The influence of non-visible damage on the performance of aircrew helmets.

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Keywords: *Aircrew Helmets, Non-Destructive Evaluation, Impact Testing*

1 Abstract

All helmets are susceptible to damage during normal use. However, this is particularly true of aircrew helmets which have to endure particularly severe in-service conditions, such as canopy strike during agile combat or 'buffeting' in the rear of helicopters or transport aircraft.

Due to the design features of helmets i.e. an outer composite shell with internal foam liner, potentially strength reducing damage is not always visible externally. The extent of the problem caused by non-visible damage is not known for current UK aircrew helmets. A study has therefore been completed within the Military Aircrew Helmet Impact Standard (MAHIS) working group [1], to determine how much energy a helmet can absorb without visible damage, and subsequently to determine what affect non-visible damage may have on helmet performance.

To determine the extent of non-visible damage, a range of non-destructive evaluation (NDE) techniques have been used to inspect helmets, prior to residual performance testing. All of the NDE techniques investigated provided some useful data to help identify non-visible damage. However, two of the techniques, thermography and CT scanning, appeared to offer the best solution for damage detection in helmets.

2 Introduction

Polymer composites exhibit a low strain-to-failure and as a result are highly susceptible to damage in the form of microcracking, when subjected to repeat thermal or mechanical loading [2]. These microcracks often coalesce, leading to other damage modes, including fibre/matrix debonding and delamination. Generally this type of damage occurs internally in composites and is therefore not detectable from a visual assessment of the surface. If this damage is not detected or repaired the structural capacity of the composite part could be seriously impaired.

Protective helmets typically consist of a fibre reinforced polymer (FRP) composite shell with an impact attenuating foam liner. As with all FRP structures these skins would be expected to show internal damage following a relatively low energy impact. Two of the current aircrew helmet types have been used for this investigation; Mk4 (for use in static seat aircraft) and Mk10B (for use ejection seat aircraft) (shown in Figure 1).

Figure 1: Photographs showing variants of the UK aircrew helmet.

The Mk4 series of helmet consists of a glass fibre reinforced polymer (GFRP) composite shell with a polystyrene attenuating foam liner. This helmet was introduced into military service in the early 1980s. The Mk10B helmet is an adaptation of the Alpha helmet manufactured by Helmet Integrated Systems Ltd (HISL) and was introduced in the early 1990s. This helmet is considerably lighter and consists of a hybrid skin containing carbon/Kevlar reinforcement and a polyurethane foam liner.

Both helmet types are subjected to hazardous environments in-service and in-particularly during emergency escape situations, where there is a higher probability of head impacts and injury. It is therefore important to ensure that the helmets offer full protection during their entire lifetime.

This paper details a study carried within the Military Aircrew Helmet Impact Standard (MAHIS) working group to determine the extent of non-visible damage possible in the Mk4 and Mk10 series aircrew helmets. Also detailed is the evaluation of methods to determine non-visible damage and the laboratory tests performed to determine the residual performance after the introduction of non-visible damage.

3 Evaluation of NDE Techniques

3.1 Techniques

Non destructive evaluation is the name given to the various techniques which allow inspection of a component without impairing serviceability. NDE techniques were developed primarily for the inspection of metal components, but in recent decades they have been commonly used for quality control and in-service surveillance of FRP composites. The most frequently used methods for NDE of FRPs are ultrasonics and x-radiography; both are readily able to detect failures such as delamination. The majority of FRPs examined using NDE techniques are simple structures. Unfortunately helmets have a complex layered structure which causes severe difficulties when using some of these techniques, particularly when attempting to detect shell/core debonding.

Four NDE techniques were selected for trial application to aircrew helmets; ultrasonic, low energy vibration, x-radiography and thermography. Pulse echo ultrasonics were used for the purposes of this study; this is a single sided technique used in both production and in-service inspection. Specifically, the QinetiQ designed ANDSCAN [3] was utilised. This system used water coupling and a hand held probe to examine the impact area. The second technique was a low frequency vibration technique using a BondMaster with a Pitch/Catch attachment. The method again uses a hand held probe which is swept over the structure recording changes in structural density. One advantage of this technique is that there is no need for a couplant. This technique has been found to be particularly suited to the inspection of thin skin, bonded structures such a honeycomb panels. Both techniques rely on the fact that, as waves travel through a structure, they are modified by the presence of boundaries (changes in the structure such as defects or bond lines). By scanning the surface, local changes (defects) in the structure can be determined.

The third technique, thermography, involves locally heating the surface while an infra red image is observed. Thermography works best on a material with a fairly uniform thermal conductivity. Typically, glass fibre materials fall into this category. The method is based on the characteristics of heat flow phenomenon. In general, all geometrical anomalies or material discontinuities influence the propagation of heat flow. Hot spots observed in the IR image are indicative of disbonds or delaminations in the material. Thermography is a very fast inspection technique, which is also non-contact and allows a large area of the helmet to be inspected in a single image. For this study a commercially available thermography system, ThermoScope, was used at Bath University.

The final technique used was x-ray computed tomography (CT). In CT scanning a flat, fan-shaped beam of x-rays penetrate a thin slice of the component and the intensity of the transmitted beam is recorded. Damage/defects within the structure influence the transmitted x-ray beam. Computed analysis of the absorption profiles enables a cross-section image of the sample to be constructed, without any interference from the underlying (or overlying) material.

3.2 Results and Discussion

Initially two helmets were investigated; one of a Mk4A and one of a Mk10B design. Each of the helmets was subjected to two impacts onto a flat anvil, producing headform decelerations of ~ 120G and ~ 50G. After impacting, the visible surface damage on each of the helmets was negligible.

The helmets were investigated using the BondMaster and ANDSCAN methods. The study found that, due to the materials and methods used in the construction of the Mk 4 helmet, a high baseline attenuation was apparent during pre-impact NDE. As a result any minor damage following impact was indistinguishable. On the Mk 10 helmet the vibration and ultrasonic techniques were able to identify areas of damage. The extent of the damage region is identified in Figure 2.

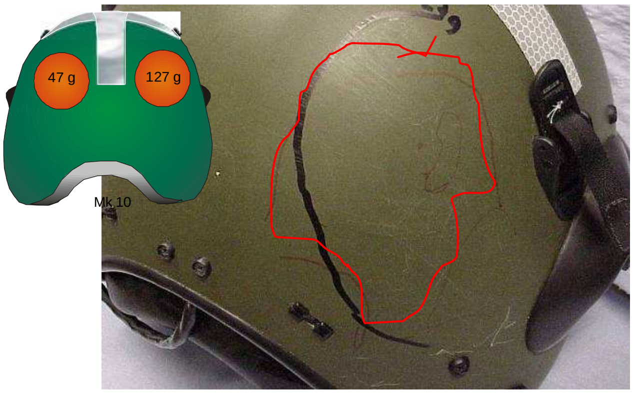

Figure 2: Photograph showing damage area detected using ultrasonic and vibration NDE techniques.

It was observed that the areas around the attachments could not be investigated due to large attenuation changes. This is likely to be a significant problem for detecting damage in in-service helmets as previous investigations [4] have shown that many accident damaged helmets have damaged areas near to helmet attachments.

Identification of any impact damage in the helmets was obtained by dissecting the helmets in the impacted region. These sections were visually examined before being examined in greater detail using a scanning electron microscope (SEM). Dissection of the Mk4 helmet revealed no evidence of specific damage to the helmet as a result of the impacts. It is therefore suspected that variation in skin thickness and bonding between the foam and skin caused the high baseline attenuation observed. For the Mk10B helmet the skin and foam were found to have debonded at the impact site, although the debonded areas were not as large as the areas indicated by NDE. The difference in the measured and actual debonded region was due to the difficulty in determining small changes in attenuation against a high attenuating background.

Further trials with these NDE techniques on impacted helmets showed that gross defects could be detected, but that the need to constantly reference the baseline structure made this a very time consuming inspection method. It was therefore concluded that the application of these NDE techniques to current aircrew helmets was not suitable.

CT-scanning was initially used within the MAHIS working group to study in-service accident damaged aircrew helmets. The study tried to identify a link between impact damage in a helmet and human injury. The initial study showed that CT-scanning was a useful technique when looking for damage in the helmet skins and within the foam of the Mk4 helmets [4]. Mk4 helmets were characterised by the compressed polystyrene foam following impact; a phenomena termed ‘residual set’. The shape of this region indicated both the impactor shape and applied force, see Figure 3. It was found to be more difficult to detect damage in the foam of the Mk10 helmets because there was minimal residual set in the polyurethane liners.

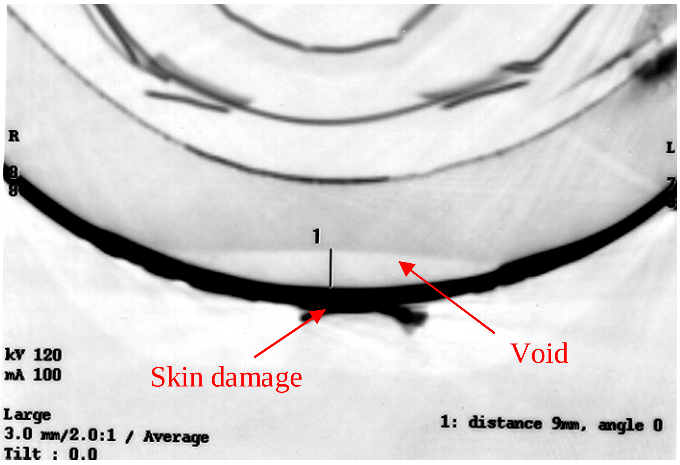

Figure 3: CT-tomogram showing damage in the polystyrene attenuating foam and skin of a Mk4 helmet.

Although the CT scanning technique was found to be successful in characterising significant foam damage (in the Mk4) it was not able to detect small skin/foam delaminations in either the Mk4 or Mk10 helmets. This was largely due to interference from metal attachments in the helmet.

Thermography was found to be the simplest and quickest technique for examining any impact damage. The technique was able to determine various forms of damage, both within the paint layer and shell. Figure 5 shows the thermography images of the helmet after a duration of 0.8 seconds and 2.4 seconds. The time of the image is directly related to the position of the artefact through the thickness of the skin. The second image shows a larger damage area, corresponding to the fact that the damage within the skin is larger towards the back (inner) surface of the helmet shell; approximately twice the delamination area.

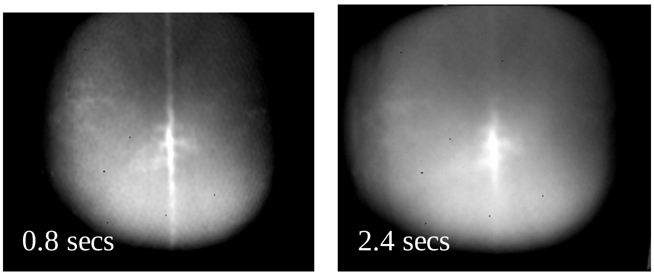

Figure 5: Thermography image of helmet after 0.8 secs and after 2.4 secs.

Unlike the previous NDE techniques investigated, thermography was not affected by the presence of the metallic attachments; therefore it was possible to investigate damage in all parts of the helmet (see Figure 6).

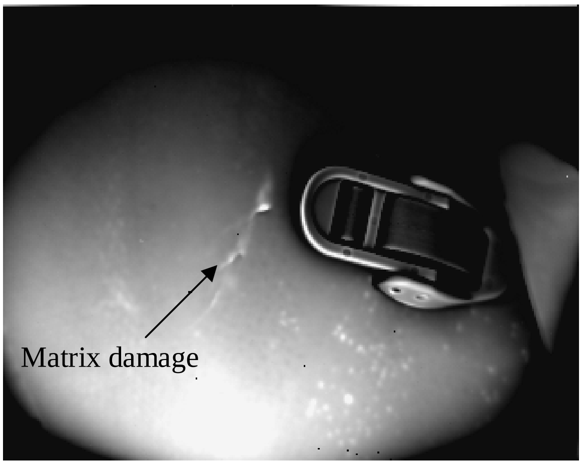

Figure 6: Thermography image showing skin damage on the side of a Mk10 helmet.

To investigate the ability of the technique to determine skin/foam debonding, a section of foam liner was removed from a Mk10 helmet. Figure 7 shows the thermography image recorded. Although it was possible to detect the missing region of foam liner, the images were not thought to be suitably reliable and hence it was concluded that the technique would not be able to determine foam liner debonding or crushing.

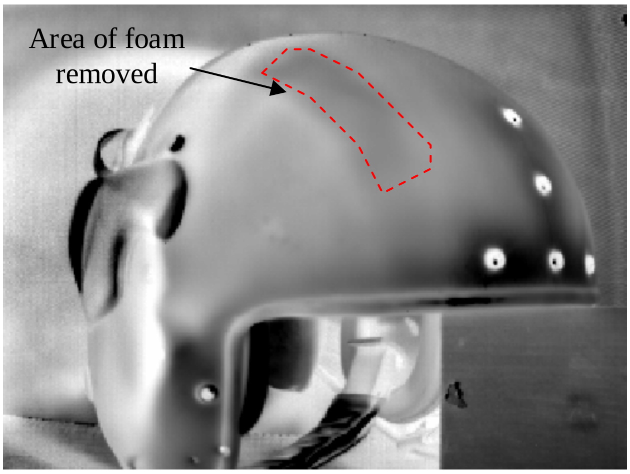

Figure 7: Thermography image showing variation in heat transfer at the skin/foam interface.

4 Development of Non-Visible Damage

A series of twenty five Mk4A and Mk10C, helmets were subjected to low energy impacts on the rear, side and crown, using a standard BS6658 drop tower and a J size ISO head form. This was carried out primarily to determine the maximum force that could be applied to the helmet without causing visible damage.

In general, it was noted that most low energy impacts onto the Mk10 helmet resulted in minor visible damage to the surface. Only impacts from less than 0.25m (approximately 50 G measured headform deceleration) resulted in an undamaged surface. The surface damage ranged from cracking in the paint layer to splitting of the shell. Figure 8 shows typical surface damage at 0.5 m impact.

Repeated low energy impacts (drop height of 0.25m) were performed for up to 20 impacts. The impact damage was barely visible (slight darkening of the paint).

Figure 8: Impact damage on the top of a Mk10 helmet after an impact from 0.5m.

For the Mk4s, however, impacts up to 0.75m (~80G) constantly resulted in no visible damage.

To determine if there was any non-visible damage within the helmets, each of them was inspected using thermography. This confirmed that there no internal damage could be found in the Mk4 unless accompanied by significant surface damage. For the Mk10s, internal matrix cracking was found in several of the helmets that appeared to show no visual damage (illustrated in Figure 9).

For both helmet types the visible damage area was usually smaller than the damage within the skin.

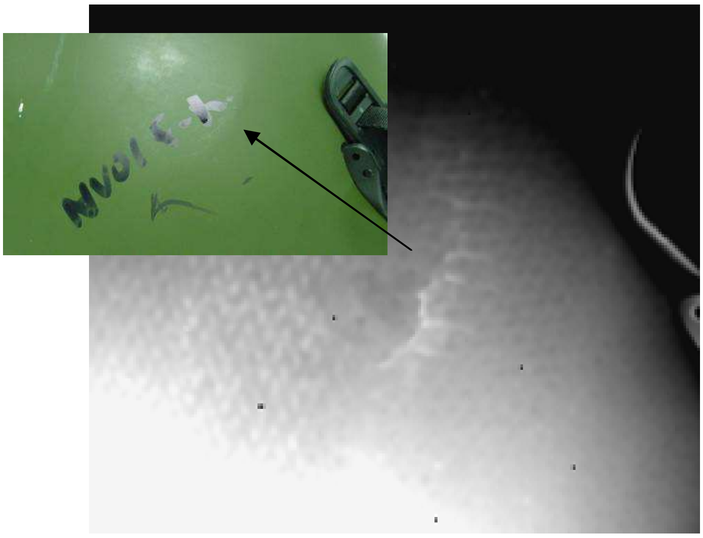

Figure 9: Thermography image showing damage in the shell.

5 Effect of Non-Visible Damage on Mechanical Properties

To determine whether the non-visible damage in aircrew helmets could reduce impact protection, helmets were subjected to the standard MAHIS impact tests (7.5 m/s impact onto flat anvil, for the 1st impact).

Figure 10 shows the peak deceleration results trace for a series of Mk10 helmets that had been subjected to a single impact from a height of up to 1m before residual testing. The data suggests that there was no detrimental affect from the previous low energy impacts.

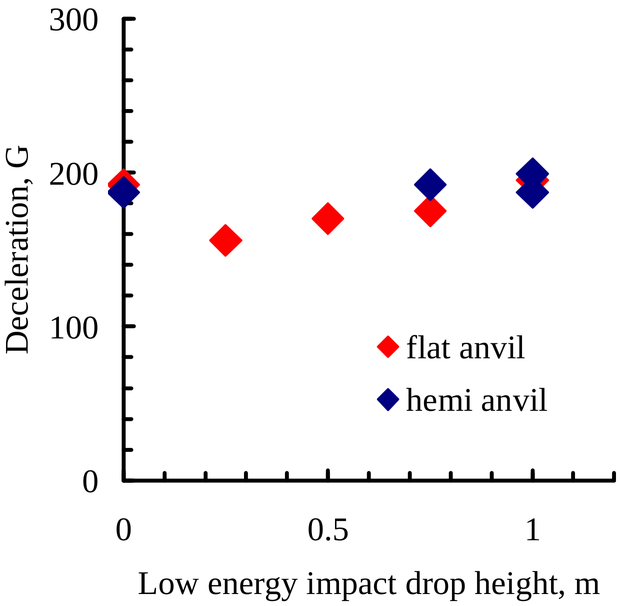

Figure 10: Residual test results for Mk 10 helmet impacted on rear after low energy impacts on hemi and flat anvils.

Four helmets, three impacted onto a flat anvil from 0.75, 0.5 and 0.25 m, and an un-impacted baseline, are compared in more detail. The results suggested that the stiffness of the prior impacted helmets was reduced to increasing extents in comparison to the baseline helmet. This was not unexpected as each of the prior impacted helmets had some visible skin damage. The data also suggested that, for all of the pre-impacted helmets, a change in the properties of the foam had occurred compared to the baseline.

Similar trends were observed for the Mk10 helmets after a hemispherical impact. That is no significant increase in the maximum G value, but a noticeable difference in the stiffness and foam response compared to the baseline.

To identify the cause of the reduction in the foam properties an impacted area of foam was removed from a helmet which had been impacted from 1m. Figure 11 shows an electron microscopy image of the extracted foam. Small discrete fractures were noted throughout the foam which were the likely explanation for the reduced mechanical properties observed.

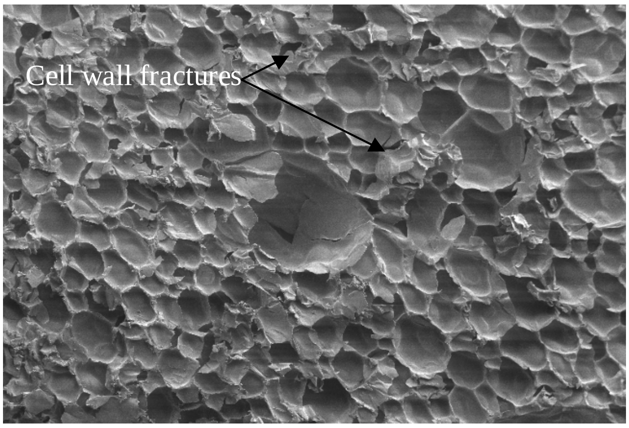

Figure 11: SEM image showing small fractures in the foam cell walls, x52.

Figures 12 and 13 show the residual test results for Mk10 helmets impacted on the top once and 20 times. The results showed that at this location there was a negligible effect on the residual skin stiffness and foam response following repeated impacts.

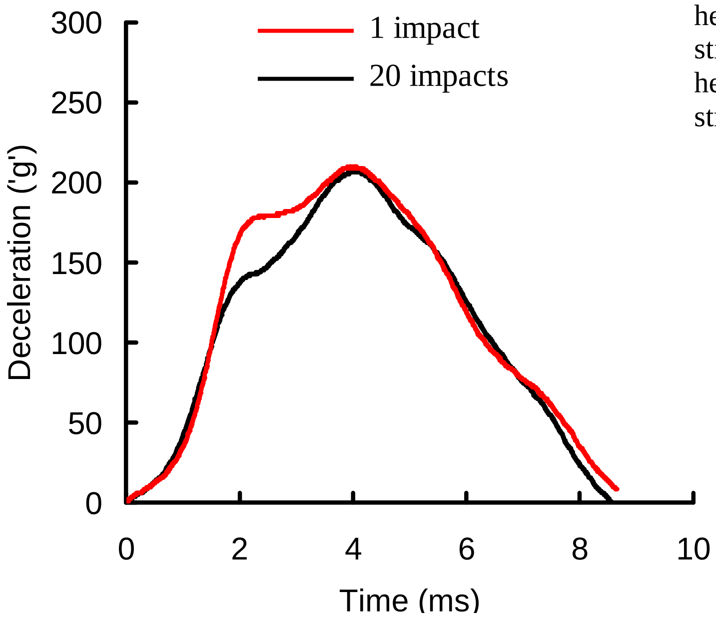

Figure 12: Graph of residual test results following repeated low energy impacts.

Figure 14 shows the peak deceleration results for a series of Mk4 helmets after residual testing. The helmets again had been subjected to impacts from a height of up to 2m before residual testing. As with the Mk10 helmets, there appears to have been no detrimental affect from the low energy impacts

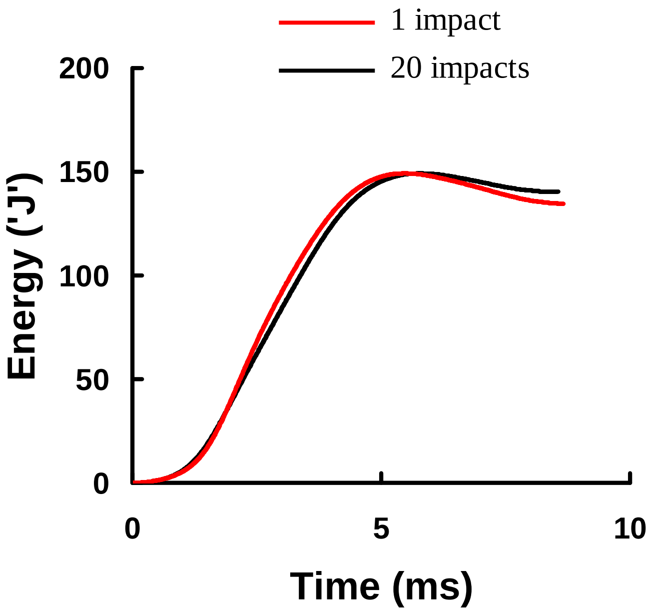

Figure 13: Graph of residual test results following repeated low energy impacts.

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Analysis of the residual data for the Mk4 helmets did not clearly show the same reduction in stiffness and foam properties as noted in the Mk10 helmets. This was most likely due to the heavier structure of these helmets.

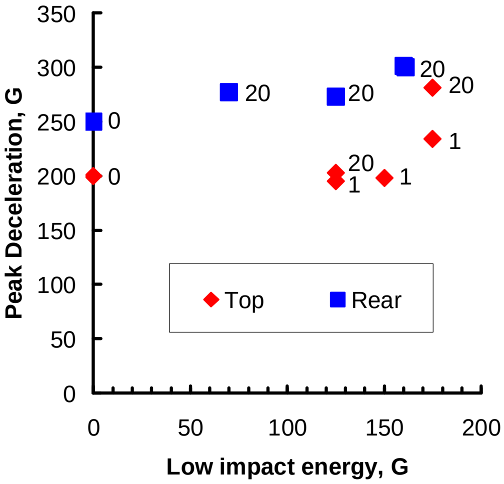

Figure 14: Residual test results for Mk 4 helmet impacted on top and rear after either 1 or 20 (indicated by number next to point) low energy impacts on a flat anvil.

6 Conclusions

A range of non-destructive evaluation (NDE) techniques have been used to inspect helmets in order to determine the extent of potential non-visible damage, prior to residual performance testing. A series of Mk4 and Mk10 aircrew helmets were impacted using the standard BS6658 guided wire drop tower, from heights of 0.2 to 2m.

In conclusion it was found that the Mk10 helmets showed visible damage after impacts of greater than ~50G. This equates to a drop height of 0.25 m or a velocity of ~2.0 m/s. The Mk 4 helmet did not regularly show visible damage below impacts of ~100G (1m or 5 m/s).

Thermography of the impacted helmets confirmed that the Mk10 contained internal damage, after impacts from 0.25m, despite the fact that no external visible damage was present. In addition, in some cases, the visible damage area was significantly smaller than the internal damage.

Non-visible damage was not observed in the Mk4 helmets.

Residual impact tests showed no reduction in the peak deceleration results for both the Mk4 and Mk10 helmets after a single impact. However there was evidence to suggest that the performance of the Mk10 foam liner had been impaired.

Increasing the number of impacts on the top of the Mk10 helmet produce no effect. Further work is currently investigating the effect of repeat impacts on other areas of the Mk10 helmet.

6 Acknowledgements

The authors would like to thank and acknowledge the help of the QinetiQ NDE group, specifically Luke Nelson and Lyn Jones and the technical support of Les Neil.

The authors would also like to thank the MOD customer and acknowledge the programme which supported this work “Improved Accident Protection for Military Aircrew” Research Entity 601, under Contract No RCT/COM/2/012 amdt 5.

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