Detection of defects in ceramic faced armour

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Abstract. To protect against high velocity AP rifle threats, ceramic plates are used as body armour. Nowadays mainly multi curved, monolithic plates are used, in order to better conform to the human torso. Ceramic is a brittle material and thus susceptible to cracking after a blunt impact or drop. These cracks have shown to decrease the ballistic performance of the plate. Therefore, regular inspections are necessary to ensure the plate is safe to use. Since the ceramic in the armour plate is covered, it is impossible to observe from the outside whether the ceramic is damaged or not. There are several non-destructive test methods to inspect the condition of the ceramic. X-ray imaging is commonly used and can reveal cracks and manufacturing defects. There are also techniques on the market that merely distinguish plates in good condition from defect ones. These are available as simple, portable systems, for use in the field. This paper gives an overview of different detection methods known to be available and their potential to identify different types of defects. It compares the results obtained by two different techniques on a set of plates.

1. INTRODUCTION

Nowadays, several types of ceramic body armour plates are used to protect against incoming high energy, small calibre, Armour Piercing (AP) bullets. Ceramic body armour plates are made of two basic parts: a hard ceramic top layer and a ductile composite backing glued together. Additionally, in some types an impact absorbing layer is placed in front of the ceramic and around the edge to protect the ceramic against impacts.

Cracks within the ceramic are easily caused by impacts, falls or improper storage. Cracks could have a reducing effect on the ballistic performance [1][2] although the drop in performance depends on the distance between the point of impact of the projectile and the pre-existing crack [3].

To assure the quality of ceramic armour plates during storage and use, regular inspections of the ceramic in the plate are necessary. The methods used need to be reliable, not endangering the condition of the plates and are preferably quick and easy to perform. Since the ceramic top layer of the armour plate is always covered, it is impossible to observe from the outside whether the ceramic is damaged. There are several Non-destructive Inspection (NDI) techniques possible to inspect the condition of the ceramic.

2. NDI TECHNIQUES TO INSPECT CERAMIC PLATES

This paragraph gives a short overview of different NDI techniques applied to ceramic body armour plates. The aim is not to be comprehensive, but to illustrate various techniques and their visualization capabilities.

2.1 X-ray and CT scan

X-ray imaging machines work by using electromagnetic radiation to create images of the internal structure. In a shielded cabinet, the ceramic plate is placed between an X-ray source and a detector, such as photographic film or a digital sensor. The X-ray image is a black and white image that is formed by absorption, transmission and scattering of the incoming X-ray radiation. Cracks and defects in the ceramic plate become visible because they alter the intensity of the radiation passing through the material. Cracks create gaps or changes in density, resulting in varying levels of X-ray absorption. Additionally, ceramic manufacturing defects, such as porosity from incomplete infiltration or unsintered material, will also appear due to density differences, as illustrated in Figure 1.

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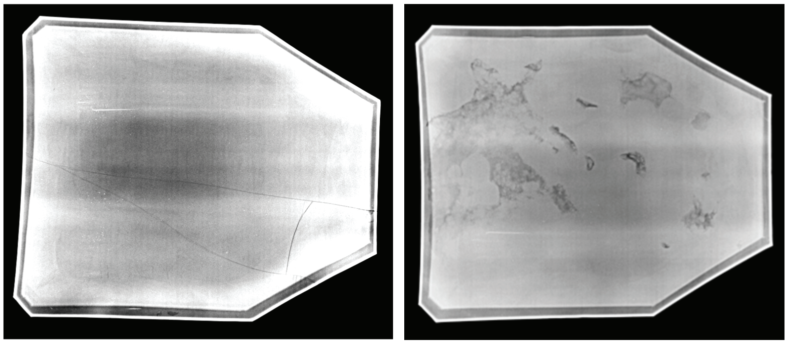

Figure 1. Example of two X-ray images. Left: with visible cracks. Right: with ceramic manufacturing defects.

A CT scan is an advanced imaging technique that combines multiple X-ray images taken from various angles to produce detailed cross-sectional images (slices). CT scans provide more detailed and comprehensive images compared to standard X-rays. They can visualize: cracks parallel to the surface, the through-thickness direction and size of the cracks and delamination of the ceramic from the backing layer. However, this technique is more expensive and time-consuming, and the equipment requires more space and infrastructure, including specialized rooms with shielding to protect against higher radiation levels.

2.2 Infrared

TNO investigated Infrared (IR) photography techniques for crack detection in ceramic armour plates [4]. The IR detection technique involves three steps: heating the plate, cooling down the plate in one direction to start heat flow and a cooling phase during which an IR camera monitors the temperature distribution across the plate. As cracks obstruct the heat flow, discontinuities in the temperature distribution will become visible.

An experimental set-up was constructed using existing components. Once the plate was heated to around 80°C, it is positioned upright between two copper tubes with circulating cold water (5-10°C), which are conductively connected to its left and right side. During the cooling process, the IR camera was able to detect cracks, as illustrated in Figure 2.

The experiments were only a proof of principle and were only conducted on a few plates with clear distinct cracks from edge to edge. These large sharp cracks could be identified as shown in Figure 2 (right).

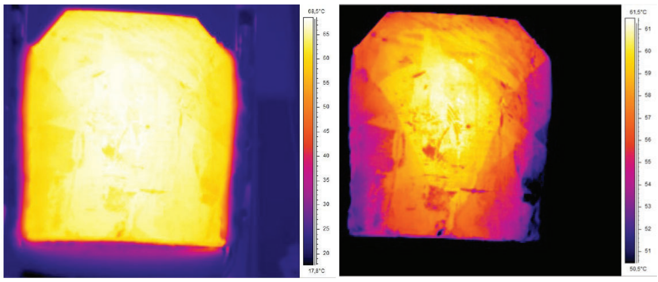

Figure 2. Two examples of IR images over time of the heated plate placed between the cooling tubes: immediately after placement (left) and after a few minutes of cooling (right). [4]

2.3 MEMS-sensor array inspection

A low-cost micro-electro-mechanical system (MEMS) sensor array and dedicated processing system has been developed by TNO for quality assurance of aerospace structures [5]. This inspection approach uses a single piezoelectric actuator in contact with the laminate to excite it with Lamb waves, a type of elastic wave that propagates in solid plates. The leaky Lamb waves lose energy to the surrounding medium through acoustic radiation. As these waves travel through the material, defects alter their behaviour. An array of MEMS sensors records the energy that radiates into the surrounding air. The processing system translates the measured wavefield into a thickness map of the inspected part.

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A first attempt has been made to apply this technique to ceramic body armour plates. Six plates were scanned, four contained visible cracks on X-ray and two did not. This was not revealed to the operator beforehand. Because of lack of detailed material information, the processing system displays velocity scans instead of thickness.

Although this technique is not developed for this material composition, first results are promising as illustrated in Figure 3. The two plates with no visible cracks on X-ray, also did also not show a large variation in output with the MEMS technique. So both techniques distinguished the undamaged plates. Of the 4 plates with cracks, the MEMS technique clearly indicated the locations of the cracks in 3 of the plates. However, for the plate with a crack at the top, the MEMS technique did not show a sufficient difference to identify a crack at that location. So, for the damaged plates the success rate was three out of four.

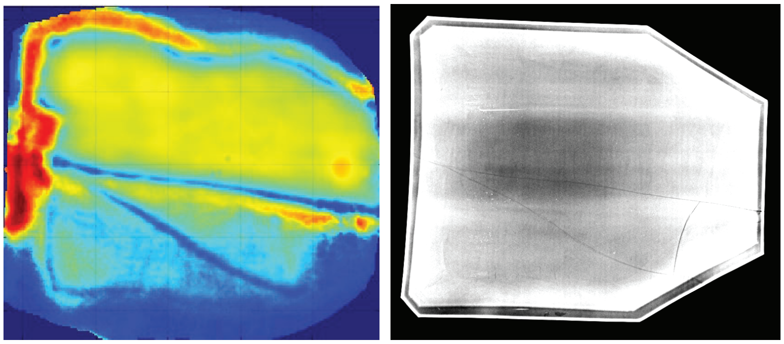

Figure 3. Example of the MEMS-sensor array inspection (left) of a ceramic plate compared (The cracks show up in blue) to the X-ray image (right) of the same plate.

2.4 Ultrasound

Ultrasound uses high-frequency sound waves to inspect materials. A transducer sends these sound waves into the material. When the sound waves hit a boundary (like a crack or defect), they bounce back. The transducer captures these returning echoes. The ultrasound machine processes the echoes into an image, showing the internal structure of the material.

There are two main types of ultrasonic testing: contact and immersion. Contact testing uses a gel or oil to transmit sound waves from the transducer into the material. For immersion testing the sample is submerged in water. The gel or water is used to facilitate the transmission of sound waves between a transducer and the object being inspected in ultrasonic testing. It helps ensure efficient transfer of sound energy by eliminating air gaps, which can interfere with the sound waves. Immersion testing is used in laboratory settings for complex shapes and detailed inspections.

The state of the sample is assessed by analysing the intensity of ultrasound signals and the transit time through the material (known as Time-of-Flight or TOF). Kesharaju conducted research using an ultrasonic immersion testing method on defected ceramic armour components [6]. This research investigated how porosity affects the ultrasonic TOF of reflected signals to establish a correlation between velocity and density across the ceramic component. Figure 4 shows an example of the generated output for the ceramic part of a body armour plate. Do note, that this was a scan of only the ceramic part and not the complete body armour plate.

An accuracy of 96% was obtained by comparing the ultrasonic results against X-ray results. An overall accuracy of 100% was achieved using ultrasonic inspection coupled with artificial intelligence based signal processing and validated against micro-CT scan results. Crouch [6] concluded that the ultrasonic detection method, coupled with intelligent signal processing, has been identified as being a useful, complementary tool for measurement of local variations in thickness and/or bulk density to be used in manufacturing process of the ceramic component.

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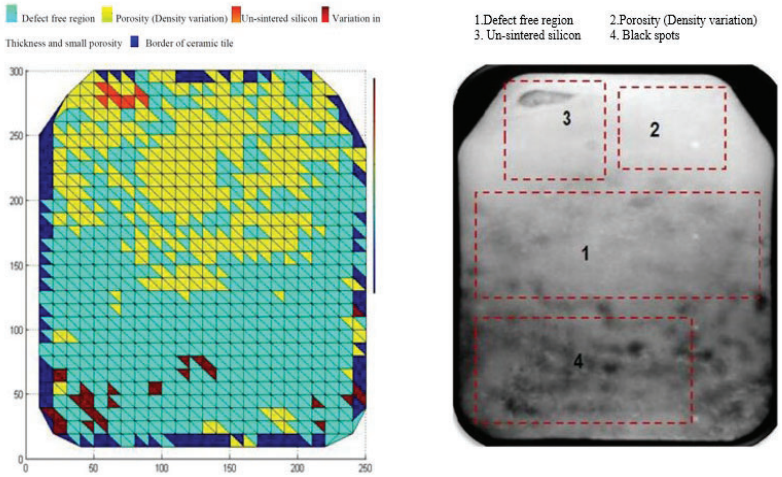

Figure 4. Example of the ultrasonic mapping of a ceramic tile (left) in a plate together with the X-ray image (right) of the plate. [6]

2.5 Ultrasonic resonance

Resonance Ultrasonic Vibrations (RUV) technology measures the ultrasonic resonance response. This involves sending ultrasonic waves selected from a broad frequency range (20 - 250 kHz) through the material and analysing the resonance frequency curve [7].

Cracks and delamination in the ceramic plates cause deviations in the resonance response. These flaws are detected by comparing the resonance response of a flawed plate to that of a standard, non-flawed plate. A crack introduced into the ceramic alters RUV peak parameters: bandwidth and peak position, as illustrated in Figure 5 (left plot). A delamination within the ceramic armour plate components alters RUV peak parameters: amplitude, bandwidth and peak position, as illustrated in Figure 5 (right plot). This method uses specific quantitative criteria, such as changes in amplitude, bandwidth, and shifts in peak position of the resonance frequency, to identify flaws.

The RUV method to inspect delamination is based on a statistical approach. The manufacturer states that in case studies, the capture rate of RUV method approaches 100%. It is not known from the website [7] how many different plate constructions were tested in these case studies.

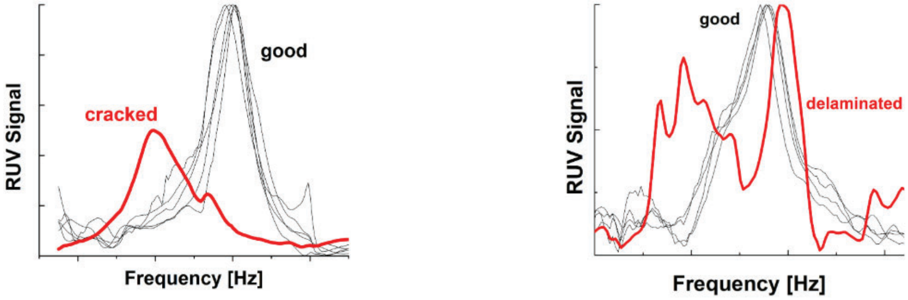

Figure 5. Examples of the frequency response of the RUV technique, showing a typical response for a cracked plate (left – red line) and a delaminated plate (right – red line). [7]

2.6 Impulse excitation

The principle of impulse excitation relies on the fact that every object has natural vibration frequencies tied to its mechanical properties. The specimen is mounted on supports that allow it to vibrate freely in one or more directions. When an object is struck with a small hammer, it vibrates at these natural frequencies. These vibrations can be detected with a transducer, and the collected data can then be used to calculate material properties or to capture the object's resonance signature. Figure 6 gives an illustration of this technique.

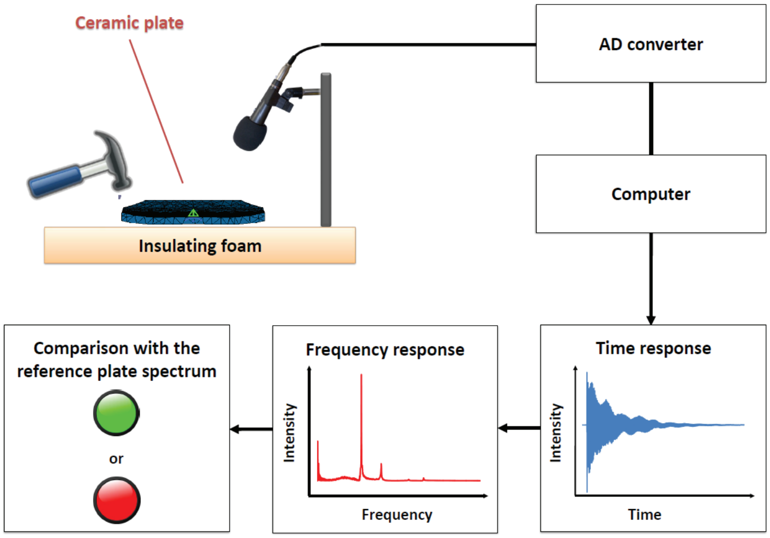

Figure 6. Schematic view an impulse excitation device; the Acoustic Test Device [8].

Impulse excitation is a fast and straightforward, non-destructive testing method for measuring the mechanical properties of materials and is commonly used in quality control, materials science, engineering, and industry. A study using this method will be presented in Chapter 3.

2.7 Summary NDI techniques

Some NDI techniques provide in-depth information about the size and location of cracks, as well as potentially other defects. They can be complex, and often require specialized equipment that could be difficult to transport. These techniques are ideal for laboratory settings, where a more scientific examination can be conducted. Other methods simply determine the presence or absence of cracks, these are classified as go/no-go methods. They are straightforward, and could be suitable for use in portable systems, making them ideal for field applications. Table 1 gives an overview of the different methods, including the complexity of it.

Table 1. Summary of NDI techniques to inspect ceramic plates

	Go-no go	Visualized defects			Complexity
		Cracks	Manufacturing defects	Delamination	
X-ray		✓	✓		+
CT scan		✓	✓	✓	++
Infrared		✓			-
MEMS sensor array		✓			-
Ultrasound			✓		+
Ultrasonic resonance	✓	-		-	--
Impulse excitation	✓	-			--

3. IMPULSE EXCITATION MEASUREMENT CAMPAIGN

3.1 Methodology

For detection of defects in ceramic body armour plates, a research demonstrator based on impulse excitation was developed by the Swiss Engineering School “HE-Arc” in collaboration with Armasuisse [8]. Figure 7 gives an illustration of the first generation Acoustic Test Device (ATD), which had a fixed geometry regarding excitation and response measurement and only one microphone to record the acoustic response.

The test equipment utilised in the measurement campaign is capable of conducting an evaluation based on the analysis of up to five microphones. These microphones are mounted on magnetic mounts (as illustrated in figure 8). The microphones are freely movable to adapt to different plate geometries. The position of the hammer is fixed. Figure 8 illustrates the positions of the microphones used for experiments on Type 1 plate.

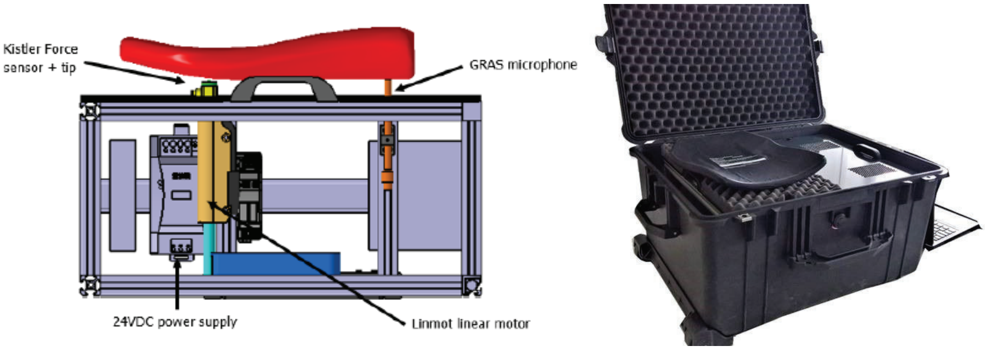

Figure 7. Illustration of the Acoustic Test Device. [8]
Left: Schematic cross section without foam layer (red indicates a plate). Right: Picture of the ATD.

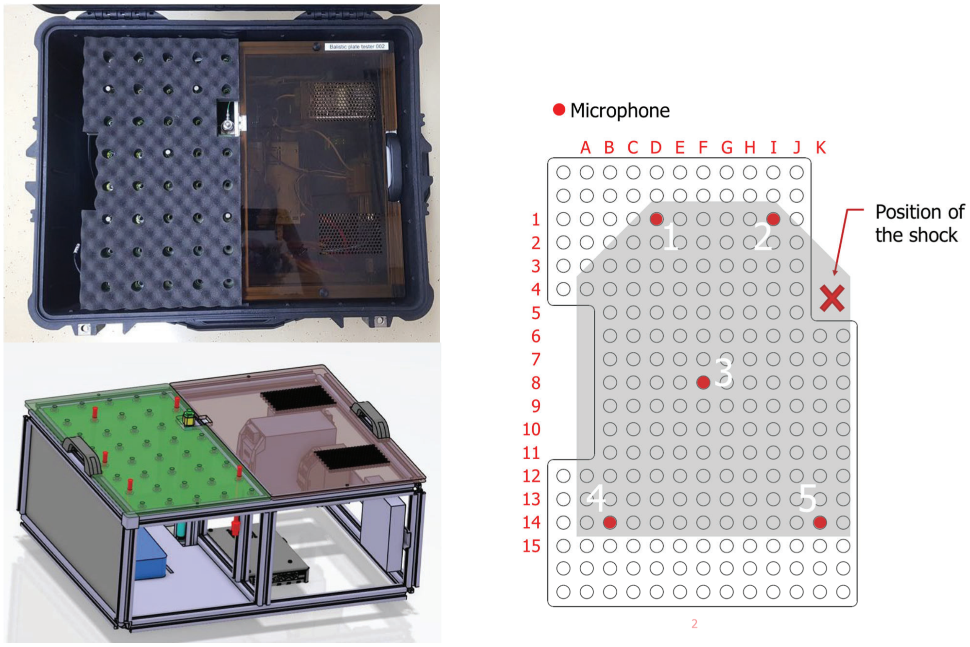

Figure 8. Illustration of the positioning of the microphones and hammer of the ATD used in the measurement campaign. Left-top: top view of the ATD with multiple microphones in the foam layer. Left-bottom: Schematic illustration without the foam layer. Right: positioning of the microphones for the experiments.

This method relies on assessing six criteria, which are derived from an analysis of the acoustic response of the plate in both the time and frequency domains: 1) frequency and 2) the peak width of the first vibrational mode, 3) mean of the Frequency Response Function (FRF), 4) damping time constant, 5) initial amplitude and 6) the damping in the time domain (R^2 coefficient derived from the exponential regression – noted as R2).

The acceptance limits for these criteria must be established on data from a significant number of pristine plates. For a plate to be accepted, all six criteria must fall within the specified limits for its corresponding plate type. If any criterion falls outside the acceptable range, the plate is rejected [9]. Once the criteria are established, this method can effectively identify whether cracks are present in a plate.

3.2 Experimental

Two types of ceramic body armour plates have been used for a measurement campaign with the ATD research demonstrator [9]. These plates were examined with X-ray imaging by TNO for the Clothing & Personal Equipment Branch of the Dutch military of Defence. The condition assessment on X-ray analysis was done by TNO and focussed on both cracks and manufacturing defects. If one or both defects were observed on the X-ray image, the plate was labelled “out of use”. It must be noted that the assessment of the plate condition based on X ray analysis is not always trivial as no clear definition is available which size of manufacturing defect should lead to a reject.

3.2.1 Result Type 1 plate

The construction of the Type 1 plate is straightforward as it consists only of a monolithic SiC ceramic glued onto a UHMWPE backing enveloped in a textile cover. First, the preliminary acceptance limits were set, based on the response of seven plates of known condition (four undamaged and three damaged). The signal of microphone number 1 was used for the analysis. Microphone number 1 is positioned in the upper left corner, opposite to the shock location in the upper right corner along the plate’s longitudinal axis as shown in figure 8 (right).

Figure 9 shows the Frequency Response Function (FRF) of the seven plates around the first frequency mode. Plots of damaged plates are in bold. As a first observation, the FRFs differ significantly between damaged and undamaged plates. For this plate type, the interval of [200 Hz, 1500 Hz] is set in the acoustic tester software to find the peak corresponding to the first vibrational mode. For each of the seven plates, the values of the six evaluation criteria were extracted from the signals, and preliminary acceptance limits were defined.

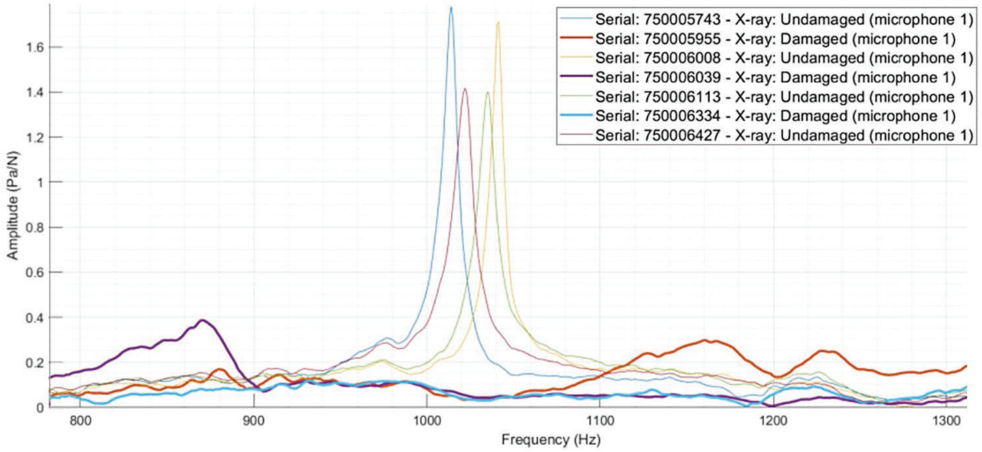

Figure 9. Frequency Response Function (FRF) of the seven plates of type 1 used for pre-tests with zoom on the 1st vibrational mode. Damaged plates are plotted in bold. [9]

Throughout the campaign, a total of 125 type 1 plates were measured using the ATD. At the conclusion of the campaign, the X-ray images of these plates, along with the corresponding assessments by TNO, were provided to Armasuisse.

As explained, for a plate to be accepted with the ATD, all six criteria must lie within the limits defined for the corresponding plate type. As soon as a criterion is out of the acceptance limits, the plate is rejected. Figure 10 shows the preliminary acceptance limits and an overview of the values for each plate criterion. The fact that the response of defect plates may fall within one or more of the criteria for undamaged plates demonstrates that multiple criteria are needed to distinguish the damaged from the undamaged plates. Table 2 compares the results of both methods.

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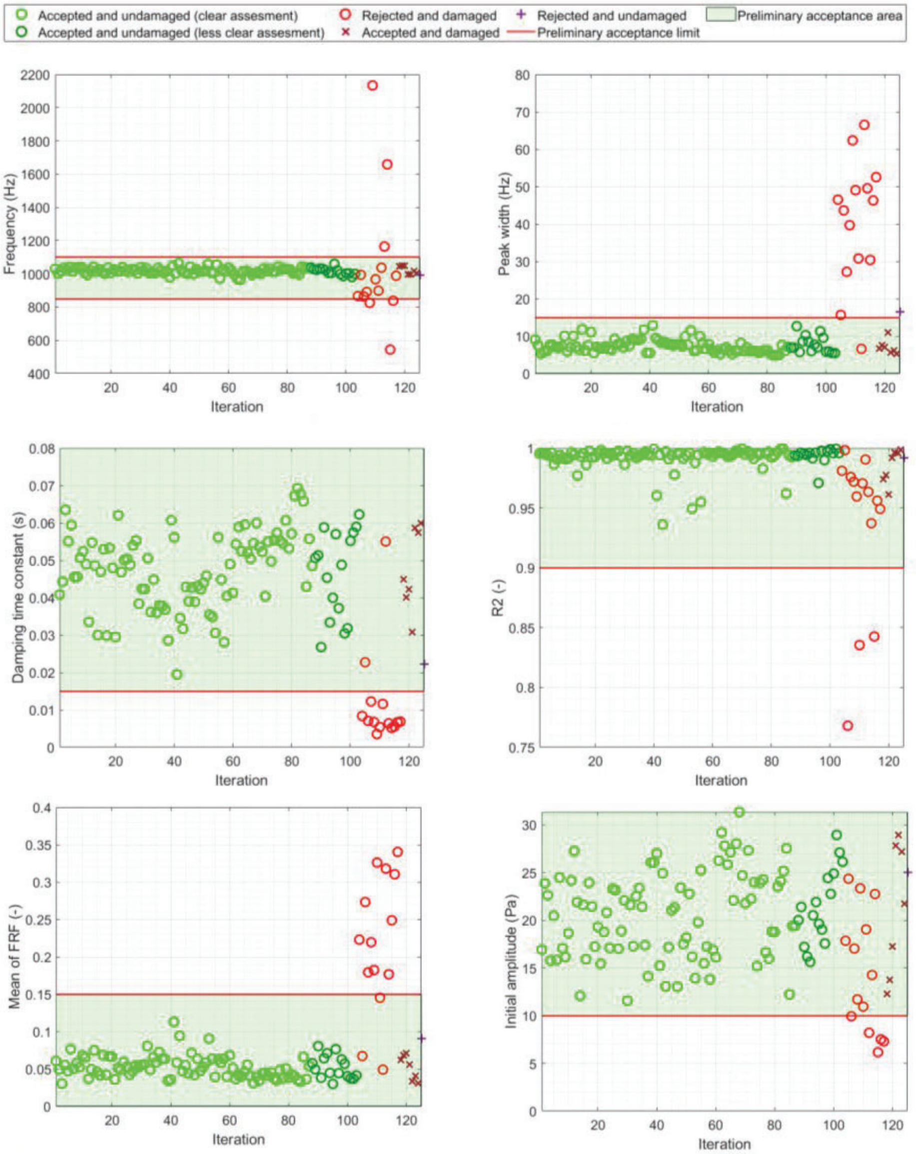

Figure 10. Overview, for each criterion, of the values obtained for each measured plate of type 1. The colour of the markers is associated with the X-ray assessment (damaged or undamaged) and indicated in the legend box. [9]

Table 2. Overview of ATD and X-ray image results for plate Type 1.[9]

	ATD result: accepted	ATD result: rejected
X-ray result : undamaged	103	1
X-ray result : damaged	7	14

Despite the very small number of plates used to determine the acceptance limit, 117 out of 125 acoustic measurements gave the same results ("match") as the X-ray analysis, i.e. 93.6%, and eight acoustic measurements gave different results ("mismatch"), i.e. 6.4%. These promising results, can be explained by the large difference in the acoustic response ("on/off character") between damaged and undamaged plates. The X-ray images revealed that the ATD failed to notice in 7 out of the 21 plates labelled as a mismatch "x", because of the following defects:

- One plate had a small piece of ceramic broken off in a corner. Such defects typically show little influence on the acoustic response.

- Three plates showed manufacturing defects on the X-ray (see Figure 11). The influence of such defect on the acoustic response is not precisely known.
- One plate showed an unusual crack pattern in a serpentine shape, possibly caused by shrinkage.
- One plate showed a crack visible on the upper right corner of the plate. The influence of such a crack on the acoustic response might be limited, as its position lies well off the path between actuator and microphone.
- One plate showed three clear cracks, but the FRF was very similar to a undamaged plate.

This analysis shows that 3 out of 17 plates with visible cracks on X-ray were undetected with the ATD.

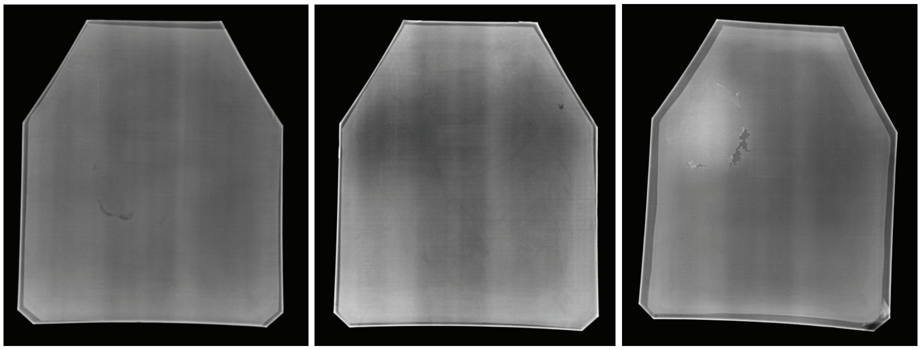

Figure 11. X-ray of the three plates which were accepted by ATD with mismatching result compared to the X-rays analysis (i.e. damaged) due manufacturing defects.

3.2.2 Result Type 2 plate

The construction of the Type 2 plate consists of a thin impact protective foam, a fully wrapped monolithic SiC ceramic bonded onto a UHMWPE backing, all enveloped in a textile cover. Evaluating their condition based on acoustic response is challenging, as in one of the damaged plate even large cracks had a less significant impact on the FRF compared to type 1 plates as shown in Figure 12.

During the campaign, 53 type 2 plates were measured using the ATD. Establishing preliminary acceptance limits was not yet possible. Further studies are taking place to understand the reasons behind this limitation of the ATD, and to improve the method's applicability and sensitivity.

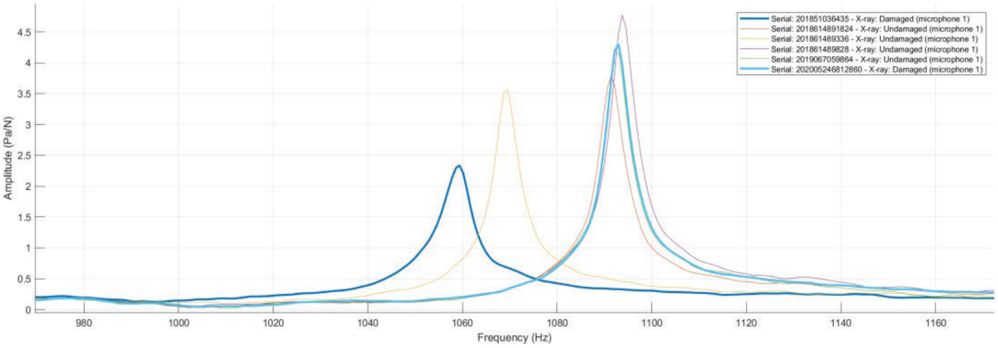

Figure 12. Frequency Response Function (FRF) of the six plates of type 2 used for pre-tests with zoom on the 1st vibrational mode. Damaged plates are plotted in bold. [9]

5. SUMMARY

Different techniques for the detection of defects in ceramic body armour were discussed. Two NDI techniques have been assessed by TNO to detect defects in ceramic body armour plates: infrared inspection during cooling down a heated plate and the MEMS sensor array inspection. Both methods provide information about the size and location of cracks and could be suitable for use in portable systems. Especially the MEMS sensor array system is an interesting technique to further investigate its potential for ceramic body armour plates.

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One go/no-go evaluation technique, impulse excitation, was evaluated with two plate types differing in construction. Although this technique is simple to use, setting the conditions for a go/no-go approach is dependent on the plate construction. The ATD shows promising results; a relatively simply constructed plate shows large difference in the acoustic response between damaged and undamaged plates; of the 17 plates with visible cracks on the X-ray, 14 were detected by the ATD. Additionally, only 1 out of 104 plates with no visible defects on the X-ray was incorrectly identified as defective. It becomes challenging when even large cracks have a less significant impact on the acoustic response as appears to be the case with a plate more complex in design. Understanding the reasons behind this is essential for further developing the ATD, to improve the method's applicability and sensitivity.

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