Simulation of Multi-Layered Ballistic-Resistant Armour with Enhanced Energy Absorption Properties

*[1]Adam O. Muritala, [1]Saheed A. Adio, [1]Abimola O. Onibi, [1]Abdulhazim I. Adebiyi, [2]Rasheed O. Azeez and [1]Omibiyi A. Idowu
[1]Department of Mechanical Engineering, Obafemi Awolowo University, Ile-Ife, Nigeria
[2]Department of Mechanical Engineering Technology, Federal Polytechnic Ede, Osun State, Nigeria
{muriadam|saheedadio|olugbengaonibi|engr.roazeez|adebiyiidowuabdulhazim|idowuomibiyi}@gmail.com

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ORIGINAL RESEARCH

Abstract- This research focuses on the simulation of ballistic impact on multi-layered ballistic resistant armour. The efficiency of spring-loaded backing plate armour was compared with armour that has solid end plate with a view to introducing a more elastic surface that enhances energy absorption properties. The design consists of three major layers of different materials: fibre cement as the first layer; Kevlar as the second; and a spring-loaded backing plate made of steel as the third layer. SolidWorks was used to model the multi-layered armour and ANSYS Workbench Explicit Dynamics and AUTODYN 3D solver were used to simulate the ballistic impact. The simulation involved testing different configurations of the multi-layered structure. Analysis of the effect of the spring wire diameter on the armour's energy-absorbing characteristics was carried out while keeping the overall weight within the acceptable range. The simulation results for the different configurations were compared and the ballistic-resistant armour designed with a spring-loaded backing plate of 0.40 mm spring wire diameter gave the least deformation. The research suggested an enhanced armour performance using embedded elastic material.

Keywords- Bulletproof armour, ballistic energy absorption, deformation, spring-loaded plate

1 INTRODUCTION

The unprecedented demand for body armour due to war and unabated terror attacks in many countries motivate the need for indigenous body armour. Developed countries that have required technology can respond to urgent need for body armour but under-developed or developing countries that are in dire need of protective devices usually used inefficient materials that endangers both civilians and military personnel. During war period, different materials such as scrap metals of old car are adopted for emergency production of bulletproof armour (Beaubien, 2022). The development of sophisticated weaponry, the invention of new firearms and the need for improved survivability requirements call for an ever-increasing demand for further improvements in ballistic resistance and weight reduction of bulletproof armour (Yang and Chen, 2016).

Enhancement of ballistic-resistant quality to ensure high protection ability and high serviceability is currently being directed towards development of high-performance materials such as shear thickening liquid, nano-reinforced fibre and Kevlar materials (Zhanga et al., 2021), and using multilayered material combinations in form of matrix. The main object of the bulletproof armour is to absorb impacts as well as to stop or reduce penetration from firearm-fired projectiles (Muruganantham et al., 2019). The needed material must have exceptional strength to weight ratio, absorb impacts and dissipate energy that could cause unbearable harm to the body.

*Corresponding Author
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The composites from Kevlar are commonly used because of their ability to absorb impact and energy from ballistics and its excellent strength to weight ratio. The energy absorption capability of Kevlar composites is facilitated through elongation of the polymer fibres and delamination in system with multiple stacked layers (Cen et al., 2006) and (Kang and Kim, 2000). The retardation of projectile motion is achieved through gradual reduction of velocity as the projectile progressively perforates the fabric layers. Yang and Chen (2016) has established that the impact from the projectile and the response from the fabric layers are different for each layer. Hence, using the same material for each layer in the panel may not present the most efficient solution in providing the optimised ballistic performance and lightweight.

Earlier works on material development by Ii et al. (2015) investigated addition of Carbon nano-tubes and nano-sized core shell rubber particles for thermoset resin systems to enhance toughness and energy absorption of Kevlar. Two primary experiments: one utilizes V50 ballistics testing and the other one used post shot Raman for characterization. In addition, effectiveness of the nano-sized additives on the performance of the composite under extreme testing conditions was investigated. This study showcases the influence of nano-particle additives on the energy absorption of the composite via the Kevlar 29 fibres. The enhanced toughness and energy absorption of Kevlar that is achieved may not be enough to minimize "Behind Armour Blunt Trauma (BABT)" and this suggested further improvement in various components that made up the layers of the body armour.

Steel and Kevlar are widely used materials in the ballistic armour industry today ((Banerjee et al., 2017) and (Cunniff, 1992)): steel is used as backing plate in structural and body armour; while Kevlar composites form the outer layer to absorb energy of the ballistic projectile. The backing plate is the last layer in the multilayered armour which makes it the innermost layer of the armour for structural types and the layer closest to the body for the body armour type. The extent of body protection is measured by energy absorption by the outer layer and the extent of deformation minimization by the inner layers, hence the importance of its enhancement.

Presently, bulletproof armour can be categorised into two major types; soft body armour and hard body armour (Hani et al., 2012). Soft body armours are made of layers of Kevlar or para-aramid materials and are used to protect against low to medium level threats. They can protect against NIJ (National Institute of Justice) level IIA and level II threats. On the other hand, the hard body armour is made by integrating the soft body armour with layers of durable materials, such as ceramics, ceramic composites, steel, and polyethylene. The hard armours are designed to protect against NIJ level IIIA and above (Hani et al., 2012). Although body armours today are efficient enough to stop the projectile completely, they do not completely absorb the impact. There is often significant deformation of the armour after the projectile is stopped. This deformation sometimes inflicts a nonpenetrating injury to the wearer called Behind Armour Blunt Trauma (BABT), and the development of lightweight body armour with increased energy absorption mechanisms is now of utmost importance.

2 Materials and Methods

2.1 The Modelling and Simulation Software

In this research, the modelling of the ballistic projectile was carried out in SolidWorks while Ansys was used for the simulation. For each simulation, the 3D geometry of the ballistic-resistant armour and bullet were modelled and the materials for each layer of the ballistic resistant armour and the bullet were selected from Ansys engineering data as earlier done by Soyden et al. (2018). The geometries generated from SolidWorks were imported into Ansys. A setup was carried out in Ansys Mechanical and AUTODYN 3D solver to implement meshing, setting of initial conditions, introducing fixed supports and displaying of solver output. Series of simulations were conducted following the same procedure and the results were analysed using graphs and pictures of the real time interaction between ballistic projectile and the armour.

2.2 The Projectile

The projectile geometry was modelled in two parts: the inner part is the bullet core while the outer part is the bullet jacket. In this research, a projectile of BR2 ballistic level is used. This is one of the tests levels defined based on geometry, the tip shape, the shooting distance, the mass, the speed, and the material of the projectile. According to the European EN 1063 Ballistic Standards (Soydan et al., 2018), the assigned material to the core is lead and the jacket is full metal (FMJ). Like the model employed above, the lead and brass in the explicit material database of Ansys were assigned to the core and the jacket, respectively.

2.3 The Ballistic-Resistant Armour

The armour consists of three layers of different materials, a high-strength material to slow down the projectile and cause significant plastic deformation, an orthotropic wave-spreading layer to spread the shock laterally away from the axis of penetration and a spring-loaded backing plate to replace the rigid type, which acts as an energy-absorbing layer. The model was designed using SolidWorks and the geometry was imported into Ansys. Each layer of the 3D model has a length and breadth of 10 cm (i.e., 10 cm x 10 cm). The first layer, fibre cement, has a thickness of 8 mm, followed by a Kevlar layer, about 2.4 mm in width, and then the spring-loaded backing plate.

The Kevlar layers will be modelled with macro homogeneous model that considers the whole layer as homogenous in geometry with orthotropic mechanical properties. In modelling Kevlar materials, this approach is commonly used with limited resources, and it gives satisfactory results (Soydan et al., 2018). The backing plate design consists of three layers; a front plate, the springs, and a second plate. The front and back plates are 1 mm thick. Four geometries were tested, each with springs of different wire diameter. Wire diameters of 0.4 mm, 0.5 mm, 0.75 mm, and 0.9 mm were tested. The springs for all geometries had equal pitches and distance between centres. The pitch used was 1.4 mm and there was 7 mm spacing between the centres of each spring. A total of 169 springs were used for each backing plate and each spring had a mean diameter of 4.5 mm. The assembly and explode view of the geometry used for the simulation are shown in Fig. 1.

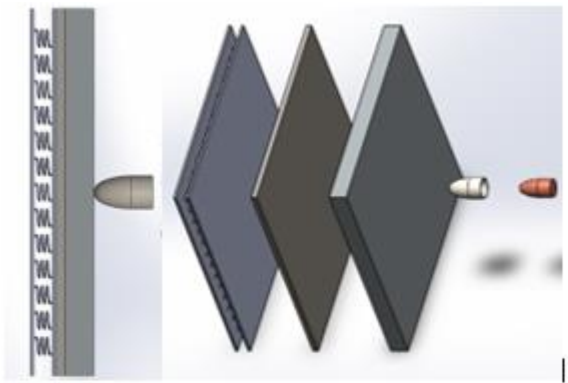

Fig. 1: Geometry model of armour and bullet (Assembly & Exploded view)

2.4 Material Selection

The materials for the different layers of the multilayered bulletproof armour are as follows:

Fibre-cement: was used as the high-strength material to slow down the projectile and cause significant plastic deformation. The properties of fibre cement used by (Soydan et al., 2018) were employed in this study.

Kevlar: was used for the orthotropic wave spreading layer to spread the shock laterally away from the axis of penetration. The fabric was modelled using the same mechanical properties as (Soydan et al. 2018). Kevlar fabric that was 2D plain woven and ± 45° fabric direction was used.

Steel: is used for the backing plate of the multilayered ballistic-resistant armour. Steel 1006 from the Ansys

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Explicit Materials library is used in this research.
Brass: in the Explicit Materials library of Ansys was assigned to the bullet jacket and shear modulus from Soydan et al. (2018) was used.
Lead: in the Explicit Materials library of Ansys was assigned to the bullet core.

3 Impact Simulation

3.1 Validation

The material properties used for this simulation were validated against the simulation and experimental setup carried out by (Soydan et al., 2018) involved testing a multi-layered ballistic-resistant armour with 8 mm thick fibre cement as the first layer, 2.4 mm thick Kevlar as the second layer and a 3 mm thick rigid steel backing plate as the third layer as protection against a BR2 level ballistic with a velocity of 400 m/s.

With 8.958e-003 as the maximum deformation for (Soydan et al., 2018) and 8.937e-003 as the maximum deformation from the simulation in this research, only 0.23% difference was observed, which successfully validates the material properties that were used in this research. A bar chart comparing the maximum deformation from this research and (Soydan et al., 2018) is shown in Fig. 2.

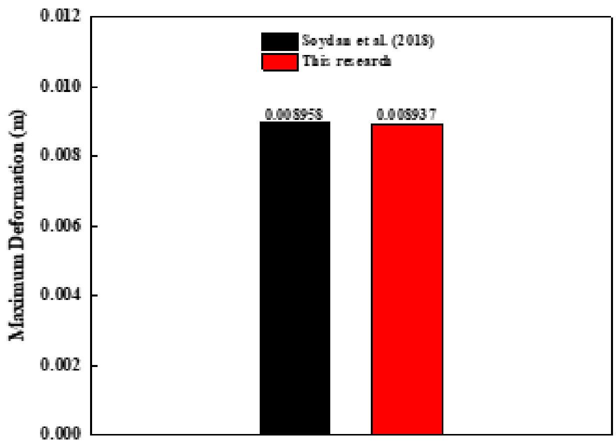

Fig. 2: Bar chart comparing maximum deformation from this research and (Soydan et al. 2018)

3.2 Impact Simulation

The modelling of the geometry was carried out using SolidWorks. After importing the SolidWorks geometry into Ansys the materials were assigned to different parts of the geometry assembly and meshing of the geometry was carried out by using Ansys's default mesh. Bonded contact was enabled between the Kevlar and fibre-cement layers and between the Kevlar and steel layers. Bonded contact was also enabled between the outer shell and the bullet core. Initial conditions involved assigning 400 m/s velocity to the bullet assembly in the positive Z-direction. Fixed support boundary was also applied to the armour's side faces, and an analysis time of 7e-04 seconds was used for the simulation.

The solver process involved using Ansys Explicit Dynamics and AUTODYN 3D solver which was set up to estimate the total deformation, total directional deformation, z-axis directional deformation of the backing plate's back face, and equivalent stress (von-mises). About 20 points were selected for analysis and the values obtained were plotted using OriginPro for directional deformation against time for each geometry tested.

4 Results

The results obtained from various simulations evaluated the performance of a spring-loaded geometry for the backing plate of multilayered armour. The total deformation of each sample and their deformation patterns are shown. The backing plate's deformation level when a bullet strikes the armour is used as a measure of the plate's energy absorption characteristics. The less efficient the backing plate is in absorbing the energy from the bullet, the more the plate deforms. Simulations carried out involve springs of different wire diameters. The plots of their deformation against time were obtained, and these results were compared with the conventional rigid steel backing plate in multilayered armour.

4.1 Rigid Backing Plate

The simulation of the multilayered bullet resistant armour was carried out using a steel backing plate of 3 mm. The backing plate has a volume of 3e-05 m3. Steel 1006 from Ansys Explicit Material's library was used and the density of the plate is 7896 kgm-3with a total mass of 0.237 kg. At the end of the simulation, the deformation of the back face in contact with the human body was studied. The maximum deformation of the face was estimated to be 6.766 mm.

4.2 Spring Loaded Backing Plate

The simulation was carried out using the same materials as the rigid backing plate sample but with the rigid backing plate replaced with a spring-loaded type. The backing plate design consists of three layers; a front plate, the springs, and a second plate. The front and back plates were 1 mm thick. Each spring used had a wire diameter of 0.9 mm. The pitch used was 1.4 mm and there was 7 mm spacing between the centres of each spring. A total number of 169 springs were used for each 10 cm x 10 cm backing plate and each spring has a mean diameter of 4.5 mm. As estimated by Ansys Mechanical software, this entire backing plate layer has a volume of 2.416e-005 m^3. The same steel grade was used here and it has a density of 7896 kgm-3. Thus, the total mass of this layer is 0.191 kg. At the end of the simulation, the deformation of the back face in contact with the human body was studied. The maximum deformation of the face was estimated to be 2.059 mm.

4.3 Comparison of Rigid and Spring-Loaded Plates of Equal Volume and Mass

The performance of the spring-loaded backing plate was compared with the conventional rigid type. The first spring-loaded backing plate that was tested had a spring wire diameter of 0.9 mm. The front and back plates of the backing plate assembly were 1 mm thick, giving them a volume of 1e-005 m^3 each and the total volume of the 169 springs used is 4.16e-006 m^3. This made the overall volume of the backing plate to be 2.416e-005 m^3.

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With a volume of 2.416e-005 m³, the spring-loaded backing plate has a volume lower than the 3 mm rigid backing plate (3e-005 m³). This difference in volume and weight will not allow for effective comparison. For effective comparison, another simulation was performed with a rigid backing plate of the same volume as the spring-loaded type. A thickness of 2.416 mm was used, giving it an overall volume of 2.416e-005 m³ and a mass of 0.191 kg, just like the 0.9 mm wire diameter spring-loaded backing plate. The same simulation setup was applied and the simulation results were obtained.

Fig. 3 shows a visual comparison between the total deformations of the 3 mm rigid backing plate, the 2.416 mm backing plate, and the spring-loaded backing plate. To show the performance of the spring-loaded geometry in comparison to the 3 mm and 2.416 mm rigid plates, a plot of the deformation of all three samples against time is shown in Fig. 4. It is evident that the spring-loaded backing plate is the most effective for the multilayered armour. The spring-loaded type has a lower deformation curve when compared to the 3 mm and 2.416 mm rigid backing plate. The maximum deformation of the 0.9 mm wire diameter spring-loaded plate is 2.059 mm, while the 3 mm thick backing plate and 2.416 mm thick plate have 6.766 mm and 7.703 mm, respectively, as their maximum deformation values.

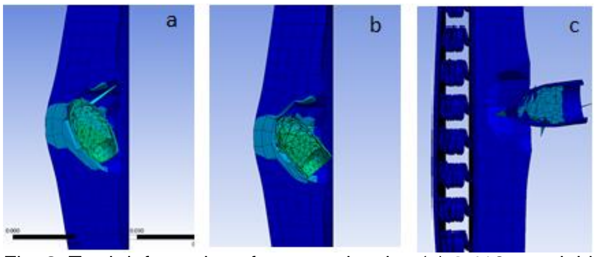

Fig. 3: Total deformation of armour showing (a) 2.416 mm rigid backing plate, (b) 3 mm rigid backing plate, and (c) 0.9 mm wire diameter spring-loaded plate.

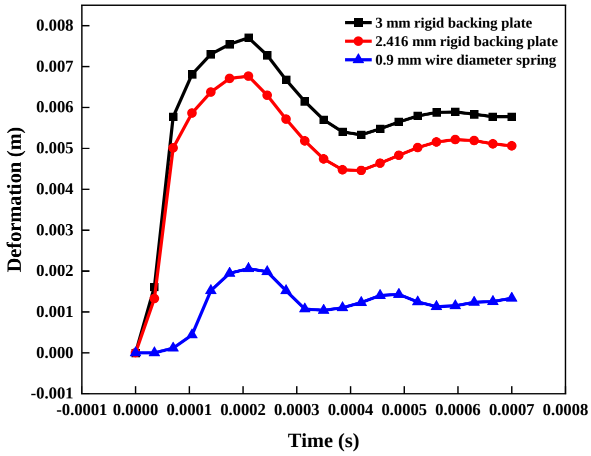

Fig. 4: Graph of deformation of armour with 2.416 mm rigid backing plate, 3 mm rigid backing plate, and 0.9 mm wire diameter spring-loaded plate

4.4 Effect of Spring Wire Diameter

After the performance of the spring-loaded backing plate was compared to the rigid type, the next phase of the research was the investigation of the effect of spring wire diameter on the deformation of the spring-loaded backing plate. All spring-loaded geometries had equal spring pitches of 1.4 mm and 7 mm spacing between the spring centres. A total number of 169 springs were used for each backing plate and each spring had a mean diameter of 4.5 mm. Simulations of four different spring-loaded backing plates were carried out. The wire diameters investigated are 0.4 mm, 0.5 mm, 0.75 mm, and 0.9 mm wire diameter. The wire diameters and their respective backing plate volume and weight are shown below.

0.4 mm Wire Diameter: Using a wire diameter of 0.4 mm, the volume of the entire backing plate was estimated by Ansys Mechanical to be 2.0821e-005 m³ and the total mass is 0.1644 kg when using Steel 1006. At the completion of the simulation, the maximum deformation was estimated to be 0.982 mm.

0.5 mm Wire Diameter: Using a wire diameter of 0.5 mm, the volume of the entire backing plate was estimated by Ansys Mechanical to be 2.1282e-005 m³ and the total mass is 0.16805 kg when using Steel 1006. At the completion of the simulation, the maximum deformation was estimated to be 1.172 mm.

0.75 mm Wire Diameter: Using a wire diameter of 0.75 mm, the volume of the entire backing plate was estimated by Ansys Mechanical to be 2.2885e-005 m³ and the total mass is 0.1807 kg when using Steel 1006. At the completion of the simulation, the maximum deformation was estimated to be 1.83 mm

0.9 mm Wire Diameter: Using a wire diameter of 0.9 mm, the volume of the entire backing plate was estimated by Ansys Mechanical to be 2.4155e-005 m³ and the total mass is 0.19073 kg when using Steel 1006. At the completion of the simulation, the maximum deformation was estimated to be 2.059 mm.

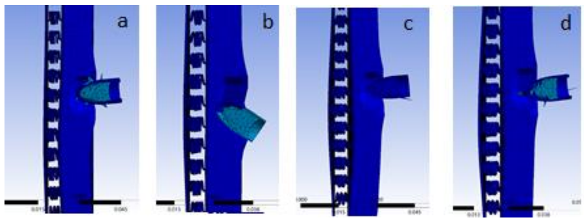

Fig. 5: Total deformation of armour with spring-loaded backing plate of diameters: (a) 0.4 mm (b) 0.5 mm (c) 0.75 mm (d) 0.9 mm

Fig. 5 shows the total deformation of the four armours tested. Fig. 6 shows a combined graph of the deformation curves and Fig. 7 shows the maximum deformation for each configuration.

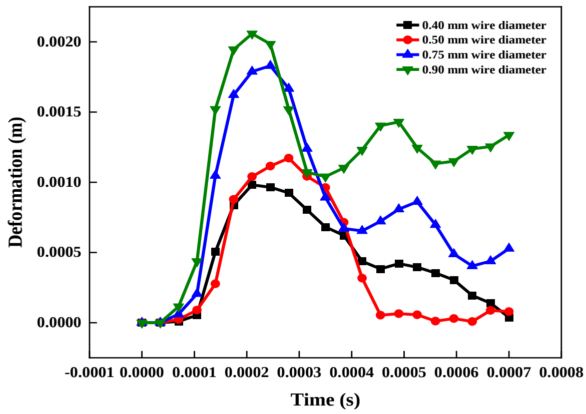

Fig. 6: Graph of deformations (m) against time (s) for different spring-loaded backing plates.

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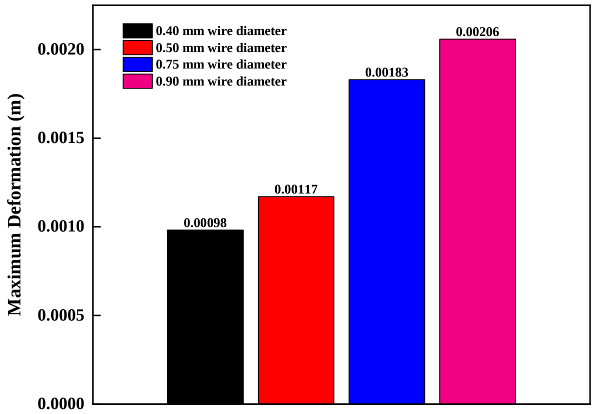

Fig. 7: Bar chart showing maximum deformation (m) with time (s) comparing the different spring-loaded backing plates

4.5 Comparison of Rigid Backing Plates and Spring-Loaded Backing Plates

A combined plot, shown in Fig. 8, compares the deformation curves of the 2.416 mm backing plate, 3 mm backing plates, and the 0.4 mm, 0.5 mm, 0.75 mm and 0.9 mm wire diameter spring-loaded backing plates. From the plot, it is observed that using the spring-loaded geometry significantly reduces the deformation of the innermost layer. It can also be seen that a reduction in the wire diameter of the spring corresponds to a reduction in the maximum deformation of the plate. This is because in all backing plates, the distance between the front and back plate is kept constant at 5 mm and then a reduction in the wire diameter leads to an increase in the distance between coils when the pitch is kept constant. Larger distance between consecutive coils allows more spring deformation before the spring compresses completely, thus giving it sufficient deformation time to absorb most of the energy.

Fig. 9 shows the bar chart of the maximum deformation of all plates investigated. It can be seen that for the rigid plates, increasing the thickness reduces the deformation of the backing plate. However, the thickness of this plate cannot continuously be increased because increasing the thickness corresponds to an increase in the plate's mass and volume, resulting in an overall increase in the total ballistic armour's mass. Fig. 10 shows the percentage reduction of the spring-loaded plate's maximum deformation compared to the 3 mm thick rigid backing plate. Fig. 11 shows a percentage reduction of maximum deformation compared to the 2.416 mm rigid plate. As seen in the bar charts, all spring-loaded geometries tested significantly reduced the deformation, with the 0.4 mm wire diameter spring having the largest percentage reduction and the 0.9 mm wire diameter spring having the least.

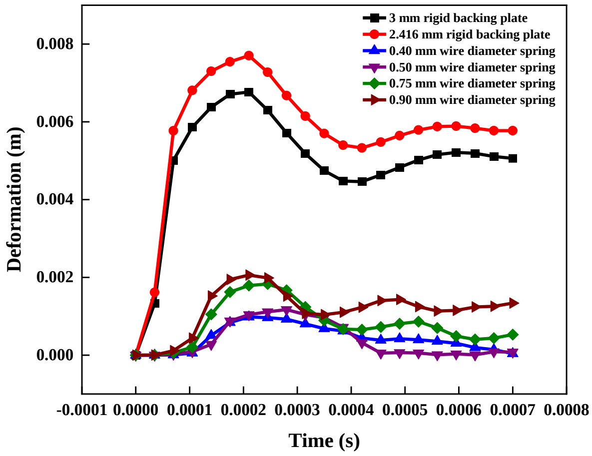

Fig. 8: Graph of deformation (m) against time (s) comparing rigid and spring-loaded backing plate.

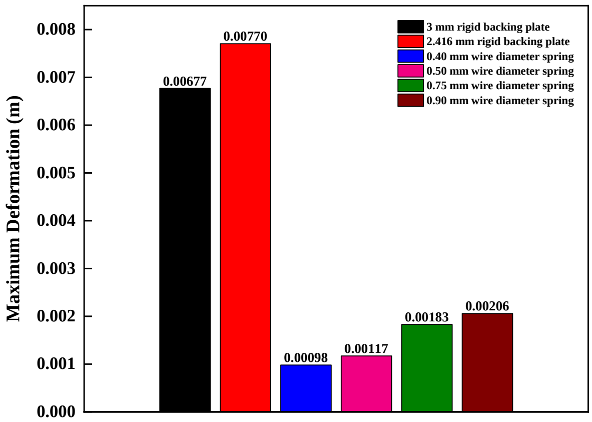

Fig. 9: Bar chart showing maximum deformation (m) with time (s) comparing rigid and spring-loaded backing plates.

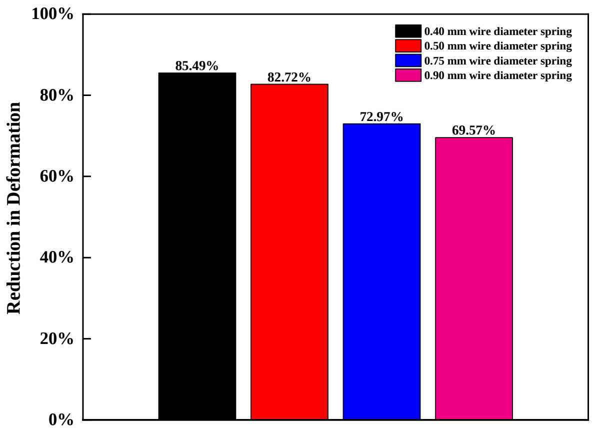

Fig. 10: Bar Chart showing the percentage reduction in maximum deformation of spring-loaded backing plate with respect to the 3 mm rigid backing plate.

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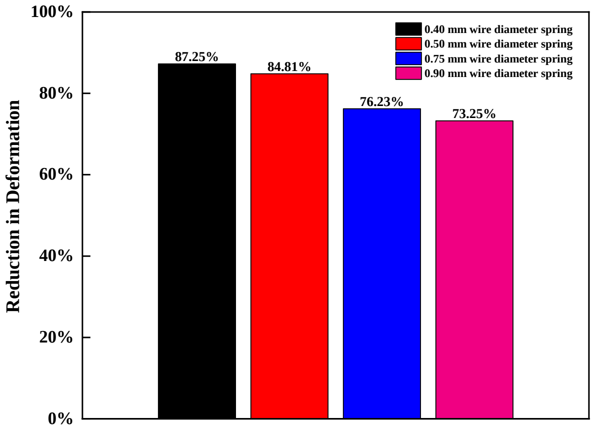

Fig. 11: Bar chart showing the percentage reduction in maximum deformation of spring-loaded backing plate with respect to the 2.416 mm rigid backing plate.

The following conclusion can be drawn from the study: An increase in the thickness of the rigid backing plate leads to better energy absorption and thus a reduction in the deformation of this plate. Although increasing the thickness helps, there is a limit to the possible increase because increasing the thickness leads to an increase in the volume and mass of the plate.

With the spring pitch, the distance between centres, the mean diameter, and spacing between the front and back plates are kept constant, reducing the spring wire diameter reduces the maximum deformation of the spring-loaded backing plate. This is because reducing the wire diameter increases the distance between consecutive coils. A larger distance between the coils allows more spring deformation before the spring compresses completely. This gives sufficient deformation time to absorb most of the energy.

Spring-loaded geometry performs significantly better than the rigid type as a backing plate for a ballistic-resistant armour. The 0.4 mm wire diameter spring-loaded backing plate came out the best with 85.49% and 87.25% less deformation when compared to the 3 mm and 2.416 mm thick rigid backing plate, respectively. This geometry was 13.9 % and 30.6% lighter than the 2.416 mm and 3 mm backing plates, respectively, and still performed better.

Data Availability Statement

The data used for this analysis are of two categories: data on the material properties of brass, lead, steel, Kevlar and fibre cement that are third party data. These are extracted from a publication in Hindawi Advances in Materials Science and Engineering Volume 2018, Article ID 4696143, https://doi.org/10.1155/2018/4696143.
The second category of data is the simulation results data which is very large and reproducible by computer simulation and will be made available upon request.

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