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Influence of boundary conditions on the ballistic performance of high-strength fabric targets

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Abstract

High-strength fabric is commonly used in personnel protection systems against small arms projectiles and fragments. An understanding of the characteristics of high-strength fabric under ballistic impact would provide useful insights for fabric armor design. A numerical model is formulated and used to study the perforation of square cross-woven fabric targets when the fabric is (i) clamped along all four edges with its yarns aligned parallel to the edges, (ii) clamped along all four edges with yarns running 45° to the edges and (iii) clamped along two edges with yarns aligned parallel to the edges. In addition, high-speed ballistic tests are carried out to validate the computational results. It is found that the ballistic resistance of such systems is sensitive to boundary conditions and yarn orientation. Targets that are unclamped on two edges can absorb more impact energy than those with all four sides clamped. Orientating the yarns 45° to the clamped edges can improve energy absorption significantly. Stresses in primary yarns (those in contact with the projectile) increase rapidly when their ends are clamped; this leads to rapid failure at the impact point and a lower-energy absorption. For fabrics clamped along four edges, the regions near the four corners are not stretched during impact if the yarns are parallel to the edges, whereas clamping with the yarns 45° to the edges facilitates energy dissipation by the entire fabric. It is also observed that slippage at clamped edges contributes to higher energy absorption by fabric targets.

Keywords: High-strength fabric; Boundary conditions; Slippage; Clamping; Yarn orientation; Ballistic performance

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1. Introduction

High-strength fabrics find many applications in areas related to protection against ballistic impact, such as personnel body armour and in external structures of aircrafts and vehicles. Armour-grade fabrics exhibit exceptionally high strength and impact resistance, and also possess unique interwoven architectures. These characteristics result in complex ballistic penetration mechanisms, of which a complete and quantitative understanding does not yet exist. In the drive to design more comfortable and reliable fabric armour, considerable research effort has been expended to elicit a better knowledge of ballistic penetration of fabrics. Various parameters that influence the ballistic resistance of fabric have been identified, such as armour system characteristics in terms of fibre properties, weave pattern, areal density and number of plies, as well as impact parameters such as impact velocity, impact angle, projectile geometry, boundary conditions, etc. Cheeseman and Bogetti [1] have presented a comprehensive review of parametric studies on fabric armour.

Experimental studies on impact penetration of fabric systems are directed at characterizing these parameters and obtaining relevant data to optimise applications of the material. On the other hand, many computational approaches [4,6–10] have also been introduced and display useful potential in identifying penetration mechanisms, some of which are difficult to study using experimental methods.

In many applications, it is believed that a fabric target will be perforated by a high-speed projectile before the stress waves generated reflect from the target boundaries. However, there are also instances whereby the impact velocity is relatively low (e.g. secondary impacts by fragments) or when the size of the fabric target is small. In such cases, the response of a target is sensitive to the boundary conditions. By testing Kevlar and Spectra fabric samples clamped between aluminium frames with different apertures, Cunniff [2] found that the ballistic limit is strongly dependent on the aperture size. A smaller aperture decreases the ballistic limit. It was explained that a smaller aperture results in greater constraints on transverse and longitudinal deflections. The authors also highlighted the occurrence of fabric slippage at clamped edges; however, no correlation has yet been established between slippage and ballistic performance. Shockey et al. [3] investigated the ballistic behaviour of PBO fabric, a new type of high-strength fabric, via impact tests on targets clamped along two and four edges. They found that fabric samples with two clamped and two free edges absorbed significantly higher energy (25–60%) than fabric systems with four fully clamped edges. As noted by Lee et al. [11], specimens of fabric material or flexible textile composites slip easily at their clamped edges. They found that when insufficient clamping force was applied to prevent slippage, the energy absorbed by a fabric-reinforced composite was 4.5 times higher than when slippage was prevented.

The impact response and energy absorption characteristics of a fabric target subjected to high-speed ballistic loading are affected when the boundary conditions are changed. Along unclamped boundaries, the ends of all yarns are free to move and they are thus pulled inwards in response to tensile forces. A clamped boundary constrains the movement of yarn ends; when tensile waves reach a fixed edge, material flow is curbed and the strain waves are reflected. The orientation of the clamped boundaries with respect to yarn direction also influences the behaviour of the fabric under impact loading. In the present study, the effects of clamping and orientation of the yarns

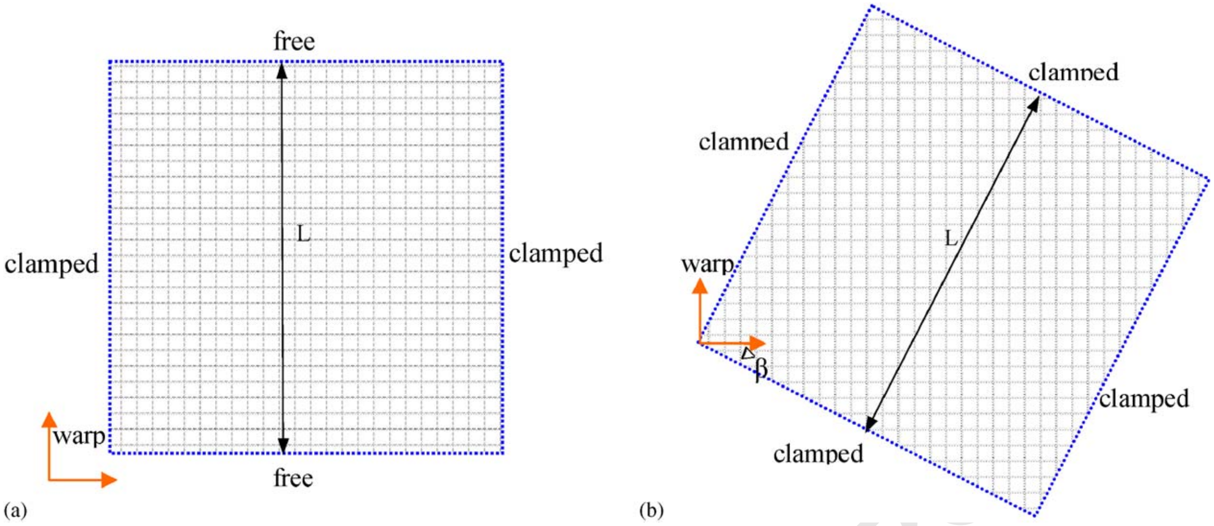

Fig. 1. Schematic diagram of fabric systems studied: (a) two-clamped-edges (b) four-clamped-edges at angle β.

with respect to the clamping direction are examined via experimental tests and computational simulations.

2. Computational simulation of fabric targets with different boundary conditions

Woven fabric is modelled by a network of linear yarn elements with their mass properties lumped at yarn crossover points. A description of the original computational model employed can be found in [4]. The fabric studied is made of aramid fibres and goes by the trade name Twaron® CT716. Rate sensitivity of the yarns is captured by use of a three-element spring-dashpot constitutive model. The accompanying constitutive parameters of this model are determined from dynamic tensile tests on Twaron® yarns. The original computational algorithm is then modified to enable simulation of different boundary conditions.

Three types of boundary conditions were studied. The first case corresponds to clamping at two edges and is shown in Fig. 1(a), whereby two opposite edges, parallel to the warp yarn direction, are fully clamped, resulting in all weft yarns being clamped at their ends while all warp yarns have free ends. The second and third situations—referred to as 0° four-clamped-edges and β° four-clamped-edges—are shown in Fig. 1(b). All four edges of square a specimen are clamped. In the case of 0° four-clamped-edges, the edges are parallel to the yarns, i.e. $\beta = 0$. For simulations relating to $\beta \neq 0$ four-clamped-edges, the edges are clamped at an angle β to the yarns.

3. Projectile impact tests

Ballistic impact tests on fabric targets with different boundary conditions were carried out using a gas gun. Details of the gas gun test arrangement are given in [5]. Fig. 2 is a sketch of the fixture

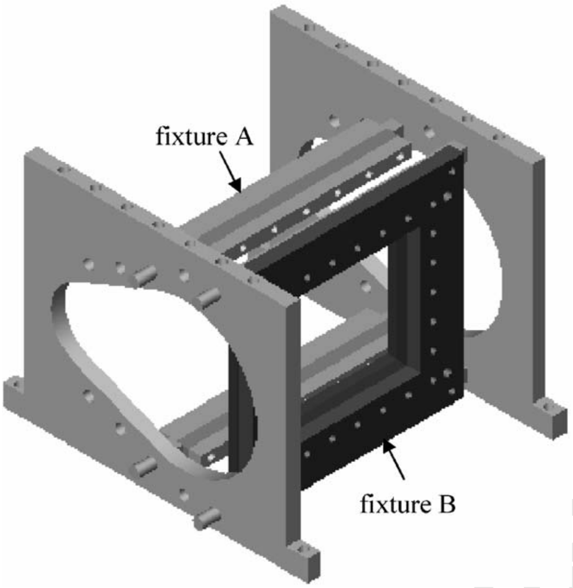

Fig. 2. Sketch of fixture for mounting fabric targets; fixture A for two-clamped-edges and fixture B for four-clamped-edges.

for mounting fabric targets. Twaron® CT716 fabric samples with a square target area of 120 mm × 120 mm were clamped according to the three different boundary conditions described (two-clamped-edges, 0° four-clamped-edges and 45° four-clamped-edges) and these were also simulated via computational modelling. The specimens were subjected to impact by 12 mm spherical projectiles weighing 7 g. Striking velocities ranged from the ballistic limit V_{50} up to 500 m/s. The impact and residual velocity after fabric perforation were measured, from which the energy transferred from the projectile to the fabric was calculated.

4. Experimental results and discussion

4.1. Ballistic limit

The ballistic limit or V_{50}, is an indication of the ability of a fabric system to fully arrest a projectile and is defined as the velocity at which perforation just occurs [12]. It is a widely recognised criterion for assessing the efficiency of armour. In the present investigation, the ballistic limits were found to be 125, 110, 120 m/s and respectively for fabric targets corresponding to two-clamped-edges, 0° four-clamped-edges and 45° four-clamped-edges.

4.2. High-speed photographs

Fig. 3 shows high-speed photographic images from a Photron Fastcam camera operating at 2000 frames per second, for tests on fabric targets with different boundary conditions. The

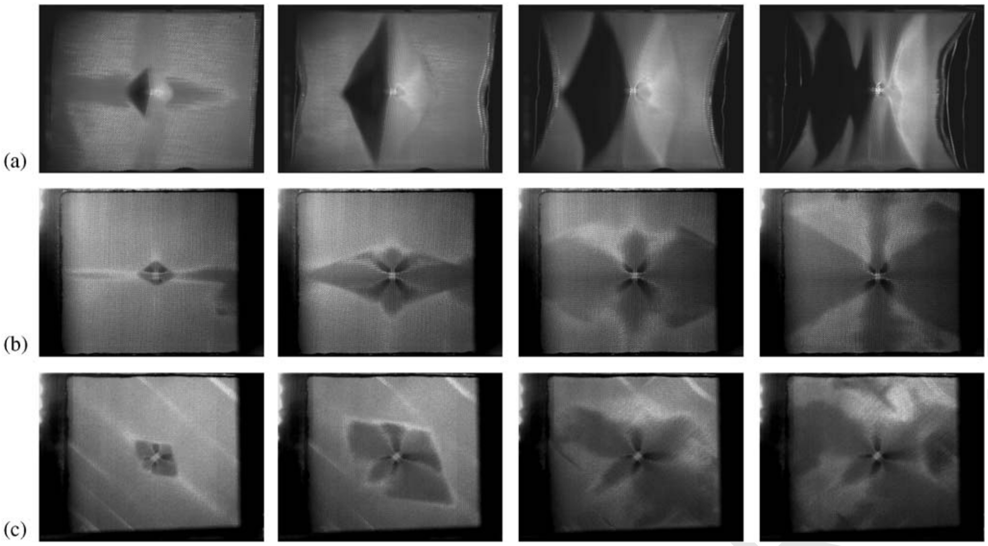

Fig. 3. High-speed images of development of fabric deformation for selected impact velocities: (a) two-clamped-edges, 122 m/s, (b) 0° four-clamped-edges, 110 m/s, (c) 45° four-clamped-edges, 103 m/s.

selected impact velocities, well below the ballistic limits for the respective boundary conditions, facilitate development of stress wave reflection from the boundaries and full development of transverse deformation. In Fig. 3(a), the fabric target with two-clamped-edges exhibits significant inward movement of the free edges, concomitant with yarn ravelling there. Figs. 3(b) and (c) show that targets with 0° and 45° four-clamped-edges constrain transverse and in-plane motion of the fabric, resulting in less energy absorption via kinetic energy acquisition by the fabric. Unlike the situation with two-clamped-edges, the symmetric conditions corresponding to four-clamped-edges were expected to yield symmetric transverse deflections. However, this expectation was proved incorrect by the high-speed images. Deformation of fabric targets with four-clamped-edges assumes the shape of a slender elongated pyramid, indicating that the transverse waves propagate unequally along the two orthogonal principal yarn directions. This can be explained by the different degree of crimp in warp and weft yarns. During the weaving process, higher tension is applied to weft yarns when they are interwoven with warp yarns, resulting in a higher crimp in warp yarns. Twaron® CT716 has a 6.5% crimp in warp yarns and a 0.99% crimp in weft yarns, as determined from measurements according to ISO 7211-3 standards. Upon ballistic impact, yarns with less crimp are more easily stretched and respond faster to the transverse disturbance. Therefore, the transverse wave speed in weft yarns is higher than that in warp yarns. Although there is a significant difference in transverse wave propagation arising from different crimp levels, ballistic tests on fabric specimens clamped along two edges, on either warp or weft yarns, show that the difference in crimp has little effect on the energy absorbed by the fabric. The major energy absorption mechanism in a two-clamped-edge arrangement is the motion of fabric from unclamped edges. The effect of difference in crimp is thus overridden. The influence of crimp may only be evident during the initial wave propagation and in fabric transverse deflection.

4.3. Energy absorption trends

The energy absorption characteristics of a fabric vary with impact velocity and boundary conditions. As shown in Fig. 4, the variation of energy absorption with impact velocity can be divided approximately into two regimes—a low-speed penetration regime below 240 m/s and a high-speed penetration regime above that. For striking velocities below 240 m/s, fabric targets clamped along only two edges generally exhibit superior energy dissipation compared to fabric clamped along four edges. In this regime, a fabric target clamped along two edges is able to absorb ~90% more energy on average than one that is clamped along all four edges. In the high-speed penetration regime, the energy absorbed by targets clamped along two edges drops significantly and fabrics clamped at four edges show better performance. A comparison of fabric clamped along four edges at 0° and 45° to the yarn directions shows that clamping at 45° yields an energy absorption capacity that is up to 25% higher for most velocities. (Note that in actual applications, the energy absorbed is not the only concern; in certain instances, minimal fabric deflection is preferred and in such cases, the fabric should be restrained at all four edges.) It is interesting to note that for a given aperture size, fabric rotated such that its clamped edges are 45° to the yarn directions yields better ballistic resistance.

The present study shows that in terms of energy absorption, clamping along two opposite boundaries yields the best performance in the low-speed penetration regime, while for four-clamped-edges, clamping at 45° to the yarn directions is generally better than clamping parallel to the yarns (0°). However, because of experimental limitations, the mechanisms governing the energy absorption characteristics cannot be fully identified without the help of computational simulation. In the following sections, the effects of different boundary conditions are analyzed from the results of numerical simulation and experimental data.

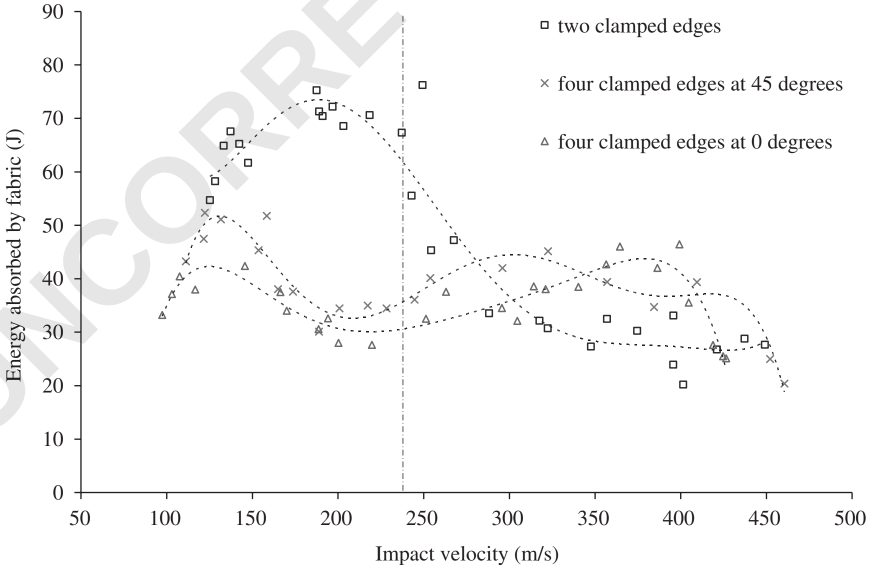

Fig. 4. Experimental results on energy absorption characteristics for fabric targets with different boundary conditions.

5. Numerical results and discussion

5.1. Slippage at clamped edges

Computational simulation allows prescription of perfect clamping conditions, which cannot be fully realised in experiments. In projectile penetration tests using a gas gun, it is noted that at low-impact velocities, a fabric target can be fully stretched and experience high levels of tension at the clamped edges, resulting in the occurrence of slippage. At higher impact velocities, the fabric may be penetrated before transverse displacements propagate to the boundaries. Consequently, slippage at clamped boundaries is typical of fabric targets penetrated at lower speeds. Efforts were made to confine the maximum slippage in experiments to within 5 mm or 4% of the fabric aperture dimensions, although there are no practical means to completely eliminate its occurrence. To match actual test conditions, slippage at boundaries was incorporated into numerical simulations. By setting a maximum lateral restraining force on elements at the boundary, the fabric was allowed to slide inwards towards the point of impact once the tensile force at elements defining the boundary exceeded the restraining force. This restraining force was determined from the limitation of 5 mm maximum slippage.

The relationships between energy absorption and projectile impact velocity predicted by the computational model, with and without slippage at the boundary, are plotted together with experimental data in Fig. 5. For all the three different boundary conditions, the numerical model provides reasonable approximations of the energy absorption trends. For the low impact velocity regime, simulations that allow slippage at the boundary exhibit a much higher energy absorption than those without slippage; this is much closer to actual experimental results. At high-impact velocities, the predictions with and without slippage gradually merge, indicating a diminishing effect of slippage. The computational results show that slippage at the clamped edges decelerates the increase in fabric strain and extends the time for perforation. Consequently, the fabric is able to dissipate more energy via strain and kinetic energy, as well as via friction through slippage at the boundaries.

The variation of energy absorbed with impact velocity in Fig. 5 shows different profiles for a target clamped along two edges and for one clamped along four edges. There is one peak for a target clamped at two edges (Fig. 5a), while two peaks are observed for targets clamped along four edges (Figs. 5b and c). Consider the numerical prediction for the case of no slippage in all three graphs. For perfect clamping, the energy transferred to the fabric initially increases with impact velocity because the fabric acquires a higher kinetic energy as the impact velocity increases, and a substantial area of fabric is set in motion. However, as the projectile velocity is further increased, failure sets in earlier, and the area of deflected fabric becomes smaller. This opposing effect defines the predicted peak in energy absorbed, because at increasingly high-impact velocities, the area of fabric set in motion becomes so small that little kinetic energy is transferred prior to failure. Consequently the energy absorbed decreases.

The preceding paragraphs have highlighted that energy absorption via slippage is significant at lower impact velocities. Hence, the presence of slippage enhances the increase in energy absorbed with perforation velocity in the low impact velocity range. However, as the projectile velocity increases, target perforation occurs earlier and so the duration for fabric slip is decreased, thus diminishing the energy absorbed by this mechanism. A combination of the two opposing effects of slippage and earlier failure, results in the generation of another peak, but within the low-velocity

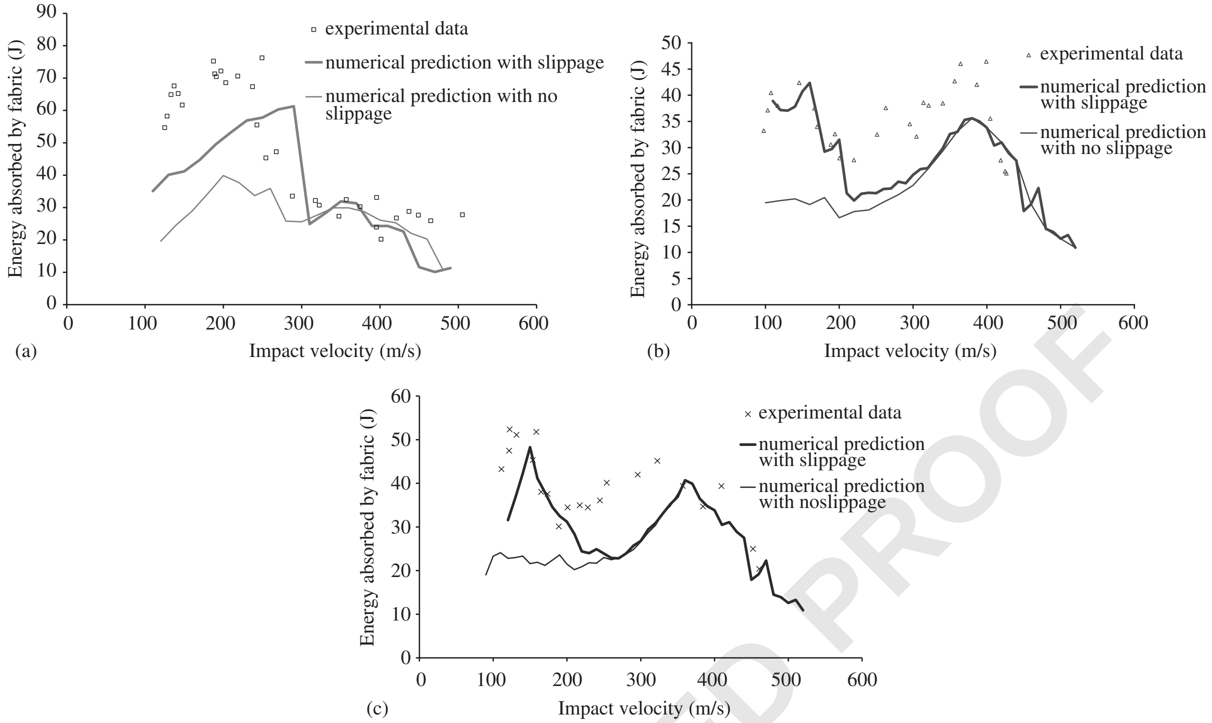

Fig. 5. Comparison of energy absorption predicted by the numerical model, with experimental data: (a) two-clamped-edges; (b) 0° four-clamped-edges; (c) 45° four-clamped-edges.

regime of the energy absorption curve. Beyond this phase, the amount of kinetic energy transferred to the fabric governs energy dissipation. These mechanisms account for the two peaks in the energy absorption curve, which are evident in the numerical and experimental results for targets clamped along four sides (Fig. 5b and c). Fig. 5a shows that for a specimen clamped on only two sides, there seems to be only one peak, even when slippage is present. This is because the two peaks described happen to occur close to each other for this particular combination of specimen size, clamping conditions and fabric properties.

It is noted that some slippage along clamped boundaries is actually beneficial in terms of energy absorption. However, the cost is a higher transverse deflection of the fabric. Appropriate adjustment of clamping conditions at the boundaries to allow for some relaxation can enhance fabric ballistic performance significantly with regard to a higher ballistic limit V_{50} and higher energy absorption upon perforation.

In the following discussion on numerical results, slippage at the boundaries is not considered and all comments made relate to full, perfect clamping.

5.2. Two- and four-clamped-edges

Experimental evidence on low-speed penetration shows that fabric with only two-clamped-edges exhibits a higher energy absorption capacity than fabric with all four edges clamped, as

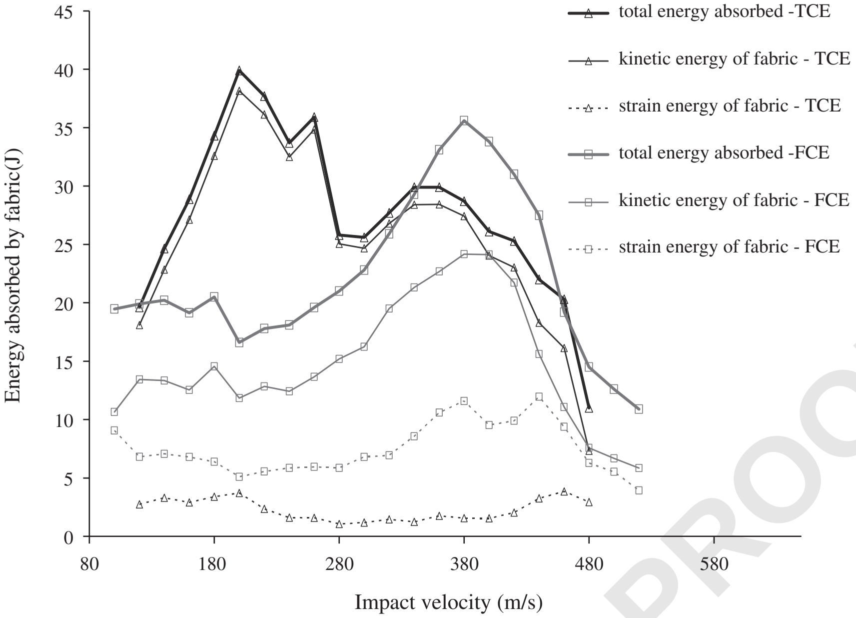

Fig. 6. Influence of two-clamped-edges and four-clamped-edges on fabric energy absorption via fabric kinetic and strain energy.

illustrated in Fig. 6. The computational results further reveal how boundary conditions influence energy absorption. When a high-speed projectile strikes a fabric target, energy dissipation by the fabric occurs via strain energy through the stretching of yarns and kinetic energy associated with transverse motion of the fabric as well as movement towards the impact point. These two energy components, calculated from the numerical model as functions of impact velocity, are plotted in Fig. 6. Fabric kinetic energy accounts for over 90% of the total energy absorbed by targets with two-clamped-edges, while for targets clamped along four edges, the strain energy is much higher and constitutes 30% of the total. This is because with two-clamped-edges, the free edges allow fabric material to undergo transverse and in-plane displacement more easily, so that the kinetic energy transferred to the fabric is much higher than for fabrics with constrained boundaries. On the other hand, clamping along four edges promotes a higher proportion of conversion to strain energy.

Another cause of the difference in energy absorbed is the difference in time taken for perforation; this arises from wave propagation. Stress waves initiated upon impact travel along individual yarns and generate secondary waves in orthogonal yarns at weave crossover points. Once the stress waves reach the boundaries, they are either reflected by fully clamped edges or converted into kinetic energy associated with inward-moving fabric material at unclamped edges. The stress waves reflected from clamped boundaries are significantly amplified in magnitude and consequently promote damage and lower the ballistic resistance. In the case of four-clamped-edges, the stress waves in primary yarns in direct contact with the projectile are reflected at all boundaries. A high stress level is generated rapidly and triggers yarn failure; thus, fabrics are penetrated much earlier. The preceding explanation is substantiated by Fig. 7, which depicts the

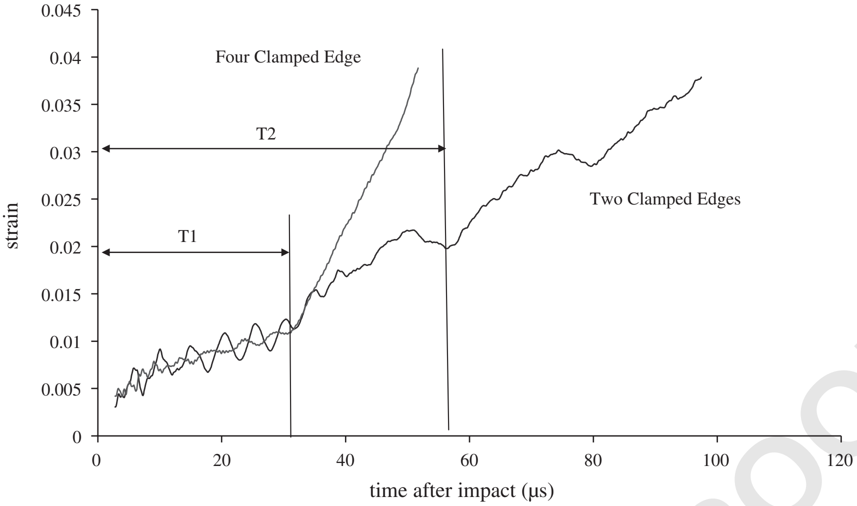

Fig. 7. Stain histories for a central element along a clamped yarn in a fabric clamped at two and four edges (200 m/s impact velocity). T1 is the instant the stress wave reflects back from the clamped boundary to the impact point; T2 is the instant the second reflection returns.

strain history of an element at the point of impact for the two different boundary conditions. Immediately after the instant T1 when the stress wave reflects back from the clamped edges to the impact point, the strain increases sharply for a fabric clamped at four edges and this results in element failure. However, the strain increase for a fabric clamped along two edges is more gradual and it arrests the projectile over a noticeably longer time, after the instant T2 which corresponds to the return of the stress wave after a second reflection from the clamped boundary.

5.3. Four-clamped-edges at 0° and 45°

Different clamping orientations lead to differences in energy absorption. Both in ballistic experiments and computational simulations, clamping at 45° to the yarn direction was found to improve fabric performance by 25% in terms of total energy absorbed, compared to clamping at 0°. The major benefit from four-edge clamping at 45° arises from an increase of strain energy in the fabric, as shown in Fig. 8, which depicts strain and kinetic energy components for clamping at 45° and 0°. This is true for impact velocities lower than 380 m/s; beyond this velocity, the influence of boundary conditions appears to diminish in significance. With a rotation in the angle of clamping from 0°, the length of primary (impacted) yarns increases to $\sqrt{2}L_{\text{original}}$ for 45°. However, yarns remote from the impact point become shorter. Fig. 9 shows the strain distribution within fabric targets clamped at 0° and 45° for impact at 200 m/s at the instant element failure initiates. Commencement of failure occurs 52 µs after impact for clamping at 0° and after 61 µs for clamping at 45°. Targets with boundaries clamped at 45° to the yarn directions require a longer perforation time. Also, as observed from Fig. 9(b), higher strain levels, generally above 0.01, are experienced by the entire fabric. In contrast, a significant portion around the four corners of a target clamped at 0° exhibits a low level of strain, of less than 0.01. For clamping at 45°, the longer primary yarns can sustain greater transverse displacement and arrest the projectile over a longer

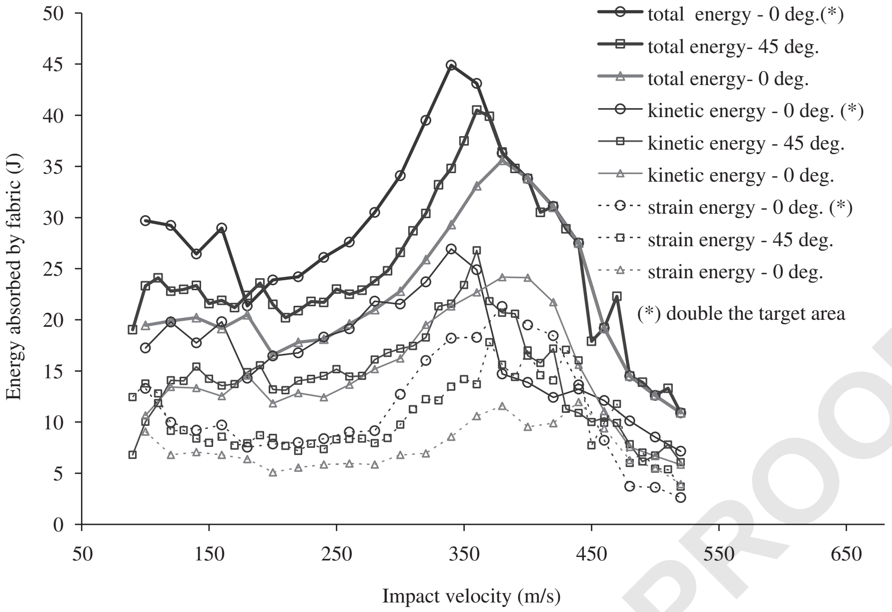

Fig. 8. Influence of clamping at four edges at 0° and 45° on energy absorbed via kinetic and strain energy.

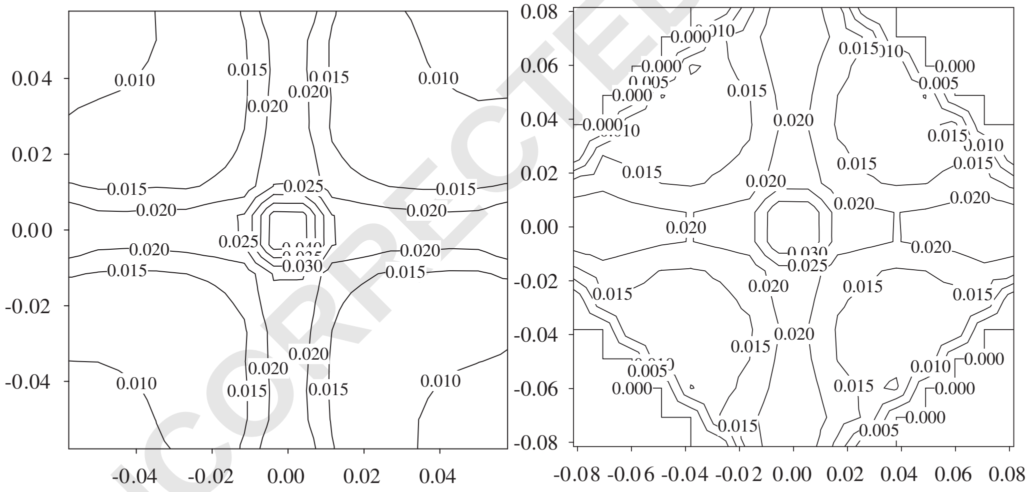

Fig. 9. Strain contours in a target clamped along four edges at 0° (left) and 45° (right), at the instant element failure commences (200 m/s impact).

duration. Shorter yarns away from the impact point are more easily stretched and more of the total fabric is involved in energy dissipation, especially via strain energy.

Fig. 8 shows another comparison, between a target clamped at 45° and a square target of double the area, clamped at 0°. These two arrangements yield the same length of primary yarns, but a different aperture size. It is obvious that the larger target clamped at 0° is able to absorb more energy. This is because the larger area enables it to dissipate more kinetic energy via greater transverse deflection. In essence, the target size governs two significant parameters, namely, the length of primary yarns and the overall size of fabric available to accommodate energy transfer.

6. Conclusions

The influence of three different boundary conditions—i.e. two-clamped-edges, four-clamped-edges at 0° and four-clamped-edges at 45°—on impact energy dissipation by fabric armour was investigated experimentally. The energy absorption characteristics show that in the low-speed penetration regime, clamping of fabric at two edges is superior to clamping at all four edges. Also, four-edge clamping at 45° to the yarn direction facilitates greater energy absorption compared to clamping along 0°. Computational simulation was employed to identify the mechanisms that give rise to these differences. Numerical results show that relaxation of completely ideal clamping at boundaries results in much higher energy absorption. Computational simulations also indicate that a free boundary contributes significantly to a larger transfer of the incident energy to fabric kinetic energy. For fabric targets clamped at four edges, those with edges clamped at 45° to the yarns are the most effective because this is the optimal yarn alignment in terms of energy absorption.

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