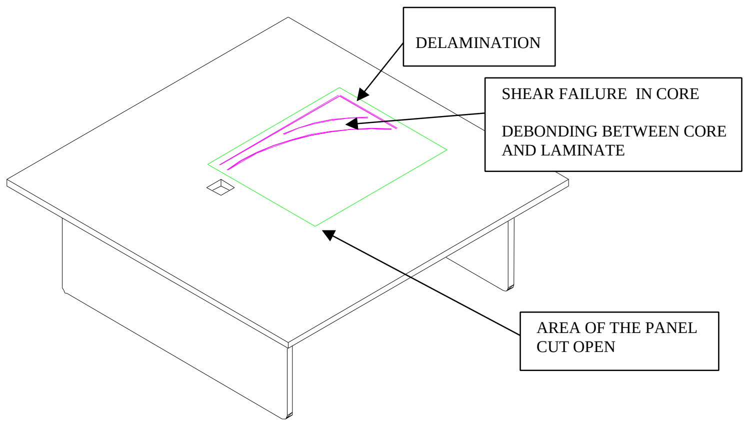

Figure 7 The defects detected by removing beams from the test section

EXPERIENCE GAINED FROM THE FIELD TESTS

Ultrasound

The results have clearly demonstrated that the ultrasound techniques can be used successfully for detecting defects in the field for single skin composites. However, it is the slowest methods as shown in Table 1. The delaminations were mainly located at the interface between the flange of the top-hat stiffener and the base plate. The ultrasound technique also successfully detected other defects such as impact, fibre crazing and surface damage. Slight variation in attenuation was also observed in each case due to the characteristics of the composite material and possible voids. These observations apply to single skin composites as for sandwich composites very few results were obtained - mainly delaminations of stiffeners.

The method can be used anywhere as long as the operator can reach the area that should be inspected. This means ladders or simple scaffolding are fully sufficient for providing access. Electricity has to be supplied unless a battery powered unit is used. Scanning is relatively slow and some method has to be provided to record where the signal has been taken. One approach is to draw a grid on the structure to be investigated and to record the signal for each square within the grid by using a co-ordinate system. However, when scanning large areas one has to decide on a certain grid size to investigate, i.e. one measurement is taken within each section of the grid. The accuracy cannot be better than the pre-determined grid size. A trade-off has to be made between scanning time and accuracy. Automated scanning devices may simplify the work. Areas with defects can be marked with chalk on the structure based on the instant signals received. However, the more frequently used procedure is to scan a certain area and to evaluate the results later in the laboratory.

Infrared Thermography

Infrared thermography was found to be a very fast method for inspecting the test sections. It could detect delaminations both in sandwich and single skin composites. In addition it was possible to find core defects. Applying heat to a large structure seems to be best done by a heating blanket. Field-testing has confirmed that infrared thermography does not work well near complicated geometries, like a stiffener. However, the method can be used for areas between stiffeners and it was able to detect some damage in these areas. The set up requires installation of an infrared camera and a heating device. Good scaffolding and weather protection is also required. This makes the set-up more complicated and time consuming than for the ultrasound or coin tap method. Electricity for equipment and the heating blanket has to be supplied. The camera has to be mounted on a stable support and the heating blanket has to be applied or attached. The scanning is very fast. However, the heating prior to scanning takes a long time; about 30 to 45 minutes for a 2 m^2 area. Defect areas can be marked with chalk on the structure based on the picture from the camera. Defect positions can be recorded afterwards.

Smart hammer

The smart hammer method is the fastest of the methods considered in this study as shown in Table 1. Delaminations located at the interface between the flange of the top-hat stiffener and the base plate were easily detected. The main damage area shown in Figure 7 with shear failure and debonding between core and laminate was detected by inspecting from the inside and the outside. The smart hammer method was the only method that could detect defects by inspecting the structure from the outside. The field trials have also demonstrated that the smart hammer method can be set up quickly. Access requirements are minimal, the method can be used as long as the operator can reach the area of interest. This means ladders or simple scaffolding is fully sufficient. The only ancillary items needed are pressurised air and a power supply to run the PC. The fastest way to scan an area seems to be to inspect the structure quickly by using a hammer to identify possibly critical areas. In a second step the smart hammer method is applied to evaluate the critical areas more carefully. Areas with defects can be marked with chalk and positions can be recorded afterwards. If a very accurate inspection is desired the structure can be inspected carefully at every point.

Table 1 Inspection time obtained from field testing

	Preparation of scanning area	Scanning	Analysis	Scanning area per day
Ultrasound	Just cleaning	Slow, depends on grid size to inspect.	Later in the laboratory	1.5-2 m^2
Infrared Thermography	Cleaning; Needs smooth surface. Possibly painting	Heating of the area about 30 minutes. Scanning very fast	On the spot, some analysis later.	6-8 m^2
Smart Hammer	Slight cleaning	fast	On the spot analysis	~ 30m^2 (with recording) 45-75 m^2 (no recording)

CONCLUSIONS

The following conclusions can be drawn from the benchmark study and field testing:

- It was found that most defects in single skin laminates can be detected successfully even for very thick structures. However, sandwich structures are more difficult to inspect, especially when defects in the skin-core interface or inside the core are to be found.
- Infrared thermography detects core damage and skin-core debonds in the PVC sandwich panels.
- The ultrasound method is the best method for detecting delaminations in top-hat stiffeners and T-joints. It was found for infrared thermography that heating the surface can be difficult. Furthermore it was very difficult to inspect the curved surfaces of the joints with the camera because the varying angle changed the emissivity.
- The fastest and simplest method for use in ship yards is the automated coin tap method using the "smart hammer". However no tests were carried out in the benchmark programme to make a direct comparison with the other methods.
- Results or experience gained in the laboratory can not always be transferred directly into practice. For example infrared thermography requires considerable support structures like scaffolding which are sometimes difficult to provide. Furthermore it appeared that a different heating method from that normally used in the laboratory is more efficient.

It should be born in mind that throughout this study off-the-shelf equipment was used when available. It may be expected that further development of the hardware and/or software (and particularly their adaptation to marine composites) can increase the detection rate and resolution considerably.

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