



Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor

Gaurav Nilakantan¹, Steven Nutt^{1,*}

1. Mork Family Department of Chemical Engineering and Materials Science, M.C. Gill Composites Center, University of Southern California, Los Angeles, CA 90089, USA.

Abstract: The effects of target shape and size on the V_{50} ballistic impact response of non-backed woven aramid fabrics is studied by considering 4-sided, circular, and diamond clamped fabrics with cross-sectional areas varying between 5 cm² and 525 cm². The fabric targets show an initial very sharp rise in V_{50} velocity which then plateaus out with increasing fabric areas. At impact velocities around the V_{50} velocity for each clamped fabric shape, there is a critical fabric size beyond which the projectile residual kinetic energy shows a sharp jump in magnitude, which continues to grow with increasing fabric sizes. Regardless of fabric size, all impacts show sensitivity to the precise projectile impact location with yarn-based impacts generally resulting in greater energy dissipations than gap-based impacts. Over the range of target sizes considered, the V_{50} velocities of the circular and diamond clamped fabrics were very similar to each other and higher than the 4-sided clamped fabric targets.

Key words: Aramid fiber, Fabrics, Ballistic impact, Finite element analysis, V_{50} velocity.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



1. Introduction

The ballistic impact behavior of fabric-based structures used in soft body armor is influenced by many obvious parameters such as the geometry, material, and architecture of the fabric and its constituents. Geometrical parameters include the filament (i.e. fiber) diameter, filament packing, and yarn denier; material parameters include the strength, stiffness, and frictional characteristics; architectural parameters include the weave tightness and yarn crimp. These parameters have been the focus of many experimental and numerical studies [1]. However there are several other non-obvious factors to consider when assessing and comparing the ballistic impact performances of these fabric-based structures. For example, keeping the choice of fabric material and architecture constant, the manner in which the experimental testing is conducted can have a significant effect on the estimated fabric V_{50} velocity. The V_{50} velocity is defined as the projectile impact velocity that has a 50% probability of completely penetrating through the target. To demonstrate this, we had shown in a previous study [2] that for a given fabric target area, the shape of the fabric target whether fully or partially clamped had an important effect on the fabric V_{50} velocity. Circular and diamond clamped fabrics resulted in similar fabric V_{50} velocities that were higher than 4-sided clamped fabrics and much higher than 2-sided clamped fabrics, with corner clamped fabrics showing the poorest overall performance. One reason was that circular and diamond clamped fabrics resulted in a more efficient distribution of the exposed fabric area compared to 4-sided clamped fabrics, as they concentrated more fabric material around the impact region which sees the highest levels of deformation, stress, and energy dissipation, and lesser fabric material at far-field regions that see

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



little to no activity. It should be noted that because the fabric area was kept constant, each of the 4-sided, circular, and diamond clamped fabrics had different principal yarn lengths. The principal yarns refer to the yarns around the impact region that are in contact with the projectile during the impact event. The location of the principal yarns is exemplified later in Fig. 5d.

This two-part study extends upon our previous study [2]. The first part investigates the relative effect of the length of the principal yarns on the fabric V_{50} impact response compare to the overall exposed fabric area. The principal yarns experience the highest levels of stress and deformation that rapidly drop off in the neighboring yarns with distance away from the impact site. Consequently the principal yarns account for the highest yarn internal energies. The second part of this study investigates how the fabric V_{50} velocity changes as a function of the exposed fabric area for various fully clamped fabric target configurations. Other experimental and numerical studies have also shown the dependence of the fabric V_{50} velocity and zone of mixed results (ZMR) on the boundary conditions, clamping pressures, boundary slippage, presence of backing, and target size [3–5]. Obviously these effects are important to consider when assessing and comparing the ballistic impact performance of fabric based armors, wherein such external effects and sources of variability that tend to bias the impact performance are unwanted.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



2. Results and discussion

2.1 Effect of principal yarn length and fabric area on the V_{50} velocity

Two fabric target configurations are considered in the first part of the study. In the constant fabric area (CFA) configuration, the exposed fabric area is kept constant at 58.06 cm^2 which results in different principal yarn lengths for the 4-sides, circular, and diamond clamped fabrics. These dimensions are listed in Table 1. The diamond clamped fabric has the longest principal yarns in the CFA configuration while the 4-sides held fabric has the shortest. For the 4-sides held fabric, the principal yarn length is equal to the side of the exposed square shaped fabric. For the circular clamped fabric it is equal to the diameter of the exposed circular shaped fabric, and for the diamond clamped fabric it is equal to the diagonal length of the exposed diamond shaped fabric. In the constant yarn length (CYL) configuration, the principal yarn length is kept constant which results in different exposed fabric areas, as shown in Table 1. The 4-sides held fabric has the largest exposed fabric area while the diamond clamped fabric has half the area, which is the least of all.

Table 1 Principal yarn length (L) and fabric area (A).

Clamping	CFA configuration		Method of extraction Description of	
	L (mm)	A (cm^2)	L (mm)	A (cm^2)
4-sides held	76.20	58.06	76.20	58.06
Circular clamp	85.98	58.06	76.20	45.60
Diamond clamp	107.76	58.06	76.20	29.03

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



The impact test setup, including the particulars of the fabric material and weave, and projectile has already been described in detail in Ref. [2], and therefore only briefly repeated here for completeness. The impact scenario comprises of a single layer of plain weave aramid fabric (Kevlar S706) impacted once at the center by a 0.22 caliber spherical steel projectile with a mass of 0.692 gm and diameter of 5.556 mm. The fabric has an areal density of 180 g/m², approximate thickness of 0.23 mm, and comprised of 600 denier Kevlar KM2 yarns with a yarn span of 0.747 mm. Each yarn comprises of 400 approximately circular filaments of diameter 12 μ m and density 1.44 g/cm³. Each yarn has a longitudinal tensile modulus of 82.6 GPa and tensile strength of 3.4 GPa. Individual Kevlar yarns are explicitly modeled as homogenous continua and are discretized with solid elements. The pre-processor DYNAFAB [6] is used to set up the fabric mesh. Both the warp and fill yarns are assumed to have the same degree of undulation or crimp. To account for the homogenization of the actual filament-level yarn architecture, the material properties must be adjusted by the filament volume fraction m_f , which is computed as the ratio of the actual filament cross-sectional area to the cross-sectional area of the finite element yarn, resulting in a m_f value of 87%. The yarns are assigned a transversely isotropic material model with the following adjusted properties: E_{axial} of 71.84 GPa (E_{11}), E_{trans} of 718.45 MPa (E_{22} , E_{33}), G of 148 MPa (G_{12} , G_{23} , G_{31}), ν of 0.0 (ν_{12} , ν_{23} , ν_{31}), and ρ_{yarn} of 1.25 g/cm³. A coefficient of friction of 0.23 is used between the projectile and the fabric, and 0.18 between the warp and fill yarns. An element erosion-based failure model is used based on a maximum tensile stress failure criterion, with a r_{fail} of 2.95 GPa. A zero slippage or perfectly clamped boundary condition is modeled by constraining all the

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



degrees of freedom of the fabric nodes that are within the upper and lower clamps. The finite element code LS-DYNA [7] is used for all impact simulations.

Figs. 1–3 display the results of the impact testing for both fabric target configurations for the 4-sided, circular, and diamond clamped fabrics respectively. V_i refers to the impact velocity and V_r refers to the residual velocity. For non-penetrating impacts, the rebound velocity is not considered and consequently V_r is assumed to be zero. For each impact velocity, both yarn and gap impacts are separately considered. Impacts that occur at the gap between yarns usually result in higher projectile residual velocities. Because of the square exposed shape for the 4-sided clamped fabric, the CFA and CYL configurations represent the same configuration. Figs. 1–3 primarily display the penetrating test shot data, which is later used to compute the respective V_{50} velocities.

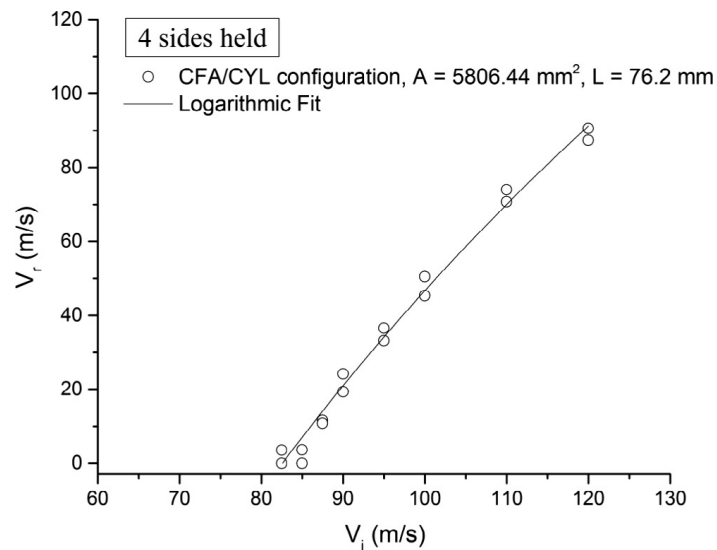


Fig. 1. Impact velocity versus residual velocity for 4-sides held.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

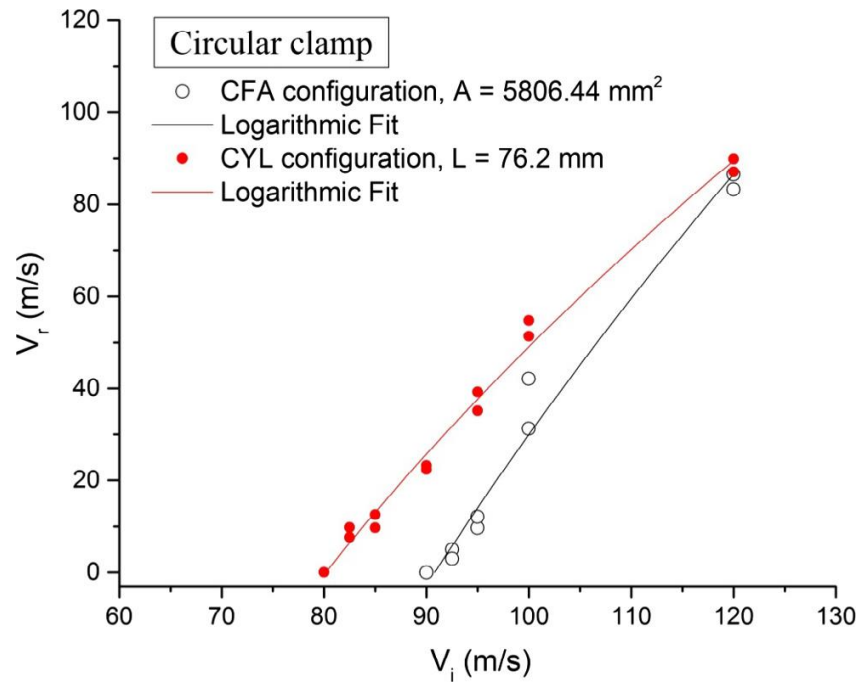


Fig. 2. Impact velocity versus residual velocity for circular clamp.

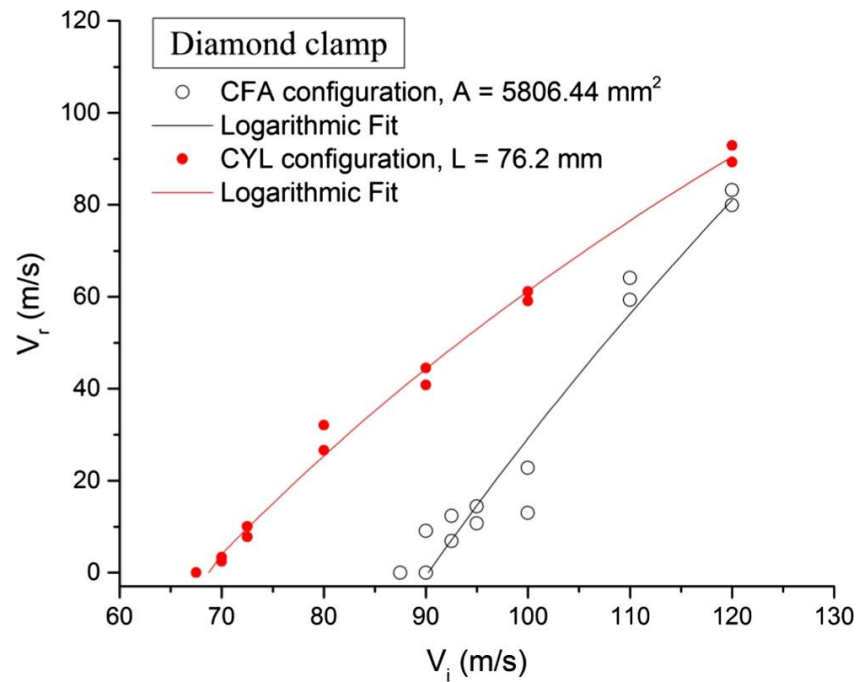


Fig. 3. Impact velocity versus residual velocity for diamond clamp.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <http://dx.doi.org/10.1016/j.compstruct.2014.06.002>



There are several methods to calculate the fabric V_{50} velocity. A 6-shot V_{50} velocity, which was used in Ref. [2], is calculated by taking the mean of the three highest non-penetrating and three lowest penetrating test shot velocities. Additional criteria may be imposed such that the mean of the three non-penetrating impact velocities must be higher than the mean of the three penetrating impact velocities (if a zone of mixed results exists), or that the difference between the two means should be within some predetermined range. Similarly a 10-shot V_{50} velocity is computed by taking the mean of ten shots (five non-penetrating and five penetrating) instead of six. Other techniques utilize the fitting of a curve to the test shot data and estimating the unknown coefficients using techniques such as maximum likelihood estimator (MLE). One well-known example is the Lambert–Jonas [8] technique, based on the principle of energy conservation, given by

$$V_r = \alpha(V_i^p - V_{BL}^p)^{1/p} + \varepsilon \quad (1)$$

where VBL is the ballistic limit, V_r and V_s are the residual and impact velocities, a and p are fitting parameters, and e is an error term. While there is no specific probability level assigned to VBL, it is considered analogous to the V_{50} velocity. In Figs. 1–3, a logarithmic function was found to well describe the test shot data, given by

$$V_r = A \ln(V_i) + B \quad (2)$$

where A and B are fitting parameters. The V_{50} (or VBL) velocity is then given by

$$V_{50} = \exp(-B/A) \quad (3)$$

The smooth color lines in Figs. 1–3 represent the logarithmic functions fit to the penetrating test shot data. Using the simulation test shot data, the differences between the logarithmic-based V_{50}

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



and 6-shot V_{50} velocities were less than 1.5%. It should be noted that the 6-shot V_{50} requires the presence of non-penetrating test shots while the logarithmic-based V_{50} is based only on penetrating test shot data.

From Figs. 2 and 3, it is seen that the CYL configuration with the smaller exposed fabric area results in reduced impact performance compare to the CFA configuration, i.e. higher V_r for the same V_i , as well as lower fabric V_{50} velocities. The difference in impact performances between both configurations for the circular and diamond clamped fabrics appears as a shrinking band that gets progressively narrower at higher impact velocities. At very high impact velocities, yarn stresses and failure are essentially highly localized around the impact zone and so both test configurations essentially produce similar impact behavior, i.e. similar V_r velocities for the same V_i velocities. It should also be noted that as V_i becomes very large, V_r will eventually approach V_i .

Fig. 4 displays normalized fabric V_{50} velocities and normalized exposed fabric areas for both target configurations. All data has been normalized with respect to the 4-sides clamped fabric (where the CFA and CYL configurations are the same). As has already been reported in Ref. [2], for a normalized exposed fabric area of 1.0 (i.e. CFA configuration where the fabric areas are kept constant), the fabric V_{50} velocities of the circular and diamond clamped fabrics are very similar and higher than the 4-sides clamped fabric, while that of the 2-sides clamped fabric is much lower. The other two data points in Fig. 4, represent the CYL configuration (principal yarn length kept constant) for the diamond clamped fabric (normalized fabric area of 0.5) and circular clamped fabric (normalized fabric area of 0.79). It is interesting to note that for the circular clamped fabric,

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



in spite of a 21% drop in the exposed fabric area, the V_{50} velocity is still 97% that of the 4-sided clamped fabric, while for the diamond clamped fabric a 50% drop in exposed fabric area still results in a fabric V_{50} velocity that is 82% that of the 4-sided clamped fabric. This trend demonstrates that there is no linear relationship between fabric V_{50} velocity and exposed fabric area, and that the precise relationship is sensitive to the shape of the exposed fabric area.

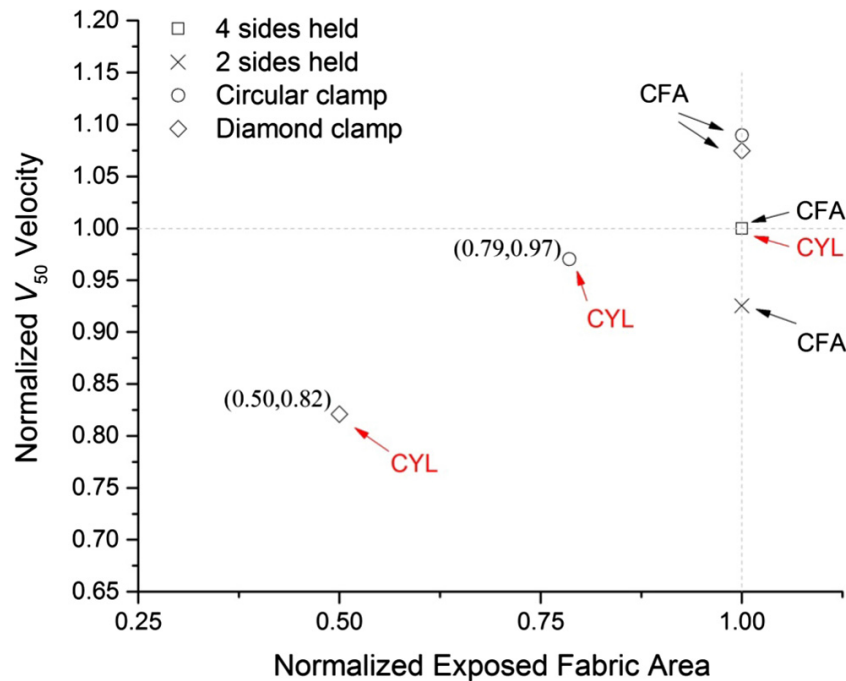


Fig. 4. Normalized impact test performance.

For the same exposed fabric area the circular clamped fabric had a higher V_{50} velocity (refer to the CFA configuration data points in Fig. 4) than the 4-sides clamped fabric. When the exposed circular fabric area was reduced but the principal yarn length was kept constant (refer to the CYL configuration data points in Fig. 4), the V_{50} velocity remained almost the same as the 4-sides clamped fabric (i.e. 97%). This trend points to the greater effect of the principal yarn length

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



on the fabric V_{50} velocity than the exposed fabric area. It also indicates that the circular clamped fabric is more efficient than the 4-sides clamped fabric in stopping the projectile. The same set of conclusions can be drawn based on the diamond clamped fabric data in Fig. 4.

2.2 Effect of increasing fabric target size on the V_{50} velocity

In the previous section, it was shown that there is a non-linear relationship between fabric size and V_{50} velocity. To further study this relationship, a wide range of exposed fabric areas was considered for each fabric shape: 4-sides held, circular, and diamond clamped fabrics, ranging between 5 cm^2 and 525 cm^2 . Fig. 5a–c display the setup of the fabric finite element models. Fig. 5d displays the location of the principal yarns (colored in red) within the fabric weave (colored in yellow) for the 4-sides held and diamond clamped fabrics. For each fabric size, similar to the process in Ref. [2], a fabric 6-shot V_{50} velocity is computed after running a series of impact test simulations in LS-DYNA. Table 2 lists the exposed fabric areas and V_{50} velocities for each of the three fabric shapes. Surprisingly a logarithmic function was once again found to well describe the functional relationship between exposed fabric areas and fabric V_{50} velocities for all three shapes, given by.

$$V_{50} = A \ln(\emptyset) + B \quad (4)$$

where A and B are the fitting parameters and \emptyset is the exposed fabric area.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



Table 2 Fabric V_{50} velocities

4-sides held		Circular clamp		Diamond clamp	
Fabric area (cm ²)	V_{50} velocity(m/s)	Fabric area (cm ²)	V_{50} velocity(m/s)	Fabric area (cm ²)	V_{50} velocity(m/s)
6.45	40.00	5.07	40.00	7.26	42.50
58.06	83.75	11.40	41.25	29.03	68.75
232.26	120.00	45.60	81.25	58.06	90.00
522.58	132.50	58.06	91.25	261.29	132.50
		182.41	121.25	464.52	137.50
		410.43	136.25		

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

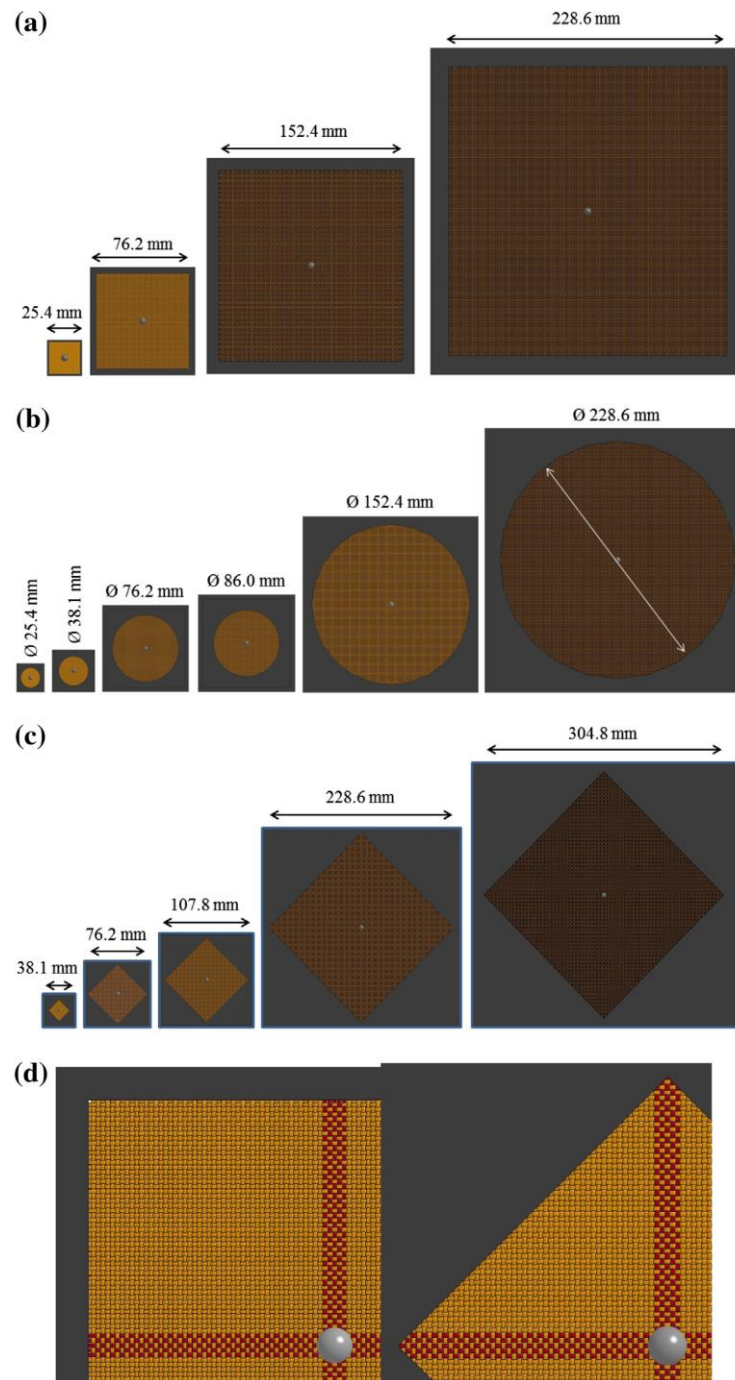


Fig. 5. Fabric target setup for the (a) 4-sides held (b) circular clamp (c) diamond clamp (d) location of the principal yarns.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



Fig. 6 displays this V_{50} data (color symbols) along with logarithmic functional fits (smooth color lines) given by Eq. (4). Table 3 lists the logarithmic function coefficients A and B, used to fit the data in Fig. 6. Once again it is observed that the circular and diamond clamped fabrics have very similar V_{50} velocities over the range of fabric areas studied, which are larger than those of the 4-sided clamped fabrics. It is seen that the fabric V_{50} velocity initially rises sharply for small increases in the fabric exposed area after which it starts to plateau out as the fabric exposed area becomes larger and larger.

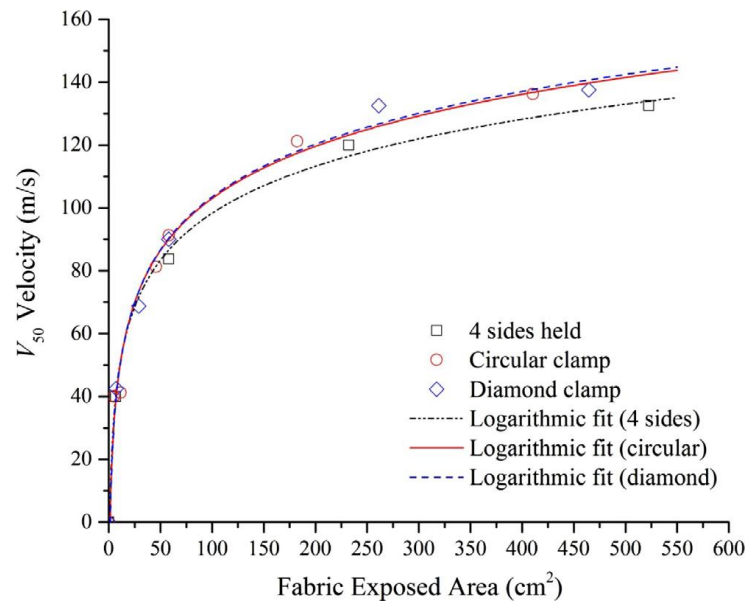


Fig. 6. Effect of fabric target size on the V_{50} velocity.

Table 3 Logarithmic fit parameters

Clamping	A	B	C
4-sides held	21.556	-0.957	0.996
Circular clamp	23.904	-7.067	0.976
Diamond clamp	24.225	-8.069	0.989

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



2.3 Fabric impact behavior around the V_{50} velocity

Fig. 7 displays the residual projectile kinetic energy (KE_r) for each fabric exposed area for all three clamping conditions. Yarn and gap impacts are shown separately. The KE_r is given by

$$KE_r = \frac{1}{2} m_p V_r^2 \quad (5)$$

where m_p is the mass of the projectile. For each data point shown in Fig. 7, the chosen impact velocity is the first penetrating shot either at or just above the V_{50} velocity for that particular exposed area. Because the test shot velocities chosen during the testing proceeded in intervals of 2.5 m/s around the V_{50} velocity (i.e. when response jumps were observed), the impact velocities for the data points shown in Fig. 7 are $V_{50} \leq V_i \leq (V_{50} + 2.5)$ m/s. Thus the impact velocities can also be approximately obtained from Table 2. Fig. 7a shows that for the 4-sided clamped fabric case, the KE_r remains very small for fabrics up to 58.06 cm² in size. In other words, the projectile is barely able to penetrate through the fabric and exits with a very low residual velocity that is much lower in magnitude compare to the impact velocity. However for the remaining two exposed fabric areas considered, viz. 232.26 cm² and 522.58 cm², the KE_r rises sharply implying much higher residual projectile velocities. What is interesting about this is that one would usually expect the projectile to barely penetrate through the fabric and exit with a low residual velocity because even for these larger sized fabrics, the impact velocity is still at or around the fabric V_{50} velocity corresponding to that particular fabric size. However we observe from Fig. 7a that for the 4-sided clamped fabric, the larger the fabric size the larger is the residual projectile kinetic energy. Similar trends are seen for

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



the circular and diamond clamped fabrics as well, respectively from Fig. 7b and c. Beyond a certain exposed fabric area for each shape, the residual projectile kinetic energy shows a very sharp increase.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

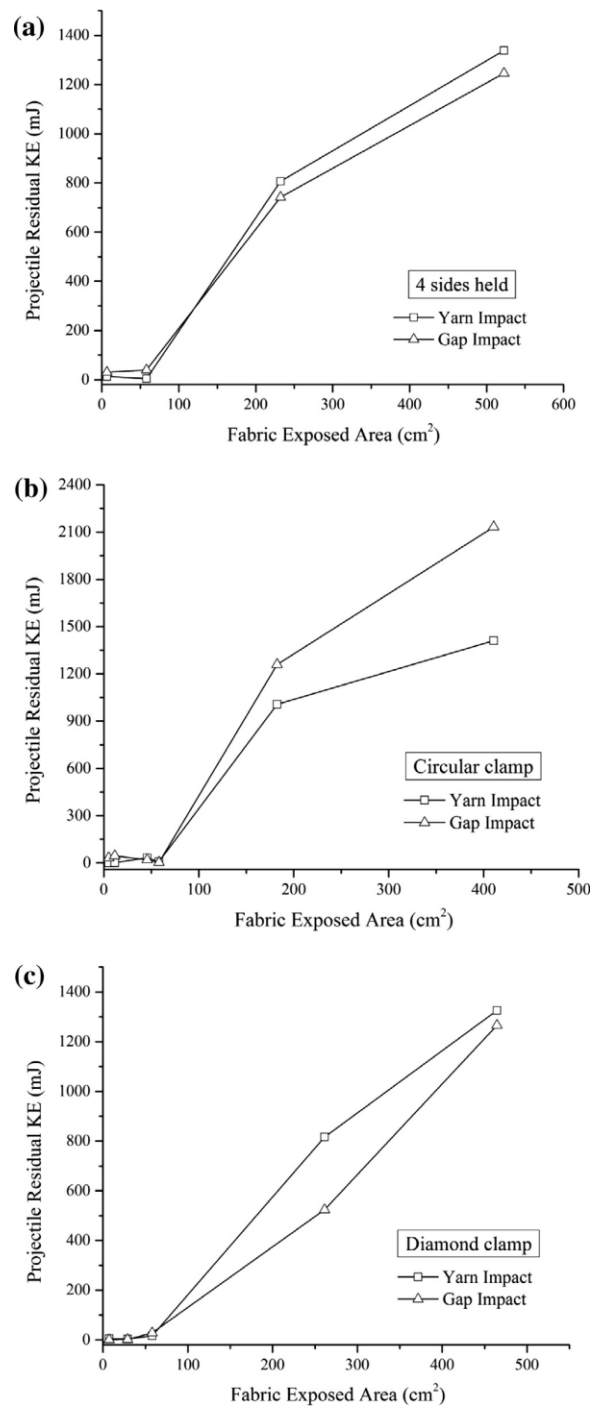


Fig. 7. Effect of fabric target size on the residual projectile kinetic energy for the (a) 4-sides held (b) circular clamp (c) diamond clamp.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <http://dx.doi.org/10.1016/j.compstruct.2014.06.002>



Fig. 8 displays the projectile velocity history for two different fabric areas for the 4-sided clamped configuration. Fig. 8a corresponds to a fabric area of 58.06 cm^2 with a V_i of 85 m/s (V_{50} is 83.75 m/s) while Fig. 8b corresponds to a fabric area of 522.58 cm^2 with a V_i of 132.5 m/s (V_{50} is 132.50 m/s). For the smaller exposed fabric area, the penetrating shot (yarn impact) results in a V_r of just 3.57 m/s which is much lower than the V_i of 85 m/s ($V_r/V_i = 4.2\%$). However for the larger exposed fabric area, while the projectile was arrested for the yarn impact shot, the projectile penetrated through the fabric for the gap impact shot with a V_r of 60.02 m/s which is comparable to the V_i of 132.5 m/s ($V_r/V_i = 45.3\%$). Figs. 7 and 8 appear to point to the existence of a critical fabric exposed area for each clamping configuration beyond which the projectile will show sharp rises in the residual velocity and residual kinetic energies for impacts that occur around the V_{50} velocity for that particular size.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

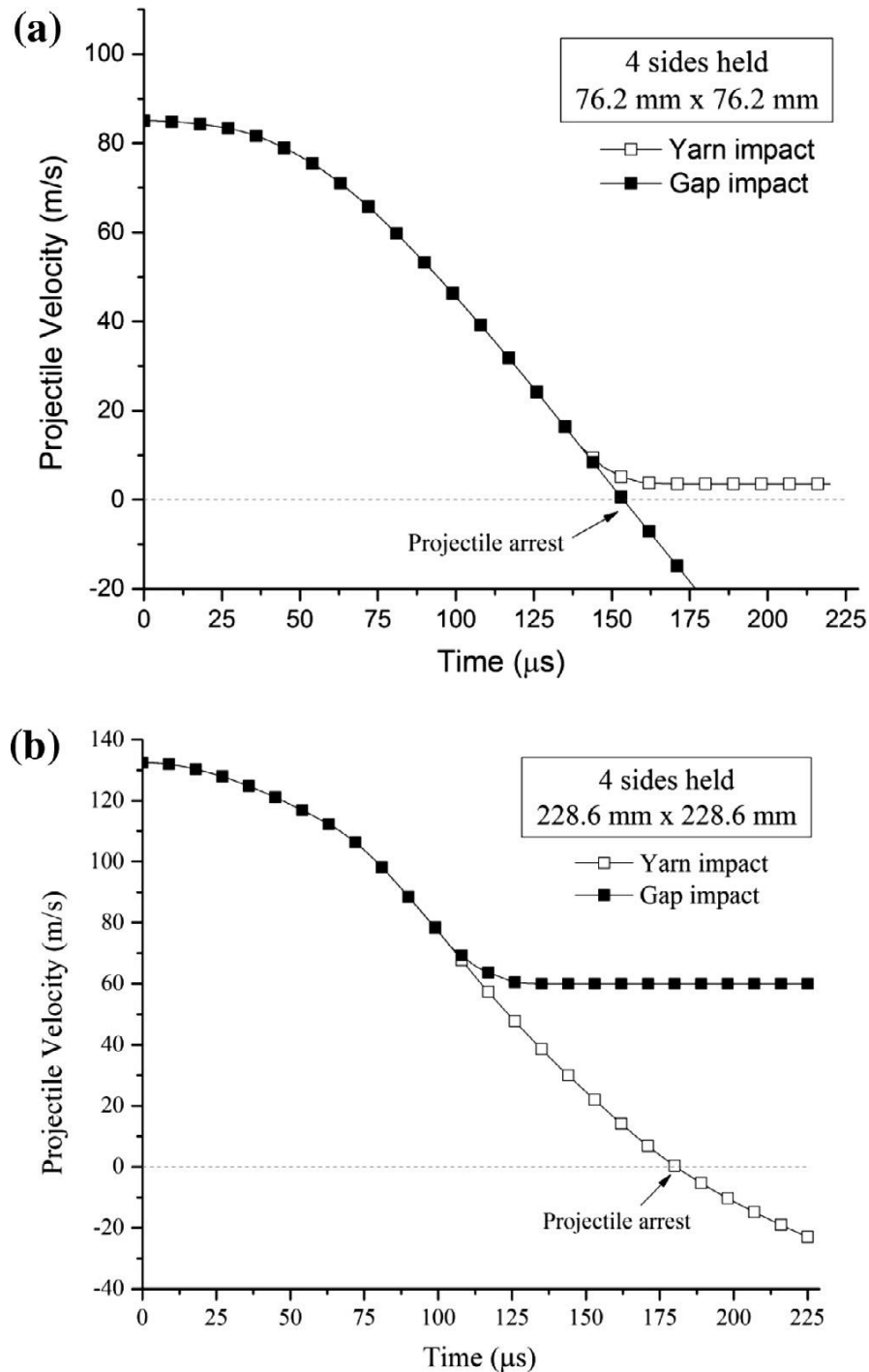


Fig. 8. Projectile velocity histories for 4-sides held (a) 76.2 mm x 76.2 mm at $V_i = 85$ m/s.
(b) 228.6 mm x 228.6 mm at $V_i = 132.5$ m/s.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



2.4 Effect of precise impact location – yarn vs gap

A general trend observed during the impact testing for all three clamping configurations and range of exposed fabric areas was that gap impacts, where the projectile impacts the gap between the yarns, generally results in a higher residual projectile velocity than yarn impacts, where the projectile directly impacts a yarn. This trend obviously only applies to penetrating shots. There was no universal trend regarding the V_{50} velocity based on precise impact location, i.e. yarn impact and gap impact based V_{50} velocities.

Fig. 9 displays fabric deformation states for yarn and gap impacts of the 25.4 mm x 25.4 mm 4-sides held fabric at a V_i of 40 m/s which also corresponds to the V_{50} velocity for that size. Surprisingly the projectile has been completely caught within the fabric weave as seen in Fig. 9a resulting in a non-penetration for the yarn impact case. In spite of being a non-penetrating event, yarn failure is observed around the impact site. Such behavior is not often seen, especially as the fabric becomes larger in size. In such cases, non-penetrations are usually accompanied by a rebounding of the projectile as the fabric springs back, without any principal yarn failure. The projectile was able to penetrate through the fabric for the gap impact as seen in Fig. 9b.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

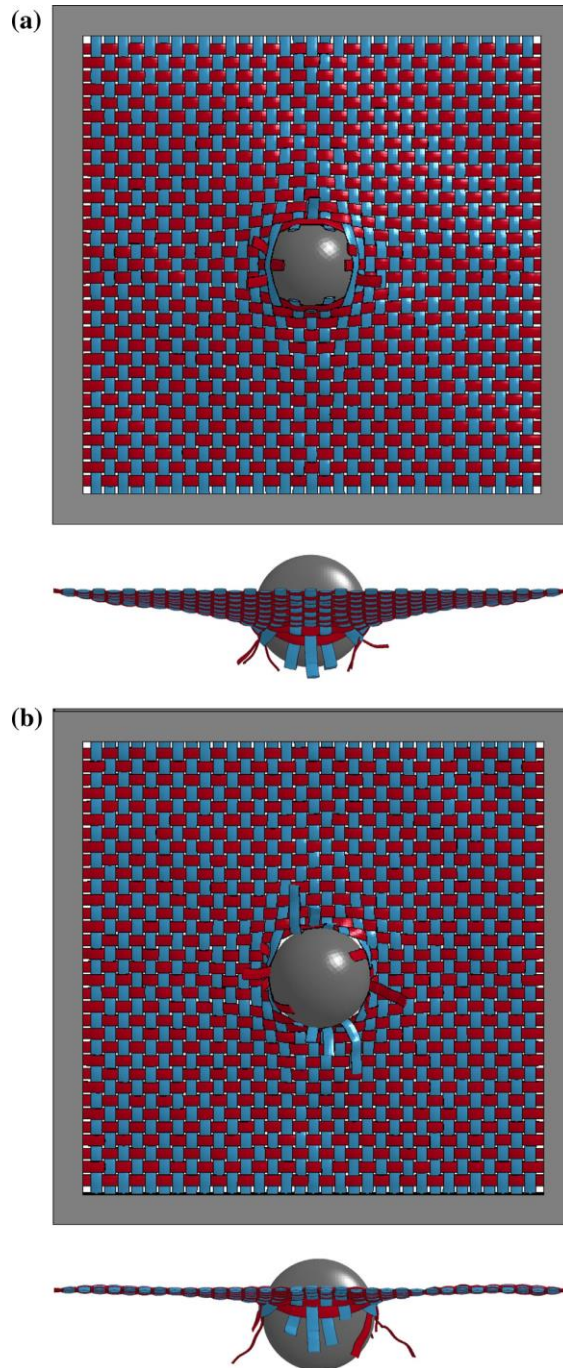


Fig. 9. Fabric deformation states for 4-sides held, 25.4 mm x 25.4 mm target at $V_i = 40$ m/s (a) yarn impact at $170 \mu\text{s}$ (b) gap impact at $40 \mu\text{s}$.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



Fig. 10 displays fabric deformation states for yarn and gap impacts of the 228.6 mm x 228.6 mm 4-sides held fabric at a V_i of 132.5 m/s, which also corresponds to the V_{50} velocity for that particular size. The transverse displacement wave has spread outwards close to the clamped boundaries. Once again, the yarn impact results in a non-penetration while the gap impact results in a penetration. However this time, the non-penetrating impact does not result in the failure of any principal yarns and the projectile rebounds after it has been arrested. Fig. 8b displays the projectile velocity history for this impact case. As mentioned earlier, the residual velocity for the penetrating gap impact was large in magnitude relative to the impact velocity, which is interesting given that the projectile for the yarn impact case at the same impact velocity was completely arrested.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

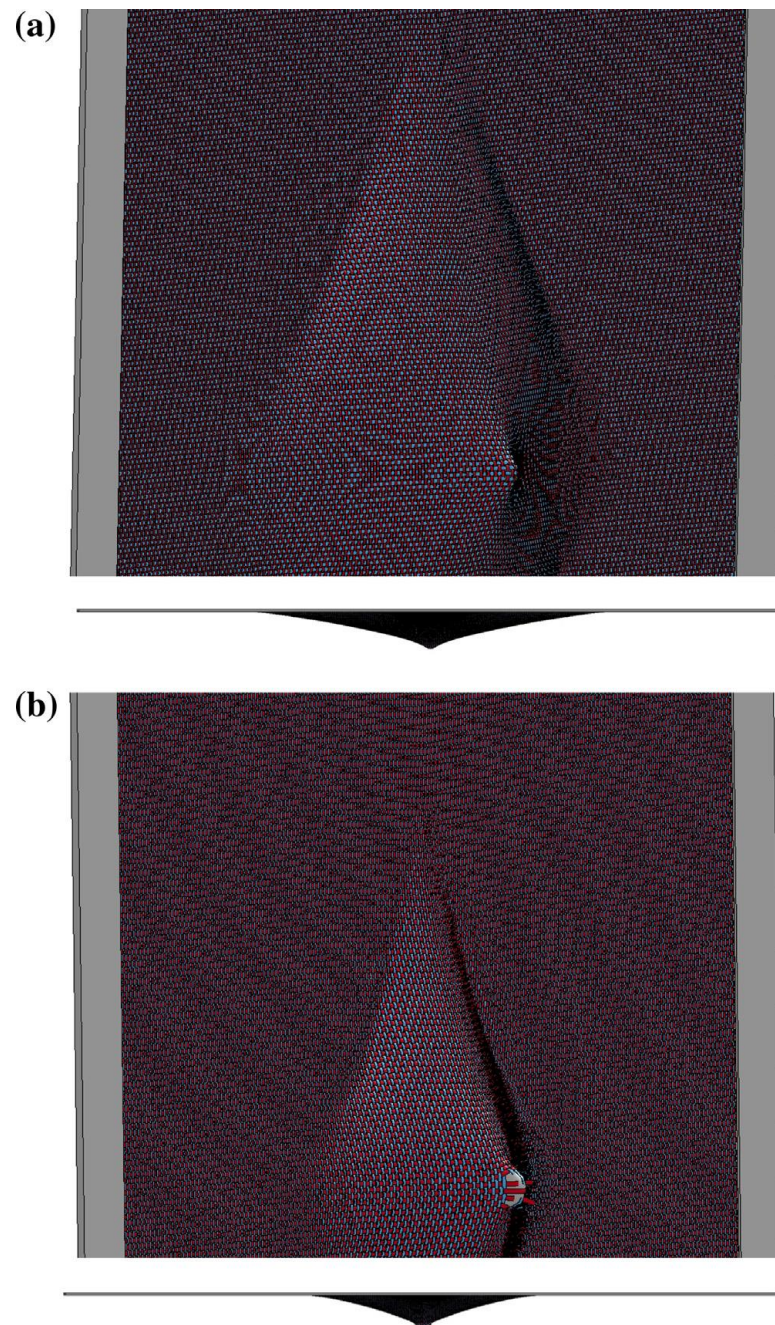


Fig. 10. Fabric deformation states for 4-sides held, 228.6 mm x 228.6 mm target at $V_i = 132.5$ m/s. (a) yarn impact at $180 \mu\text{s}$ (b) gap impact at $120 \mu\text{s}$.

2.5 Effect of fabric area on the projectile deceleration

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



Fig. 11 displays the projectile velocity histories for yarn and gap based impacts of the 4-sided clamped fabric at a V_i of 135 m/s and exposed areas ranging between 58.06 cm² and 522.58 cm². The smallest fabric target, with an exposed area of 58.06 cm² shows the fastest projectile deceleration while the largest fabric target shows the slowest projectile deceleration. The longitudinal strain wave velocity c , given as the square root of the ratio of the longitudinal tensile yarn modulus (E) to the yarn density (ρ), is the same for all three fabric target sizes because the material and weave remains the same. When considering strain wave propagation in a fabric, the effective wave propagation velocity c_* is obtained by dividing c by a factor of $\sqrt{2}$ to account for the effective doubling of lineal density at the cross-over points in the weave. Thus the strain wave propagation velocity in a fabric weave tends to be slower than that within a single straight yarn. The time taken for the strain wave to reach the clamped boundaries is shortest for the smallest fabric target and correspondingly longest for the largest fabric target. These times along with the strain wave velocities are listed in Table 4. The yarn material behind the front of the outwardly propagating strain wave elongates and becomes stressed and in the process develops internal strain energy. However the yarn material ahead of the wave front has no information about the impact event. When this strain wave reaches the clamped boundaries, it reflects back towards the impact site and during this process, the yarn stresses along the yarn length jump by a certain increment. With each passing and reflection of the strain wave at the clamped boundaries, the yarn stresses keep jumping in increments to higher and higher values and in the process dissipate more energy. Thus the smallest fabric target, which experiences the most number of wave reflections, develops yarn stresses to higher magnitudes at faster rates than the larger fabric targets. Correspondingly these smaller fabric targets develop internal strain energies at

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



faster rates than larger fabric targets that lead to faster projectile decelerations. This is seen from Fig. 12a which displays the fabric internal energy histories for yarn impacts in all three fabric targets. The smallest fabric target shows the fastest rate of increase in fabric internal energy. The same trend is observed even for the gap impact cases.

Table 4 Strain wave propagation and characteristic time instants.

Geometry and Wave Propagation Distance		Time to reach the clamped boundary		Simulation Time Instants of Interest	
Fabric edge length a (mm)	Distance d = a/2 (mm)	$t = d/c$ (μs)	$t^* = d/c^*$ (μs)	Slope change and deviation (μs)	Onset of yarn failure (μs)
76.20	38.10	5.03	7.11	15.50	45.50
152.40	76.20	10.05	14.21	26.30	69.50
228.60	114.30	15.08	21.32	38.30	100.40
Strain wave velocity (m/s)			Formula		
Yarn (actual), c	7581.03		$\sqrt{(E/\rho)}$		
Fabric (effective), c^*	5360.60		$\sqrt{(E/2\rho)}$		

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

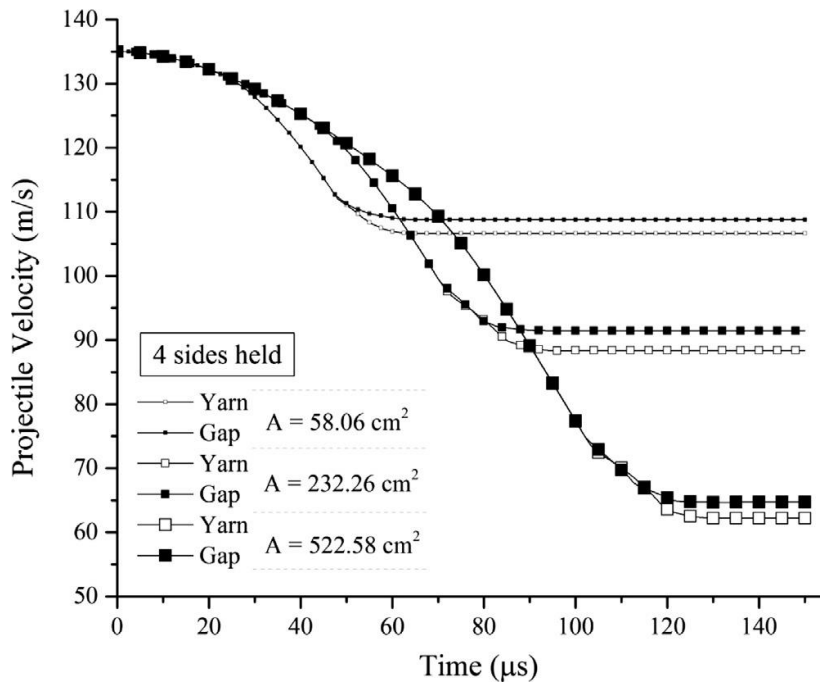


Fig. 11. Effect of fabric target size and projectile impact location on the projectile velocity history for 4-sides held at $V_i = 135$ m/s.

Fig. 12b displays a close-up of the fabric internal energies shown in Fig. 12a around the early stages of the impact event along with three characteristic time instants as denoted by the arrows. These time instants, listed in Table 4, denote a change in slopes of the fabric internal energy history plots as well as a deviation from the other plots. For example, the increase in magnitude of the fabric internal energy is the same for all three fabric targets until around 15.5 μ s at which time instant the fabric internal energy history for the smallest fabric target shows a sharp rise in the slope and deviates from the other two fabric targets. Similarly, the intermediate sized fabric target ($A = 232.26$ cm²) shows a sharp rise in slope and deviation from the largest fabric target at around 26.3 μ s. Note that time instants reported from the simulations, listed in Table 4, have already factored out the extra 2.3



μ s it takes for the impacting projectile to first make contact with the fabric. From Table 4, it appears that the time instants of the slope changes correspond to the total time it takes for the longitudinal strain wave to first travel to the clamped boundaries and then travel back to the impact site, i.e. approximately $2t^*$.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.
DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>

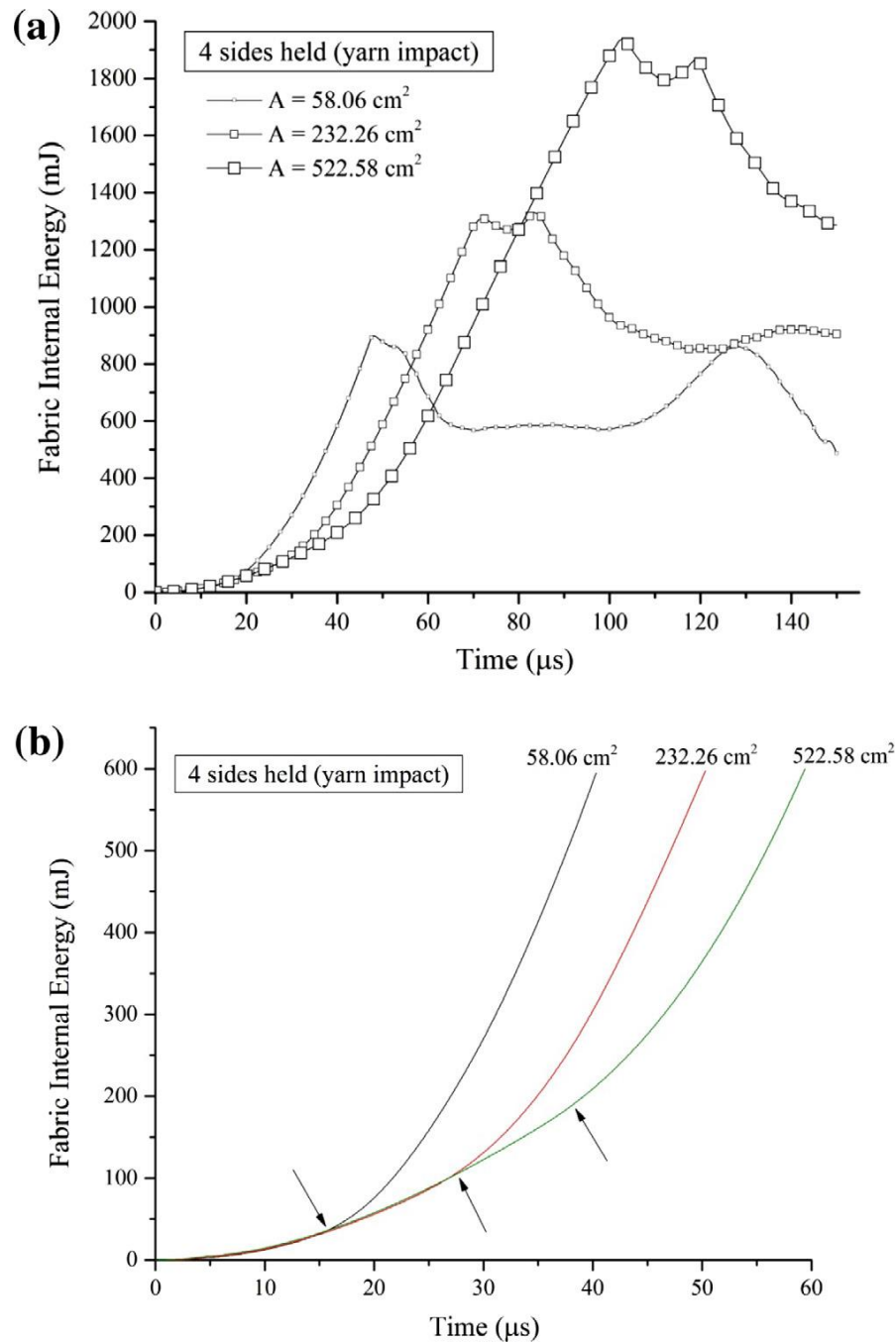


Fig. 12. (a) Effect of fabric target size on the fabric internal energy history for yarn impacts of 4-sides held at $V_i = 135$ m/s (b) close-up showing time instants of interest.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



The residual projectile velocity however is lowest for the largest fabric target because the largest fabric target is able to dissipate more energy than the smaller fabric targets by virtue of its longer yarns, that leads to increased magnitudes of fabric internal energy as seen from Fig. 12a, as well as increased fabric kinetic energies by virtue of momentum transfer between the projectile and fabric. Table 4 lists the time instants of the onset of yarn failure at the impact site for the three targets. These time instants are obtained from the sudden drops in fabric internal energy shown in Fig. 12a. Similar to the principal of the longitudinal strain wave, momentum transfer between the projectile and fabric occurs in the fabric region behind the fronts of the outwardly propagating transverse displacement wave. This slower moving transverse wave can also reflect from the clamped boundaries, however for the fabric target sizes considered and chosen impact velocity, complete fabric perforation occurs well before the transverse displacement wave reaches the clamped boundaries. Fig. 11 shows that the precise projectile impact location, i.e. yarn or gap, does not affect the rate of projectile deceleration however gap impacts lead to higher projectile residual velocities, as previously noted.

3. Conclusions

We have demonstrated that the impact performance of a woven fabric target as indicated by the V_{50} velocity is highly dependent on the size of the fabric target for fully clamped fabrics. The V_{50} velocity showed an initial sharp rise in magnitude with increasing exposed fabric areas that eventually showed a plateauing effect. The circular and diamond shaped clamped fabrics showed

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V50 ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



nearly identical V_{50} velocities over the range of fabric target sizes studied, which were both higher than the 4-sided clamped fabric.

A logarithmic function fit to the simulation data (penetrating shots) was shown to provide almost identical V_{50} velocity estimates as a 6-shot V_{50} velocity. The relationship between the exposed fabric area and V_{50} velocity was also found to be logarithmic over the range of studied target sizes.

For all three clamping configurations, there appeared to be a critical fabric size beyond which the residual projectile kinetic energy showed a very sharp rise in magnitude when the fabric was impacted at a velocity around its corresponding V_{50} velocity. It was observed that smaller sized fabric targets led to faster projectile decelerations but higher residual velocities than larger sized fabrics, attributed to the reduced time it takes the longitudinal strain wave to reach the clamped boundaries and the corresponding faster rate of increase in the fabric internal strain energy.

The knowledge of the effect of fabric clamping design and fabric size is useful when assessing and comparing the impact performances of different ballistic fabric materials and weaves, especially across different laboratories. Through this and a previous study [2], we have shown these factors to be important determinants of impact performance.

Acknowledgements:

Computation for the work described in this paper was supported by the University of Southern California Center for High-Performance Computing and Communications (hpcc.usc.edu).

GN and SN acknowledge support from the M.C. Gill Composites Center.

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>



References:

1. Tabiei A, Nilakantan G. *Ballistic impact of dry woven fabric composites: A review*. Appl Mech Rev 2008;**61**:010801–13
2. Nilakantan G, Nutt S. *Effects of clamping design on the ballistic impact response of soft body armor*. Composite Struct 2014;**108**:137–50.
3. J Singletary, T Steinruck, P Fitzgerald, *Effects of boundary conditions on V_{50} and zone of mixed results of fabric armor targets*, 23rd International Symposium on Ballistics, Tarragona, Spain. (April 16–20, 2007).
4. Zhang GM, Batra RC, Zheng J. *Effect of frame size, frame type, and clamping pressure on the ballistic performance of soft body armor*. Composites: Part B 2008;**39**:476–89.
5. G Nilakantan, ED Wetzel, R Merrill, TA Bogetti, R Adkinson, M Keefe, et al. *Experimental and numerical testing of the V_{50} impact response of flexible fabrics: Addressing the effects of fabric boundary slippage*, 11th International LS-DYNA Users Conference, Dearborn, MI, USA. (June 6–8, 2010).
6. G Nilakantan. *DYNAFAB User Manual Version 1.0*, Nilakantan Composites. ISBN 978-81-910696-0-0. (May 2010).
7. Livermore Software Technology Corporation. *LS-DYNA Keyword User's Manual Version 971*, (May 2007).
8. JP Lambert, GH Jonas. *Towards standardization in terminal ballistics testing: Velocity representation*, BRL Report No. 1852, U.S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, MD. (1976).

Please cite this article as: Nilakantan G, Nutt S. *Effects of fabric target shape and size on the V_{50} ballistic impact response of soft body armor*. Composite Structures 116 (2014) 661–669.

DOI: <<http://dx.doi.org/10.1016/j.compstruct.2014.06.002>>