Numerical investigation of a shock-absorbing layer for a ballistic helmet capable of stopping rifle projectiles

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Abstract. Fielded ballistic helmets, both military-style and specialised police helmets, are currently unable to give appreciable protection against the AK-47 weapon system using the M43 (mild steel core) projectile. The Belgian Armed Forces (BAF) have thus a considerable interest in developing optimised systems, both for regular high-intensity conflicts, special intervention operations (e.g. Special Forces Group) and homeland operations against this wide-spread threat. Due to this capability gap, a research project was started to develop a ballistic helmet capable of stopping the Kalashnikov M43 round at muzzle velocity. The current helmet concept design consists of four layers. Whereas for the first three layers the design criteria are relatively clear and straightforward (stop the M43 Kalashnikov round with a minimum weight design) and a composite design had already been developed, designing the fourth layer poses a challenge as no internationally accepted method and threshold for behind-helmet blunt trauma (BHBT) exists. In order to reduce the risk of injury due to the local loading of the head without dramatically increasing the required standoff of the helmet, a possible approach is to maximally reduce the dynamic deflection of the helmet shell by 'pushing back' the deflection using a shock-absorbing layer. As this shock-absorbing layer is in direct contact with the head, all forces exerted on the shock-absorbing layer by the deflecting shell, will be transferred to the head. The aim of the present work was to study an innovative structure for energy absorption that minimises the likelihood of head injuries caused by a ballistic impact. The innovative helmet liner consists of an array of thermo-plastically formed cylinders manufactured by Koroyd® absorption liners. Energy is absorbed via a combination of folding and collapsing of the cylinders. The main advantage of using such liner is an optimised energy absorption for different helmet configurations and impact locations. Numerical simulations for orthogonal impacts on two different cylinder configurations of the novel liner in conjunction with the other three layers were carried out with LS-Dyna®.

1. INTRODUCTION

The most commonly found small calibre threat, both in military and in law enforcement operations, is the ubiquitous AK-47. More than 100 million AK-47s have likely been produced worldwide, and the weapon system has proliferated extensively around the world, both in the legal and in the illegal circuit. Due to this, it has often been encountered by both military and police forces [1]. Recent criminal investigations and the recent terrorist activities in Belgium and abroad have only confirmed the universal presence of the AK-47 weapon system [2-4].

A typical military-style ballistic helmet only offers protection against high-velocity fragments, which until the conflicts in Iraq and Afghanistan was also the only required level of protection as in conventional warfare, the fragmentation threat from artillery and mortar fire, is by far the most common threat. Although efforts have been made to increase the level of protection offered by current ballistic helmets, the mass constraints do not allow for any significant increase in protection by adding additional layers of protective materials [5, 6].

For continuous usage such as in a military context, the maximum allowable helmet mass is 1.8 kg, whereas for specialised helmets typical of special intervention forces, the maximum allowable mass is typically around 2.5-3.0 kg, which excludes them from being worn over extended periods. Several helmet manufacturers claim to have developed ballistic helmets offering protection against handgun and even rifle projectiles, but these helmets have never been evaluated for the risk on behind-helmet blunt trauma (BHBT) caused by the dynamic deflection of the inside of the helmet upon impact. This is due to the lack of an internationally accepted test method and associated criterion. Nevertheless, specialised helmets (generally made of titanium to reduce the dynamic deflection) offering protection against handgun threats have been developed that largely reduce the risk on BHBT, typically for use by special intervention forces.

Fielded ballistic helmets, both military-style and specialised police helmets, are currently unable to give appreciable protection against the AK-47 weapon system and the M43 projectile. The Belgian Armed Forces (BAF) have thus a considerable interest in developing optimised systems, both for regular high-intensity conflicts, special intervention operations (e.g. Special Forces Group) and homeland operations.

https://doi.org/10.52202/078352-0012

Due to this capability gap, a research project was started within the Belgian MOD to develop a ballistic helmet capable of stopping the Kalashnikov M43 round at muzzle velocity. The final design of helmet shell would consist of four layers:

- a first ceramic layer capable of breaking and eroding the impacting projectile, especially the steel core;
- a second composite layer able to absorb the kinetic energy of the impacting projectile;
- a third stiff layer to limit the back-face deflection of the first two layers;
- and finally, a fourth layer able to absorb the shock wave of the initial impact and to provide the necessary standoff for the first three layers so that direct contact between these layers and the head is avoided.

Whereas for the first three layers the design criteria are relatively clear and straightforward (stop the M43 Kalashnikov round with a minimum weight design), designing the fourth layer poses a challenge as there is no internationally accepted method and threshold to quantify and/or evaluate behind-helmet blunt trauma (BHBT). Although several standardisation organisations have published helmet test standards with methods to assess BHBT, most of them do not specify threshold values for acceptance (or not) of a specific helmet design [7]. Those that do state a threshold value generally have no clear biomechanical basis for the specific threshold [8, 9].

A literature study was performed to identify relevant injury criteria and ways to experimentally assess the risk of injury based on these injury criteria. Looking at the different mechanisms leading to head injuries, a distinction can be made between injury mechanisms based on contact loading of the head due to the deformation and inside deflection of the helmet shell, and the associated head motion (translational, rotational, angular) [10]. Whereas the latter can be easily mitigated using the inertia of the helmet shell, the contact loading poses a significant challenge. This is mostly because light ballistic shell solutions generally have higher dynamic deflections, requiring larger helmet shell standoff in order to sufficiently decrease the risk of BHBT. A larger standoff, however, also means a larger average radius of the helmet shell, which leads to an increase in helmet weight, and a higher rotational inertia effect (which is very important from an ergonomic point of view). However, if localised loading cannot be sufficiently reduced, there is a high risk of skull fracture and injury to the brain due to dynamic wave propagation and possibly reflection.

In order to reduce the risk of injury due to local loading of the head without dramatically increasing the required standoff of the helmet, a possible approach is to maximise the reduction of the dynamic deflection of the helmet shell by ‘pushing back’ the helmet deflection using a shock-absorbing layer. As this shock-absorbing layer is in direct contact with the head, all forces exerted on the shock-absorbing layer by the deflecting shell will be transferred to the head. Due to natural physiological limitations, it is necessary to avoid excessive forces transferred from the shock-absorbing layer to the head. Analysing the available literature for the maximum allowable dynamic loading of the head (generally based on cadaveric experiments) a threshold seems to have been identified by several researchers for frontal head impacts of approximately 5 kN [11, 12].

In order to control the force transmitted through the shock-absorbing layer, an interesting approach is the use of crushable structures, which can be designed to crush at controllable pre-defined force levels. New shock absorbing materials based on crushable structures, such as the Koroyd material structures used for this research [13], are designed specifically for applications requiring exceptional energy absorption characteristics or excellent strength-to-density ratios.

Koroyd is a new material created by thermally welding miniature tubes together to form a whole that crushes on impact, absorbing energy in a measurable, effective way. It may look like a honeycomb, but unlike those materials it is made without glues or adhesives which can be weak or difficult to manufacture. Instead, each tube is created with a co-polymer extrusion process (see Figure 1). The inner layer is much thicker, providing the energy absorption and strength, while the outer layer is a thin membrane just a few microns thick. Its melting point is lower than that of the inner structure so, to build a sheet of the material, the tubes are stacked together and heat is applied. They then bond together across their entire length, creating a unified, consistent structure. This “sheet” of Koroyd tubes can then be bent in three dimensions, allowing it to wrap a head form with consistent thickness. Its ability to absorb varying levels of energy can be tailored by the thickness of the tube walls. Unlike EPS (expanded polystyrene) as found in many automotive helmet applications, Koroyd is also able to provide meaningful dampening for low energy impacts by elastically deforming.

The objective of this study was to perform numerical simulations for orthogonal impacts of the M43 projectile on different cylinder configurations of a novel liner concept based on the Koroyd material.

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The different cylinder configurations were modelled in conjunction with the remaining three layers of the aforementioned advanced helmet concept. All the simulations were carried out with LS-Dyna.

The desired output of the present study was aimed at:

- evaluating the effectiveness of the two different cylinder configurations in providing force transmission at constant level between the helmet shell and the head at different impact locations.
- indicating ways in which the cylinder configurations can be optimised to reach a constant force transmission.

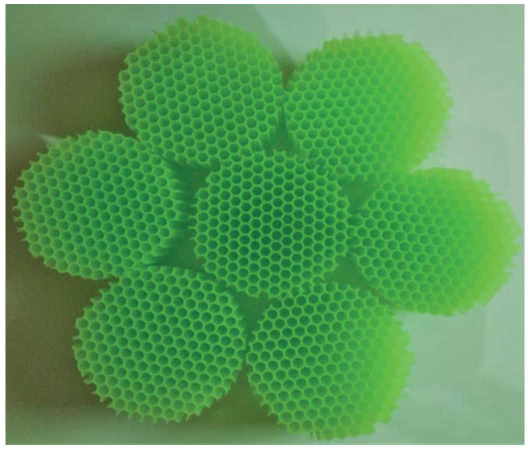

Figure 1. Koroyd cylinders.

2. EXAMINED CONFIGURATIONS

Contrary to other typical helmet applications (bicycle, motorcycle, skiing, etc.), the basis of the shock-absorbing layer investigated here is not a continuous layer of Koroyd, partially or completely moulded to match the inside shape of the helmet. It is instead composed of an array of short, crushable cylinders made out of Koroyd. These cylinders are attached to the inner surface of the newly developed helmet shell and support the helmet on the head. The reason for this is that ballistic impacts are more localized than typical impacts experienced during automotive or sports accidents. It can thus not be assumed that the impact load can be redistributed sufficiently fast onto the whole helmet shell (and head) to assist in absorbing and mitigating the impact energy. This also makes it a lot more difficult to 'tune' the crushing resistance of the Koroyd structure to remain under specified thresholds and keep the injury risk low.

The main aim of the research here described is to determine the optimum cylinder size and spacing. The study of the cylinder size is limited to the radius, as the height of the cylinders has already been determined [14]. Azevedo et al. [14] determined the radius and height of a stand-alone cylinder crushed by the newly developed helmet shell, based on an optimum crush strength and hence transmitted force of 5 kN. The work shown here was performed to investigate the effect of an array of multiple cylinders attached to the helmet shell.

Initially, two main configurations were considered for the array of cylinders: a regular hexagonal, close-packed spacing (configuration A), and an 'extended' hexagonal spacing (configuration B), i.e. the same hexagonal pattern as for the first configuration, with additional spacing between the cylinders.

In a hexagonal, close-packed structure, different principal directions can be identified corresponding to the most-closely packed directions (see Figure 2). These are the directions along which the units of the structure are in contact with one another in a fully dense structure. These are also the directions in which it is necessary to ensure an equal, constant inter-distance between the different units, to go from a fully dense configuration to an extended configuration.

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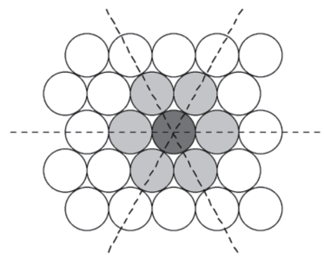

Figure 2. Schematic representation of a close packed layer of equal sized spheres/cylinders. The close packed rows (directions) are shown by the dashed lines (configuration A).

The two examined configurations are shown in Figure 3. Configuration B is basically the same as configuration A, but with a constant (non-zero) spacing along the most-closely packed directions. Figure 3 also shows the considered unit cell (dashed red line), i.e. the basic element that, if repeated, reproduces the whole structure, that is, the full array of cylinders.

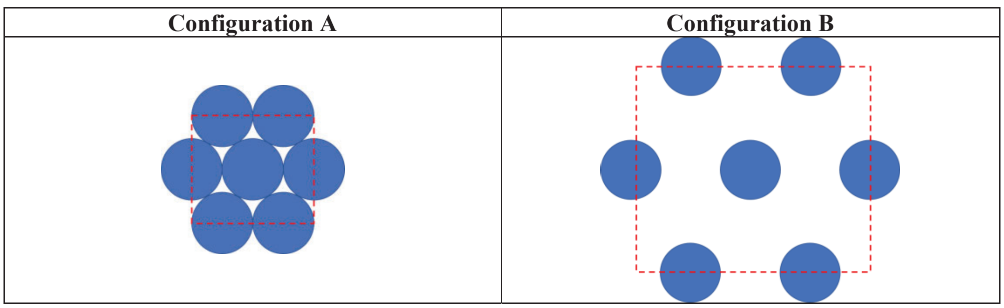

Figure 3. The two different configurations (top view): Configuration A – no space between Koroyd cylinders; Configuration B – one cylinder diameter distance (50 mm) between Koroyd cylinders.

After the initial comparison of configurations A and B, it was decided to perform further simulations using configuration B to investigate the effect of the impact location on the response of an extended structure based on configuration B. This was done as it was suspected that the transmitted force levels might be very different for an impact directly over a cylinder than for an impact in between the cylinders. The same behaviour has been observed for helmets equipped with pads [15]. Different impact locations were again selected along the most closely packed direction. Four impact locations were considered in this second phase, of which the first location corresponds to the location used for comparing configurations A and B (centre cylinder), as shown in Figure 4.

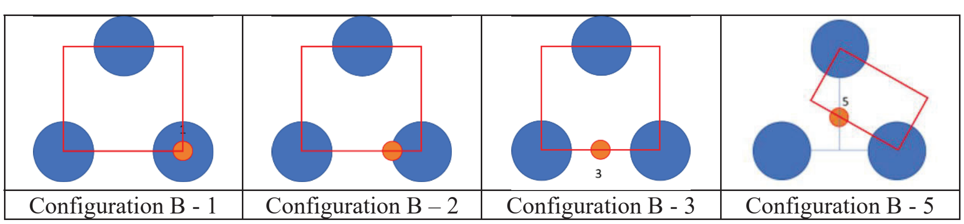

Figure 4. Different impact locations for configuration B (half model represented): (1) impact on centre; (2) on the edge, i.e. 25 mm from the centre; (3) half-way between two neighbouring cylinder; and (4) centroid of three neighbouring cylinders.

3. FINITE ELEMENT SETUP

3.1 Projectile

https://doi.org/10.52202/078352-0012

The finite element model of the projectile was previously developed and validated for different impact conditions. The model incorporates the main components of the M43 projectile: the steel jacket, the steel core, and the lead filler. An overview of the modelled components is shown in Figure 5.

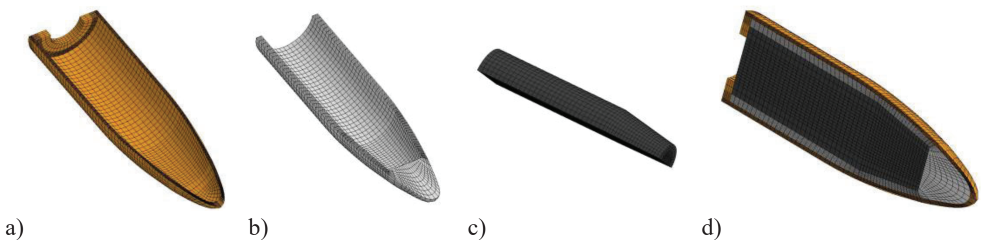

Figure 5. Numerical model of the 7.62 x 39 mm projectile: (a) steel jacket; (b) lead filler; (c) steel core; and (d) assembled projectile.

The CAD model of the projectile was developed using the commercial package Solidworks^{TM} and exported to the commercial HyperMesh^{TM} software to create a hexahedral mesh. The finite element mesh was then imported to LS-Dyna^{TM}. The Johnson-Cook constitutive relation was used to simulate thermo-mechanical deformations of the steel jacket and the steel core. The lead filler of the projectile was modelled with the MAT_ISOTROPIC_ELASTIC_PLASTIC material model in LS-Dyna^{TM} [16]. More details on the material properties and the validation of the model can be found in [17]. The impact velocity was 720 m/s for all simulations.

3.2. Helmet shell

3.2.1 Helmet shell geometry

The helmet geometry was simplified to a flat panel geometry, as this is also the way in which the experiments were performed to optimize and evaluate the ballistic shell concept [17]–[19]. Additionally, the simplification of the geometry considerably reduces the CPU time. Although both numerical and experimental results have not shown any significant difference between the local behaviour of respectively the flat panel and full helmet geometry, the global behaviour of a flat panel sample and a full helmet can be slightly different. The global behaviour is however also significant for the final load transfer between the helmet shell and the head and the movement of the head after impact on the helmet shell. The difference between the tested flat panels and the full helmet geometry can be mostly attributed to the difference in inertial effect and boundary conditions.

3.2.2 Helmet shell materials and models

The first layer of the helmet is a silicon carbide (SiC) ceramic layer, followed by a composite layer and a metallic layer, and finally the shock-absorbing layer. The material properties of the ceramic layer are those published by Miranda-Vicario et al. [17]. In order to reduce the computational time (and once this is a preliminary study) the size of the ceramic layer is smaller compare with the dimensions of the composite and the metallic layer.

The composite layer is a Dyneema^{TM} HB80 plate (unidirectional ultra-high molecular weight polyethylene, UHMWPE), with the material properties given by Azevedo et al. [20]. The metallic plate at the back of the target is Al5754 aluminium alloy and is used to limit the back face deformation.

The shock-absorbing layer was modelled using the MAT_HONEYCOMB material model in LS-Dyna [16], which is suited for describing material with real anisotropic behaviour such as foam and honeycomb materials. All normal and shear stresses can be defined separately to describe nonlinear elastoplastic behaviour of the material. The stresses are treated as fully uncoupled. The material properties implemented in the model were based on experimental compression tests and summarised in Table 1. The stress-strain curve of the shock absorbing material is shown in Figure 7. Koroyd has an immediate loading curve meaning a large amount of energy is absorbed from the moment of

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impact. It should be noted that the stress plateau is almost completely flat (see Figure 6). The obtained compressive force using the numerical model was also compared with experimental results for dynamic impact tests using a drop weight. The results in Figure 7 show that the model can reliably predict the actual material behaviour.

Table 1. Material properties of the shock absorbing layer [13].

Property	Value
Density [kg/m^3]	130
Young's modulus [GPa]	2.4
Poisson's ratio	0.37

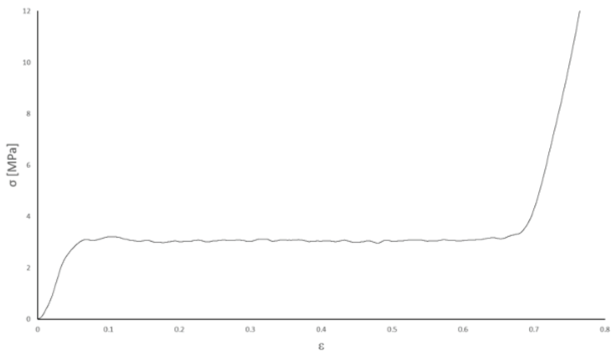

Figure 6. Stress-strain curve for the shock absorbing material (Koroyd).

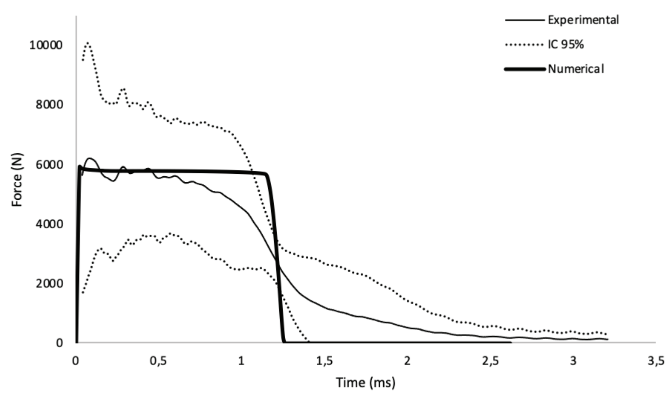

Figure 7. Comparison of the experimental (average of 3 experiments) and numerical force curves for the shock absorbing material (Koroyd) when subjected to a drop weight test.

The shock absorbing cylinder had dimensions of 30 mm length and 50 mm diameter and was modelled using eight nodded hexahedral solid elements, hence replicating exactly the experimental drop weight and impact test. A mesh convergence analysis was done on the shock absorbing material and an edge of 1 mm was chosen for the shock absorbing material.

The CONTACT_TIED_SURFACE_TO_SURFACE contact algorithm was used to simulate the interaction between the ceramic tile and the first layer of the Dyneema^{TM} composite plate, and the interaction between the aluminium layer and the Dyneema^{TM} plate. The element size in the impacted region was chosen to be relatively small (approximately 0.3 mm) for the composite material and for the metal layer at the back of the target. For the ceramic material, the element size was kept constant in the whole plate in order to ensure consistent crack propagation and evolution. The target was modelled with hexahedral solid elements. An example of the complete target and projectile model and discretisation is

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shown in Figure 8. The ceramic layer was also reduced to a small plate in order to reduce considerably the computational cost.

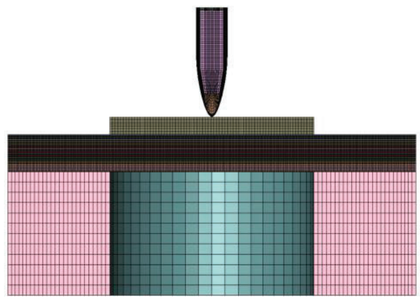	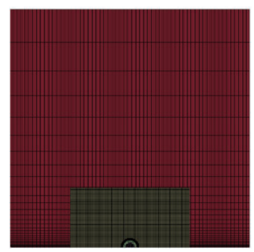	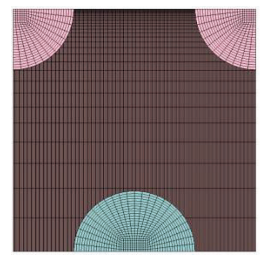
Front view	**Top view**	**Bottom view**

Figure 8. Different views showing the model setup and the discretisation of the target (half model) and the projectile (configuration B).

4. RESULTS AND DISCUSSION

4.1. Influence of the spacing for a centre-cylinder impact

Based on previous work by Azevedo et al. [14], 30 mm high cylinders with a 50 mm diameter were used as the basis of the evaluated configurations. The main difference between the two tested configurations A and B is the distance between the shock absorbing cylinders. In the case of configuration A, the cylinders are in contact. For configuration B, a spacing of 50 mm was selected.

The numerical setup is shown in Figure 8. Based on the unit cell shown in Figure 3, two symmetry planes were identified to minimise the required calculation time, leading to the simulation of only a quarter of the setup for an impact aimed at the centre of a cylinder (Figure 8 shows half of the model instead of one quarter for clarity). Only the nearest six neighbouring cylinders were considered to interact with the deflecting armour shell, based on the size of the actual bulges observed during experimental testing of the new helmet shell configuration. The head was considered to be a rigid wall (i.e. infinite inertia), as a worst-case scenario.

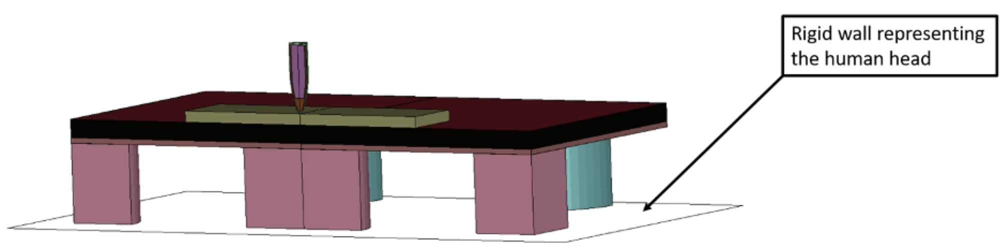

Figure 9. Illustration of the numerical model including the rigid wall representing the resistance of the human head on the inside of the helmet shell.

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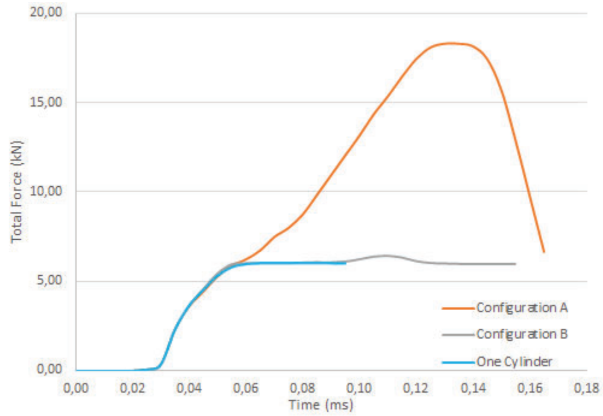

Figure 10. Total force as a function of time for configurations A and B, and a single cylinder case.

The results in Figure 10 show the total force transmitted by the Koroyd cylinders to the rigid wall for both configurations. This force is calculated using a rigid frame under the Koroyd cylinders to represent the head (see Figure 9). Configuration A shows a maximum absorbed force three times higher than configuration B. The two configurations are also compared to the force experienced by a single cylinder. As expected, configuration A shows a much higher force as the neighbouring cylinders to the central cylinder will also transmit a considerable load to the head. This is due to the fact that the bulge formed at the inside of the helmet shell is larger than the diameter of a single cylinder, and hence is in contact with several crushable cylinders. Conversely, as there is a considerable spacing between the individual cylinders in Configuration B, the load transfer in this case is limited to only the central cylinder, giving almost exactly the same force transfer as for a single cylinder.

Based on the results presented in Figure 10 and the maximum allowable dynamic loading of the head (5 kN), only configuration B seems to give reasonable results, although the transmitted force is 20% too high. This could however easily be solved by choosing a slightly smaller diameter for the Koroyd cylinders.

4.2. Influence of the impact point for an extended hexagonal configuration

Based on the results presented in Figure 10 and the maximum allowable dynamic loading of the head (5 kN), only configuration B seems to give acceptable results. Consequently, the following simulations were done with configuration B only, changing the impact location but keeping the distance between the Koroyd cylinders fixed. The four different impact locations are shown in Figure 4.

Figure 11 shows the total absorbed force for the four different impact locations as a function of time. As can be seen, configuration B-1 shows the highest total force. The remaining three configurations show a total absorbed force under 4 kN, demonstrating that the crushable cylinders are not used up to their full potential in these configurations. According to these numerical results for all different impact locations, configuration B can hence still be further optimised by changing the diameter of the Koroyd cylinder and the spacing between cylinders. In this way, the minimum standoff, and hence the mass of the helmet shell of a rifle-resistant ballistic helmet, can be obtained while still ensuring a constant maximum load transfer.

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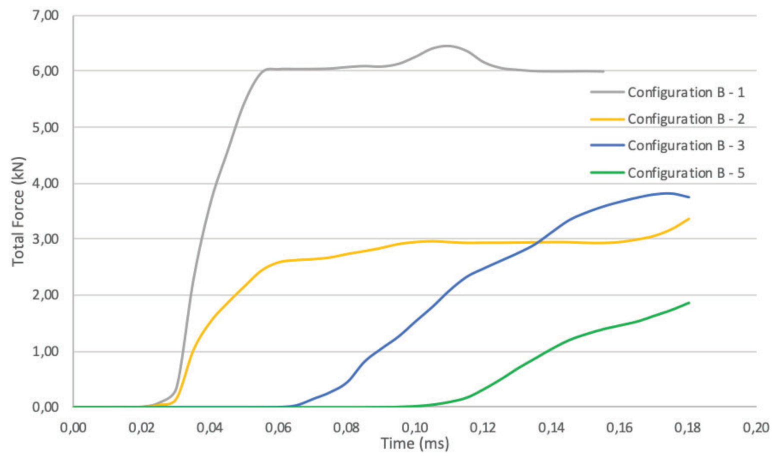

Figure 11. Total force as a function of time for the four different impact locations (configuration B).

5. CONCLUSIONS

From the simulation results, it is clear that it is possible to develop a ballistic helmet able to stop Kalashnikov ammunition keeping an acceptable BHBT.

Further research will focus on the optimisation of the shock absorbing cylinders, namely the diameter of the cylinder to have a maximum of 5 kN transmitted force, and the spacing between the cylinders in order to have a transmitted force as constant as possible, independent of the impact location. Currently only a proof of concept has been demonstrated. The next steps will include the development of a technology demonstrator and ballistic testing of the technology demonstrator under laboratory conditions. This technology demonstrator would combine the results from the different experimental and numerical approaches, in order to illustrate the available design possibilities to increase the survivability of law enforcement and military personnel during high-risk interventions (hostage rescue, high-profile arrests, forced entry, close quarters battle, etc.) This might however require the development of a new experimental setup as the testing solutions currently used in the framework of this project (US Army headform, Ballistic Load-Sensing Headform) are not suitable in their current form due to the limited size of the witness/measurement zone, compared to the expected bulge size of the helmet shell and the dimensions of the supporting array of crushable cylinder absorbing the impact (configuration B).

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