Experimental-based numerical simulation of the drop test within NIJ Standard-0101.06 for personal hard armour development

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Abstract. Personal hard armour systems seeking certification within the NIJ Standard-0101.06 have to meet the minimum required ballistic performance after being adequately conditioned. Said conditioning process is detailed in the same standard and comprises a drop test scenario. Passing the drop test currently involves extensive experimental testing that has to be carried out at a late stage in the armour system development, with consequently high costs and business risks. This often results in unnecessarily over-engineered plates. The current study details the creation and use of a numerical tool able to accurately predict drop test performance with the Finite Element Method at a fraction of the cost and risk involved in the purely experimental approach. This work is the result of multiple years of experimental testing and correlation work on both ceramic materials and UHMWPE. Particular care was taken in ensuring the correct behaviour of the material models at the strain rates involved in drop testing, as opposed to usual ballistic testing; the study also involved a sensitivity analysis on the resolution required to adequately capture the fragmentation behaviour, leading to an element size as small as 0.25 mm. This was made possible by the latest progress in the simulation software and hardware. Simulated drop test results from the numerical model are compared to laboratory-controlled experimental testing based on the NIJ Standard-0101.06 and successfully validated with high-speed videos, X-ray and thermal analyses. The tool has deepened the authors' understanding of the response of the plate to drop test and is currently being used to develop a personal armour system able to meet the NIJ requirement at minimum weight and bulkiness.

1. INTRODUCTION

Personal armour systems, due to their intrinsic and very specific destination, are often worn in harsh environmental conditions: this applies both in terms of being subjected to adverse external agents (i.e. extreme temperatures, exposure to water and/or other liquids, etc.) and in terms of mechanical loads due for example to accidental drops.

In order to provide the end user with confidence that a personal armour system would be able to deliver the expected ballistic performance in the field, armour manufacturers can choose to certify their products under a recognised minimum performance standard. One of the most recognised standards worldwide is the current NIJ Standard-0101.06 "Ballistic Resistance of Body Armor" [1], which is part of the Standard and Testing Program of the National Institute of Justice (NIJ), Office of Justice Programs, U.S. Department of Justice.

Apart from specifying the minimum ballistic performance against a variety of threats, the NIJ Standard-0101.06 also provides detailed information regarding the pre-conditioning phase that all personal armour systems have to undergo before the actual ballistic testing; said pre-conditioning is meant to provide some indication of the armour's ability to maintain ballistic performance after being exposed to conditions of heat, moisture, and mechanical wear.

In modern composite hard armour systems, the primary strike face often comprises a type of ceramic. The undamaged ceramic is not adversely affected by weathering, ageing and exposure to other external agents, however impact loads can have a detrimental effect on it due to its brittle nature [2].

A particularly strict requirement is thus given by the drop test scenario, which under the current NIJ standard applies to all personal hard armour systems.

Currently, personal armour systems have to be tested in a late stage of the product development: in fact, the mere production of a prototype requires a thorough design study and the availability of suitable tooling for sintering the ceramic plate. In case the prototype fails to meet the required minimum performance, the product development is forced to step back to the design study, in a resource-consuming iterative process. This is connected to very high business risks, which are currently often mitigated by over-engineering the personal armour system. Furthermore, apart from adding undesirable weight and bulkiness to the product, this approach can potentially discourage manufacturers from investing in innovative – and consequently high-risk – solutions [3]. An example of a high-risk solution is represented by double curved plates, as opposed to single curve plates: although the former are preferable from an ergonomic standpoint, if dropped their shape causes a single point contact that is more likely to initiate damage. Consequently, if a drop-resistant certified solution is required, in the authors' experience several manufacturers rely on the simpler and well-proven single curve plates, despite their ergonomic drawbacks, or use tougher materials with a lower ballistic performance, thus sacrificing weight.

An alternative and currently unexplored risk mitigation strategy relies on anticipating the drop survivability by means of Finite Element Analysis (FEA). If correctly applied, this technique can provide unparalleled benefits in terms of weight and cost saving, reduce product development time, and boost innovation towards newer materials and design solutions.

The current paper details the creation, correlation and validation of a tool based on the Finite Element Method (FEM) and aimed to replicate – and ultimately predict – drop test performance of a personal armour system. It includes a description of the experimental drop test and the experimental studies that led to a thorough understanding of the performance of armour materials under load conditions, as well as a detailed analysis of the damage mechanisms that may occur in a drop test. The study has been conducted by Simpact Engineering Ltd., in collaboration with Morgan Advanced Materials, Composites and Defence Systems, a subsidiary of Morgan Advanced Materials Plc.

2. EXPERIMENTAL DROP TEST

The prototype personal hard armour system, the acceleration data acquisition system and facilities were provided by Morgan, while the high-speed video recording system was jointly provided by Simpact and Morgan. The drop test, described in more detail in the following subsection, was carried out in accordance with the NIJ Standard-0101.06.

2.1 Prototype hard armour system

The personal hard armour system analysed in this study is a double curved composite hard armour chest plate – shown in **Figure 1** – currently under development by Morgan. Said personal hard armour system, referenced in the following as "armour plate", has been proven by the manufacturer to be able to withstand multiple ballistic impacts of an NIJ Level IV threat as a stand-alone item. The armour plate includes a nylon cover, a silicon carbide (SiC) plate and an Ultra-High Molecular Weight Polyethylene (UHMWPE) backing. The interface between these layers is provided by proprietary components.

Figure 1. Prototype hard armour system

2.2 Drop test

Details of the drop test procedure are specified in the *Conditioning Procedure* paragraph in the NIJ Standard-0101.06. As exemplified in **Figure 2**, the armour to be tested is attached to a purposelydesigned test rig through a harness system. A mass of 4.54 kg (10 lb) of calibrated Roma Plastilina clay – used as a backing material – is placed between the armour and the rig.

In order to be certified, the personal armour system must deliver the minimum required ballistic performance after being dropped on a hard surface in a controlled and repeatable test from a minimum height of 122 cm (48 inches).

The NIJ Standard-0101.06 calls for a total of two drops; in the current test, however, the goal is to study the damage in the ceramic tile and aim for its complete elimination – the underlying logic being that if a personal hard armour system shows no damage after a single drop, it will similarly resist to any number of subsequent, identical drops. Only one drop was thus planned.

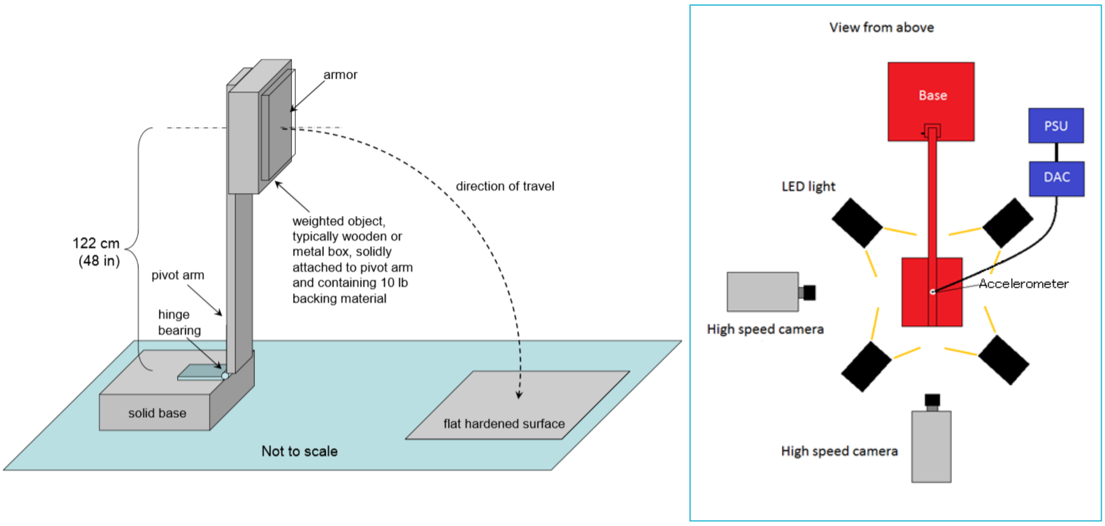

Figure 2. NIJ drop test set-up (left) and experimental set-up (right)

The test was carried out at Morgan's facility in Coventry. The experimental set-up, depicted in **Figure 2**, included an accelerometer connected to the test rig, two Photron FASTCAM high speed cameras and four 6000 lumens Simpact ICARUS LED lights.

The test armour was fractured as a result of the drop. Due to natural play in the drop rig, the armour impacted the hard target surface with a small angle that caused the impact point to be off-centre. The test was nonetheless considered valid and representative of a normal NIJ Standard-0101.06 drop test.

The outer layers of the chest plate were then carefully removed to expose the underlying damage to the ceramic tile. A penetrative dye was applied to the left side of the plate to highlight the crack pattern, as shown in **Figure 3**.

Figure 3. Test armour with visible damage pattern in form of cracks

2.3 Preliminary discussion of drop damage

In a personal hard armour system with an ergonomic shape, the double curvature of the ceramic plate usually leads to a single point of contact between the plate and the flat hardened surface, thus generating high localised forces that can damage the armour.

The damage on a fractured armour system can be qualitatively organised in four main categories, with reference to **Figure 4**:

- Cone-shaped crack (blue)
- Radial cracks (red)
- Circular shaped crack around the contact point (green)
- Laminar cracks (yellow)

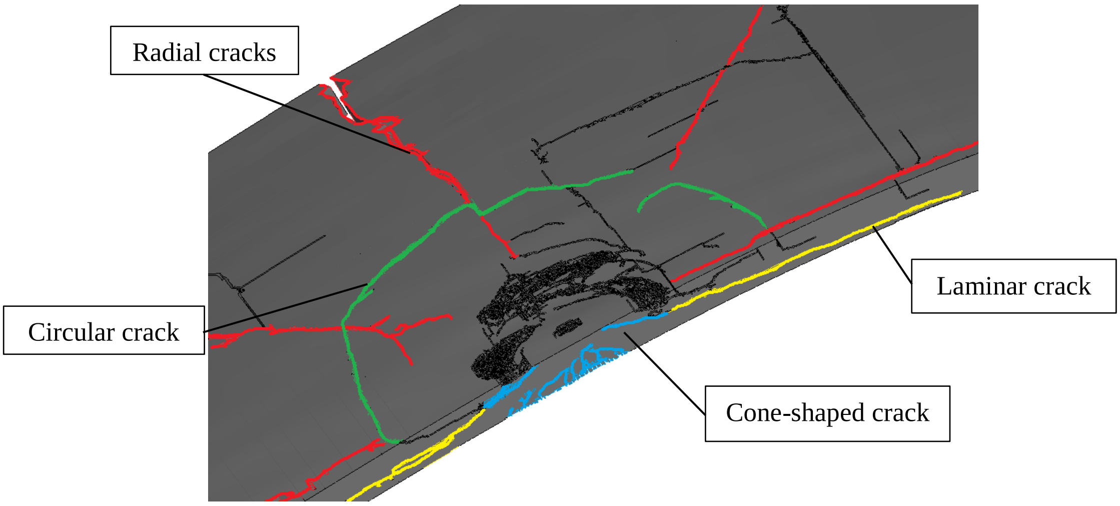

Figure 4. Damage types from FEA (sectional view)

The last-mentioned type of damage is referred to as "laminar" cracks because of the resemblance of the damage to what would be described as delamination in composite materials.

The ultimate goal of the NIJ procedure is to assess the ballistic resistance of the armour; consequently, even a personal armour system that is damaged as a consequence of the drop test can be certified under the NIJ Standard-0101.06, providing that the damaged armour does still retain the desired level of ballistic resistance.

Morgan has carried out numerous tests in order to assess the effect of various types of damage, and concluded that the visible hairline cracks in damaged armours do not have a catastrophically detrimental effect on the ballistic performance; this is also supported by other studies [4]. Damage due to laminar and cone-shaped cracks of the ceramic tile is however proven to be responsible for a critical loss in ballistic resistance. This can be attributed to a reduced confinement pressure [5]. It is thus a key priority for any successful numerical model to be able to correctly represent this fracture mode.

3. NUMERICAL MODEL

The numerical model is set up in RADIOSS, a finite element solver within the HyperWorks suite which is distributed by Altair Engineering. The software's capability of solving complex non-linear dynamic problems using an explicit integration scheme makes it well suited for this study.

Finite Element Analysis (FEA) has been successfully applied in multiple branches of engineering, and is becoming more widespread together with the increase in available computational power. FEA is a fully repeatable environment, insensitive to experimental and measurement errors, which allows the obtainment of stress and strain information that is otherwise difficult – if not impossible – to achieve. Another advantage of FEA is its potential to provide a deeper understanding of the dynamics involved in complex and fast interactions between different components, like in the case of impact simulations [6][7].

In order to provide accurate and reliable results, finite element models need to be tailored to the case at hand by defining the exact geometry of the system and the mechanical behaviour of the various materials. Experimental testing is thus required to support FEA.

3.1 Experimental tests and material modelling

The ceramic and UHMWPE material models that will be used in the FE model are the result of a two-year Technology Strategy Board (now Innovate UK) funded collaborative Research and Development project "Transforming the Role of Simulation in New Product Development" in which the authors of this paper have been involved. Said project included a vast amount of ballistic tests and Hopkinson-bar experiments carried out at different impact velocities and with varying sample sizes. These studies allowed the authors to get a deeper understanding of the fracture mechanism of silicon carbide, and in particular of its dependency on strain rate: the ceramic material model developed by the authors thus replicates the typical behaviour of the silicon carbide when subjected to impacts occurring at the comparatively low speeds that characterise drop scenarios [8].

An extensive analysis was also carried out to investigate the element size dependency of the UHMWPE material model [9][10], in order to obtain an optimised correlation between the experimental and the numerical results.

The model used for reproducing the behaviour of the Roma Plastilina clay [11][12] was calibrated accordingly to the *Backing Material Consistency Validation* subsection of the NIJ Standard-0101.06.

Finite element modelling of the nylon cover required some *ad hoc* testing, since most of the available technical literature such as [13][14] does not focus on dynamic transverse loading. Compressive quasi-static tests on nylon samples of varying sizes were carried out in collaboration with WMG, part of the University of Warwick. A series of drop tests involving a steel ball dropped on a nylon sample were performed as well to capture the dynamic response of the material. The experiments were replicated using FEA and the finite element models correlated to the physical experiments.

3.2 Acquiring the geometry

To achieve the desired level of detail in FEA results, it was the authors' priority to have in the numerical model an exact representation of the actual geometry of the armour. Due to the nature of ceramic sintering, there is a certain degree of variation between plates, and consequently no fully representative CAD was available. Thus, the required accuracy was achieved by acquiring 3D scans of the armour itself with a Konica Minolta *VIVID VI-9i Non-Contact Digitiser*, shown in **Figure 5**. With the set-up described in **Table 1**, the laser scanner has been verified to achieve a positioning accuracy of ±0.13 mm, which is regarded by the authors as a satisfactory value.

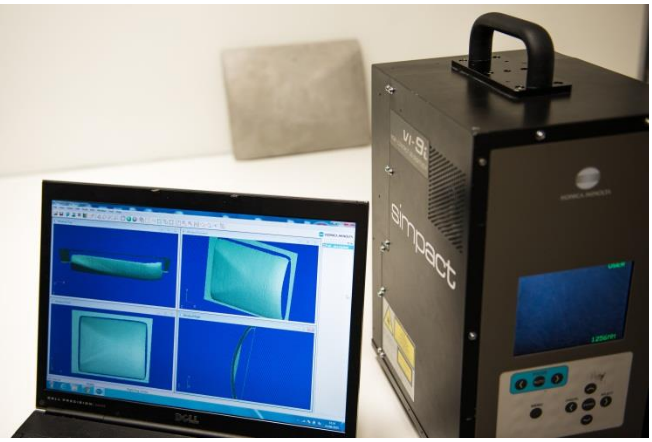

Figure 5. Example of scanning set-up for chest plate acquisition

Table 1. Scanning set-up

Scanner name	Scanner type	Distance	Background	Surface treatment
Konica Minolta *VIVID VI-9i*	Non-contact	600 mm	White, non-reflective	White powder coating

The acquired stereolithography (STL) data of the armour was then imported in Altair's HyperMesh and constituted the basis of all the subsequent finite element modelling.

3.3 Building the model

The number of elements that constitute a Finite Element model is critical in determining the accuracy of the results, with high numbers of elements leading to an increase in resolution and accuracy. However, an excessive number of elements can slow down the analysis. As an optimum solution between accuracy and resources, it was decided to maintain a relatively high resolution in the central part of the ceramic tile – which is known from the experimental tests to be the part most affected by the cracks – and to use a progressively coarser mesh towards the external parts of the tile. The chosen element size determines the reference length used in the Finite Element strain calculation. This was taken into account during the definition of the material properties for the respective elements. This approach led to a lean model which still allowed the crack to grow freely, with minimal detrimental mesh-induced effects.

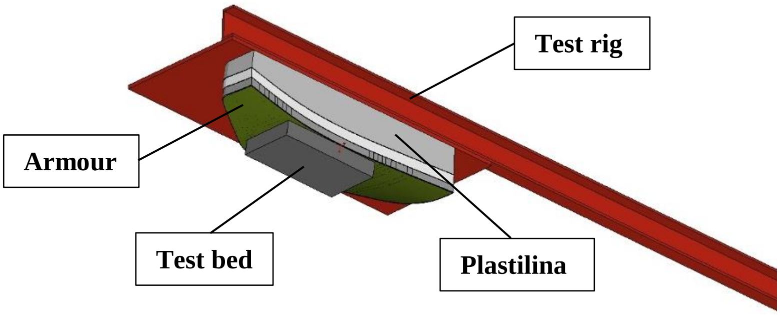

Figure 6. Complete FE model showing components of the finite element model assembly

Furthermore, as seen in **Figure 6**, due to the symmetry of both the armour and the load case, only half of the geometry was represented in the model. The resulting number of elements that constitute the plate is in the order of $5x10^6$, which gives a suitable balance between the computational time and the desired accuracy.

The model is calibrated to simulate the events between the first contact and the completion of crack propagation. Damage due to secondary impacts is not considered.

3.4 Results

Figure 7 illustrates the progression of the damage in the ceramic plate as predicted by the FEA.

The first damage occurs approximately 35 µs after the first contact. This is due to two main damage mechanisms: the shock wave propagating through the thickness of the plate initiating failure due to spalling and a bending moment acting on the ceramic plate due to inertia and the curved shape of the armour.

All the subsequent cracks are driven by the bending moment and propagate in a predictable way, mainly dependent on the shape of the plate.

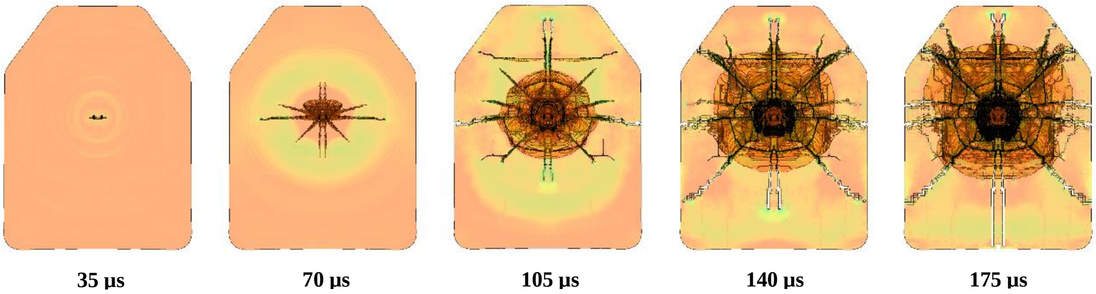

Figure 7. Progression of damage in the ceramic plate

The first crack, starting to develop between 35 and 70 µs, is directed radially along the latitudinal direction due to the main curvature of the plate; similarly, the second radial crack is longitudinal and reflects the secondary curvature of the plate. At 70 µs, the cone-shaped crack starts to propagate. At 100 µs after the first contact, the cone-shaped crack has developed in a laminar crack, and the plate is already divided by radial cracks into several sectors; each sector is then split width-wise by another series of cracks, which forms the roughly circular crack pattern visible in **Figure 8**. This sequence of events can also be inferred by the shape and positioning of the cracks from the X-ray scan discussed in the following: in particular, it is possible to notice that the circular fracture is formed of smaller segments that spread from two pre-existing radial cracks.

The components other than the ceramic element in the set-up do not show any noticeable deformation, and they have no effect on the fragmentation of the ceramic plate.

4. OBSERVATIONS AND ANALYSIS

The above-described results were correlated and validated using different tools and techniques, as shown in the following subsections.

4.1 Visual evaluation of damage and crack patterns

The first, visual assessment was carried out on the basis of the type and appearance of the cracks, shown in **Figure 8**.

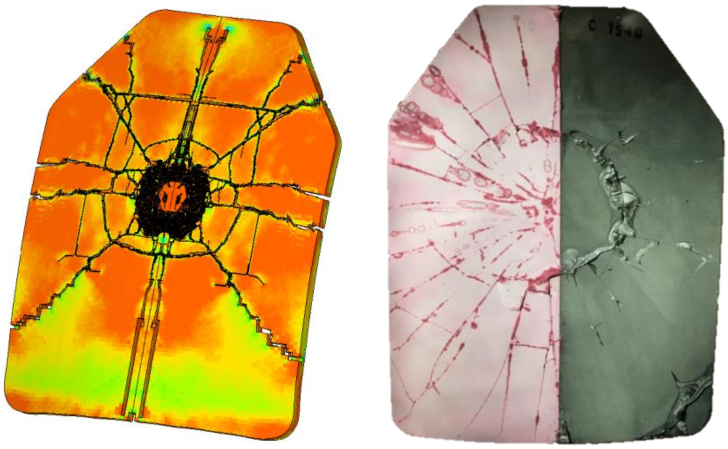

Figure 8. Damaged armour showing pressure contour

Although the model appears to overestimate the damage in the contact area, all the characteristic damage types described in paragraph 2.3 are clearly distinguishable; the numerical model thus appears to be able to effectively reproduce all the required damage behaviours.

4.2 X-ray correlation

A further correlation was carried out by comparing the FEA results with a series of X-ray scans shown in **Figure 9** and **Figure 10**. Due to the limited field of view of the X-ray scanner, it was not possible to fit the entire armour in a single scan. Instead, 24 smaller scans were taken and subsequently merged in a single image (see **Figure 9**, on the left). Unfortunately, the gap created by laminar cracks is below the resolution allowed by X-rays, and the internal damage of the actual plate could thus not be seen from the scans. It can instead be clearly seen in the FE model. Regarding external damage, the only difference lies in the number of radial cracks, which are more numerous in the physical plate.

It should nonetheless be considered that in the experimental test the armour actually impacts the test floor several times due to rebounds, while the numerical model reproduces one single impact event; this can at least partly explain the difference in the number of radial cracks, since some of the cracks could be formed during a secondary impact.

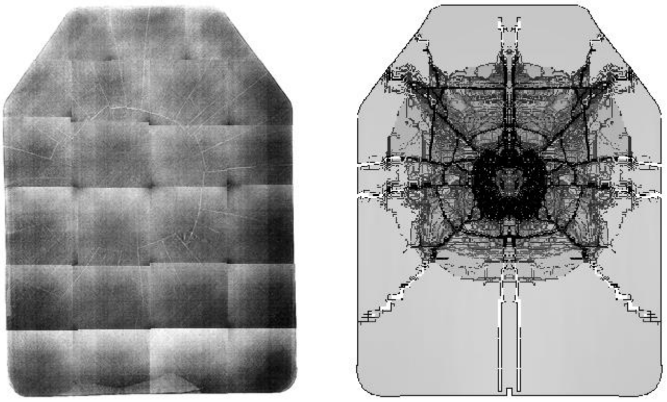

Figure 9. Comparison between X-ray scan (left) and numerical results (right) shown in transparency

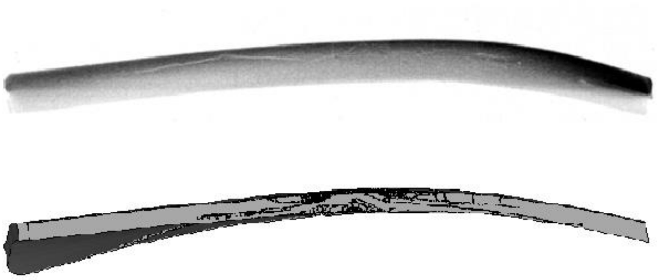

Figure 10. Comparison between lateral X-ray scan of a similar plate (top) and numerical results (bottom)

The X-ray scanner at the disposal of the authors did not succeed in obtaining a side view of the ceramic plate, due to its excessive width. For correlation purposes, an X-ray scan of a similar plate [15] was used instead. Although said plate had been dropped twice (instead of once, like in the test under study) the conical-shaped fracture and the laminar cracks are clearly visible in both the scan and the FEA results.

4.3 Accelerometer results

During the experimental drop test, the test rig was instrumented with an accelerometer. The acceleration values (**Figure 11**) were intended to aid the correlation process, however the authors found that the time scale of the acceleration seen by the accelerometer was one order of magnitude larger than the duration of the crack propagation. The duration of the impact from first contact to null velocity is 4.45 ms, while from the FE model it is known that the propagation of the crack is complete after less than 0.2 ms; this value has been experimentally found compatible with the speed of cracks propagating through glass obtained from high-speed video analyses carried out by the authors.

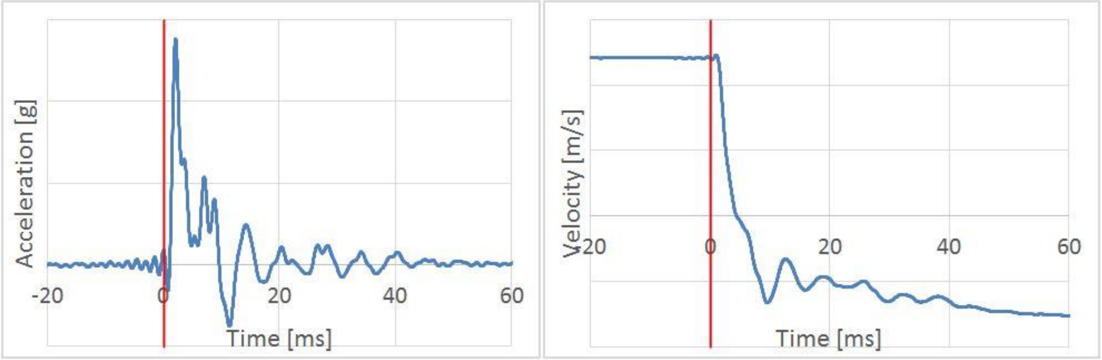

Figure 11. Accelerometer results. The red bands indicate the duration of actual cracking phenomenon

The crack propagation is complete at a very early stage during the impact event. Similar to what is shown in the FEA, neither the accelerometer nor the high-speed camera were able to detect any effect on the fragmentation behaviour attributable to the components laid behind the ceramic plate. This supports the thesis that the fragmentation – or lack thereof – of the plate is mainly dependent on its own characteristics and suggests that the outcome of the drop test is only dependent on the characteristics of the hard armour itself and on the cover of its strike face.

However, in the acceleration results it is possible to recognise a distinct oscillation, showing a period of approximately 6.5 ms. In order to better understand this behaviour, a linear modal analysis was carried out.

4.4 Modal analysis

In the observed oscillation period range, the model showed a flexural mode of the test rig with a frequency of 155 Hz, corresponding to a period of 6.45 ms. Said flexural mode can be seen in **Figure 12**.

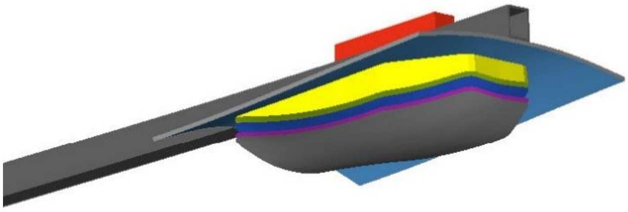

Figure 12. Amplified 155 Hz flexural mode from modal analysis

The same flexural mode was directly observed in the high-speed video of the experimental drop test, showing again the same oscillation period of approximately 6.5 ms. The accelerometer values are thus reflecting this motion, and are not directly relevant to the fragmentation behaviour of the plate.

4.5 Thermal analysis

A thermal analysis was conducted using a FLIR A35 thermal camera, the purpose of the experiment being to highlight any damage that was not apparent from the X-ray correlation. The damaged armour was heated with a 1200 W infrared heater until uniform temperature of 27±0.5 ºC was achieved. The temperature range was monitored throughout the heating procedure by means of the thermal camera to ensure uniform heating. After reaching the desired temperature, ice was locally applied to the point of impact. While in an undamaged armour the resulting temperature gradient would be circular, due to the discontinuities now present in the material, the thermal image clearly highlights the crack boundaries. These results are similar to the numerical results shown in **Figure 13**. Further analyses based on the Pulsed Phase Thermography technique [16] are currently under consideration.

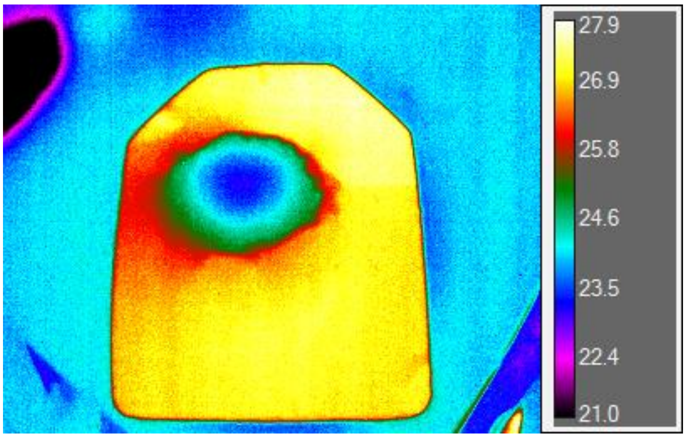

Figure 13. Results of thermal analysis

5. CONCLUSIONS

The survivability of a personal hard armour system subjected to accidental or test-related drops is confirmed to be a critical aspect to be considered in the product development phase. In this respect, Finite Element Analysis proved to be a reliable and accurate tool to predict drop test performance. Furthermore, the application of FEA to the NIJ Standard-0101.06 drop test allowed the authors to get a deeper understanding of cracks occurring during the drop test which are not visible by simple optical inspection.

The developed model will allow its users to investigate the effects of different materials and design solutions on the outcome of a drop test in a preliminary phase of product development, minimising the need for experimental testing and reducing costs. The availability of a numerical model will also encourage the development of innovative solutions that would otherwise present high business risks.

The knowledge acquired during this study and the numerical tool here detailed are now the basis of an ongoing study aiming to achieve a robust pass of the NIJ Standard-0101.06 drop test at minimum weight and bulkiness.

Acknowledgements

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