Effect of obliquity on ballistic impact response of plain-woven fabric

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Abstract: This numerical study presents the effect of obliquity on ballistic impact response of plain-woven fabric. A numerical model of plain-woven fabric subjected to a high-velocity impact at yarns crossover is simulated with the help of commercial finite element tool ABAQUS. The FE analysis depicts that the ballistic impact response of plain-woven fabric largely depends on the obliquity of impact due to phenomena like uneven strain distribution in different directions and sliding of the projectile on woven fabric yarns about the point of impact. The total energy dissipated by the fabric showed a decreasing-increasing behaviour with an increase in obliquity. This transition in the trend of total energy dissipated by fabric came in between 30°–45°, which depends on relative dominance of sliding of yarn and uneven strain distribution.

Keywords: plain-woven fabric; ballistic impact; obliquity; Kevlar.

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1 Introduction

With the development of high strength and low weight fabrics like Kevlar, Dyneema, Twaron, etc. which show good resistance to high strain rate loading, like ballistic impacts, etc., conventional metal armours have been replaced with more flexible and lightweight armours. Yang et al. (2015) did a comparative study of various fabric weave architectures concluding that plain-woven fabric had the best ballistic resistance. Various modelling approaches have been adopted to investigate the behaviour of plain-woven fabrics. Giglio et al. (2013) emphasised the use of simulation packages like ABAQUS and ANSYS for high-velocity impact problems by comparing different approaches with an experimental approach. Fang et al. (2016) developed an FE model based on a shell-element based approach which could not capture the phenomena at yarn and fibre level. Barauskas (2005) and Barauskas and Abraitiene, (2007) combined the meso-mechanical approach with the macro-mechanical approach approximating the lenticular shape of yarns by joining four shell geometries near the point of impact and simple 2D shell elements at locations remote to the impact point. This approach also could not capture the phenomena at yarn and fibre level. Also at the interaction of both approaches, some properties were altered accordingly. Tan and Ching (2006) used bar elements with viscoelastic material properties to approximate the yarns' behaviour but as the inter-yarn frictional contacts could not be approximated accurately; the results obtained by this modelling approach were not compatible with that of obtained by experimental studies. In another approach, Wang et al. (2016c) did a micro-modelling of fabric by fibre-level digital element approach (DEA). Apart from these, a yarn based modelling approach has been also used in which a close agreement of FE results has been observed with experimental results. By adopting the same approach, Dimeski et al. (2015) reviewed various factors influencing the ballistic performance of a plain-woven fabric and concluded that almost all the factors are interrelated and effect of only one factor can not be determined individually. Nilakantan et al. (2011) used a probabilistic velocity response curve to describe impact response of three different yarn strength models. In Nilakantan et al. (2012) they simulated the effect of statistical yarn strength distribution on probabilistic impact response of flexible woven fabric for five different strength distributions with different distribution widths and mean strengths. It was concluded that mean yarn strength alone can not determine the probabilistic penetration behaviour of woven fabrics. Chu et al. (2017) investigated the effect of a local and global change in impact location by an FE model and described various failure mechanisms. Yang and Tuan (2015) presented a mesoscale yarn model which was validated both experimentally and analytically. They investigated the effect of weave architecture on the energy absorption and ballistic performance for both single and multi-layered Twaron fabrics. Chu et al. (2016) did a numerical study of the effect of yarn mechanical property, Young's modulus, and physical property, yarn density, on the ballistic impact behaviour of plain-weave Kevlar fabric. Tapie et al. (2017) investigated the effect of pre-tension and impact obliquity on the ballistic limit of the plain-woven fabric concluding that pre-tension results in an increasing-decreasing behaviour of ballistic limit and obliquity results in asymmetric deformation. Wang et al. (2016b, 2016a) investigated the effect of yarn friction and yarn crimp on ballistic performance and energy absorbed by the fabric. Nilakantan and Gillespie (2012) studied the combined effect of inter-yarn friction, fabric clamping conditions, yarn tensile strength and projectile impact locations relative to the yarns on the probabilistic impact response of plain-woven Kevlar KM2 flexible fabric. In Nilakantan et al. (2013) the effect of projectile characteristics like projectile shape and size were investigated. Based on the previous studies, various parameters that affect the performance of a woven fabric can be categorised as

a projectile related variables like shape, size, mass, velocity, impact location, etc.

b target related variables like the number of filaments comprising a yarn, linear and surface density, maximum force and elongation, Young's modulus and tensile characteristics, type of weave, isotropy in the weave, friction, crimp, number of layers and their interconnection, boundary conditions etc.

It is observed that most of the research has been carried out for predicting the ballistic response of woven fabrics for normal impacts whereas, in field applications, the probability of a perfectly normal impact is negligible. Shim et al. (2012) experimentally investigated and compared the responses of a pliable laminate, Spectra Shield, and woven fabric, Twaron CT, for oblique impact loadings. These oblique impact tests were done in only one plane containing normal to the fabric and a yarn direction and so sufficient analysis on the ballistic response of woven fabric when impacted obliquely was not done still. In the present study, an attempt to investigate the effect of oblique impact on the ballistic impact response is done for plain-woven fabrics. Various failure and energy absorption phenomena with their consequences are analysed.

2 Modelling of woven yarn and projectile

2.1 Material and geometrical modelling of the yarns and projectile

In the present study, the plain-woven fabric is modelled by adopting the yarn-level modelling approach. The fabric is having same geometrical features and material properties for both weft and warp yarns. The geometrical parameters like fabric thread density, the wavelength of yarn waviness, the radius of the arc of waviness, the radius of the arc of the cross-section of plain-woven yarn are calculated for a given yarn linear density of 158 tex and yarn crimp wavelength of 2.8 mm. Accordingly, the thickness of fabric will be 0.345 mm with an areal density of 245 gm/m^3. For calculating the mean strength of a yarn, a single yarn is usually tested experimentally which has a circular cross-section. But when this yarn is woven in a fabric, its cross-sectional shape changes from circular to lenticular, which consists of two arcs facing each other and curvature of these arcs depends on various factors like the diameter of yarn, crimp of yarns, weave architecture, etc. For our analysis, the curvatures of both arcs facing each other are assumed same. For geometrical aspect, the path of the yarn and the cross-sectional shape is sufficient to describe its geometry. Path of the yarn is considered in the form of a curve, which also comprises its waviness. In modelling of yarn, the lenticular cross-sectional shape is assumed same along the whole length of the yarns, both warp and weft yarns are having same geometrical features as well. For our analysis, yarns are supposed to be made up of a homogeneous material and instead of being orthotropic in nature, they are considered as isotropic because there is the very minute difference in energy absorption due to orthotropic nature and this difference is insignificant to the other energies absorbed by the fabric during impact. For the present approach, Kevlar is considered as a fabric material. Volumetric density, Poisson's ratio and Young's modulus are considered as 1,440 kg/m^3, 0.34 and 93.5 GPa respectively. For plastic and failure behaviour Johnson-Cook model (Johnson and Cook, 1983, 1985) is used after neglecting the effect of thermal softening on material behaviour and a total elongation of 4% and tensile strength of 3.5 GPa are taken as a fracture point for a single yarn. Rest of the material constants for effect of strain-hardening and strain rate are taken from the literature. The projectile is supposed to be made up of stainless steel with a volumetric density of 7,860 Kg/m^3.

2.2 Description of FE model

ABAQUS v6.16 (Dassault Systemes Simulia Corp., 2016) is used for simulating the transverse and oblique impact on plain-woven Kevlar fabric with constrained environment. A user-defined meshing is adopted which is governed by the two facts, one being the high computational cost for a fine mess and another being the requirement of a node at the critical point of the yarn geometry. Therefore, an appropriate meshing with ten elements, providing nodes at all four critical points while having equal number of elements at both sides of mid-section of yarn, at cross-section and 24 elements, balancing the each quarter wavelength of yarn in terms of number of elements in order to provide nodes at each critical point, at one yarn wavelength is used as shown in Figure 1(a). For meshing, 3-D solid brick type elements (C3D8R) are used. Friction coefficient of 0.22 is also introduced for sliding contact by using a hard contact-penalty algorithm. The edges of fabric are 68 mm each and are constrained as fixed. Projectile is given an initial velocity of 500 m/s which lies in the range of high velocity impact (ballistic impact) where the longitudinal stress waves reach the edges before complete perforation of fabric and transverse deflection waves would not have sufficient time to reach up to the edges of fabric. After perforation the residual velocity is measured for each impact test. A meshed view of projectile is shown in Figure 1(b).The fabric is modelled in xz plane and projectile is made to impact at the centre of the fabric with velocity in three dimensions, components of which are given as:

$$V_x = V \sin(\theta) \sin(\phi) \tag{1}$$

$$V_y = V \cos(\theta) \tag{2}$$

$$V_z = v \sin(\theta) \cos(\phi) \tag{3}$$

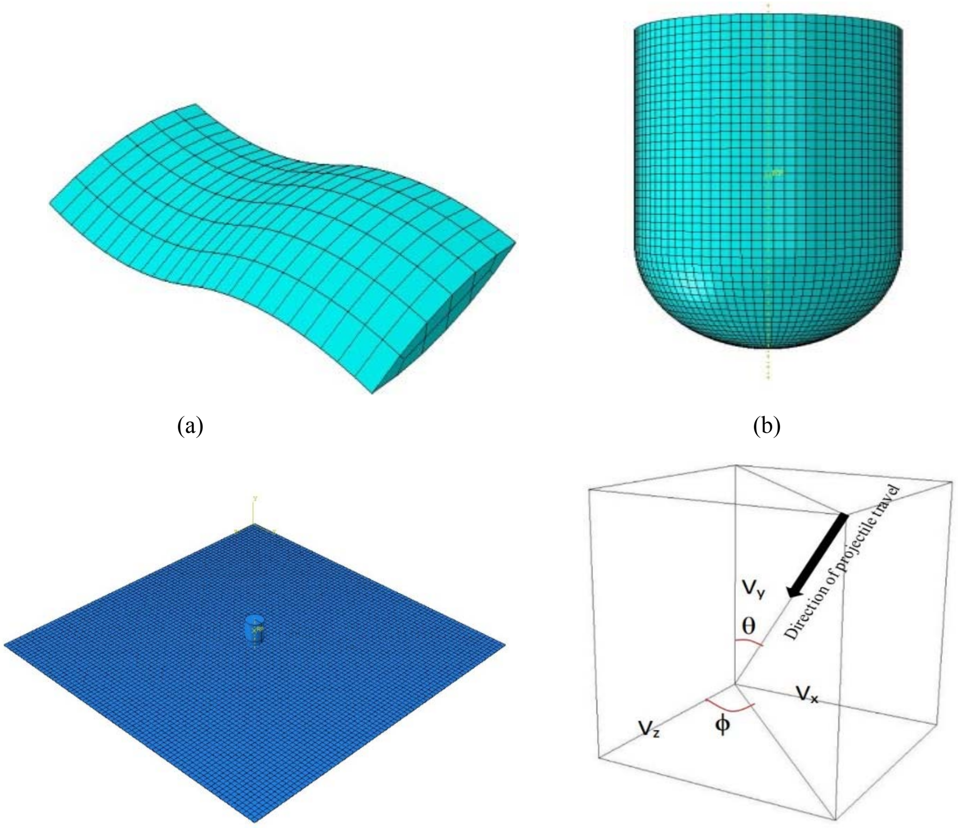
where V is magnitude of velocity, ϕ is the angle of plane in which projectile travels before impact with respect to plane containing wrap yarn (plane yz) and θ is the in-plane obliquity, which are depicted in Figure 1(d).

In practical applications, it is seen that a ceramic or metal plate is placed at the front side of these patches of woven fabric. When a conical or ogival shaped projectile impacts upon hard faceplate, deformation of projectile takes place and nose radius increases which makes projectile blunt from the front end. In order to capture this behaviour, the nose of the projectile is approximated to a hemispherical front and since the projectile is assumed to be made up of a rigid material, for further analysis its mass remains constant. For the current numerical analysis, the diameter of both cylindrical and hemispherical portion is taken as 5.5 mm and the total length of the projectile as 8.25 mm. This approach directly gives us the energy absorbed by the fabric during impact phenomena (ΔE) as the kinetic energy lost by the projectile after neglecting the acoustic losses, air resistance, friction between fibres, etc., which is given by

$$\Delta E = \frac{1}{2} m \left(V^2 - V_r^2 \right) \tag{4}$$

where m is the mass of the rigid projectile and V and V_r are the absolute striking velocity and absolute residual velocity respectively.

Figure 1 (a) Meshed view of woven yarn of one wavelength (b) Meshed view of projectile (c) Assembly (d) Components of velocity in 3-dimensions (see online version for colours)



(a) (b)

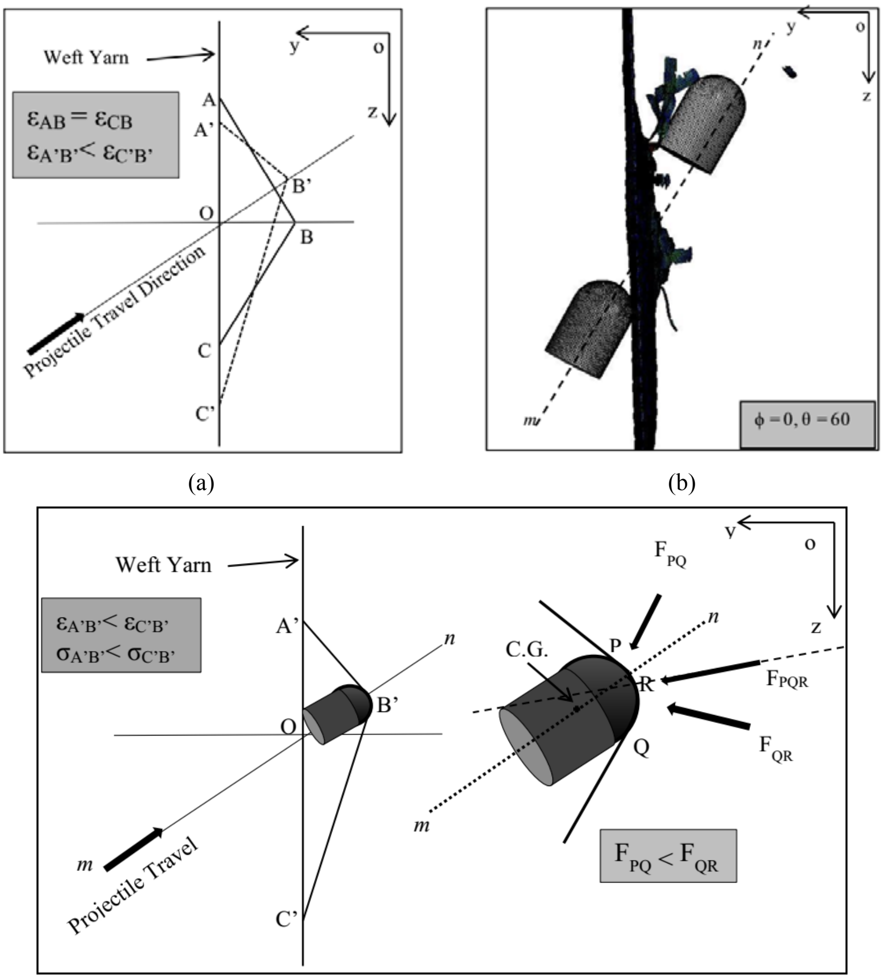
(c) (d)

3 Results and discussion

3.1 *Effect of impact obliquity on transverse displacement and strain in fabric and projectile movement*

For normal impact on all-sides clamped fabric, a pyramidal transverse deflection shape is obtained with a square base which is symmetric about both wrap and weft yarns passing through the point of impact. But for all-sides clamped fabric under the oblique impacts, the transverse deflection shape is either symmetrical about only one of the yarns when projectile travels in the plane containing that yarn or completely unsymmetrical. This behaviour of unsymmetrical deformation is understood by the oblique impact response of a single yarn as shown in Figure 2.

Figure 2 (a) Deformation of a single yarn subjected to normal and oblique impact (b) A FE simulation snapshot showing drifting of projectile (c) Forces experienced by the projectile during oblique impact



(a) (b)

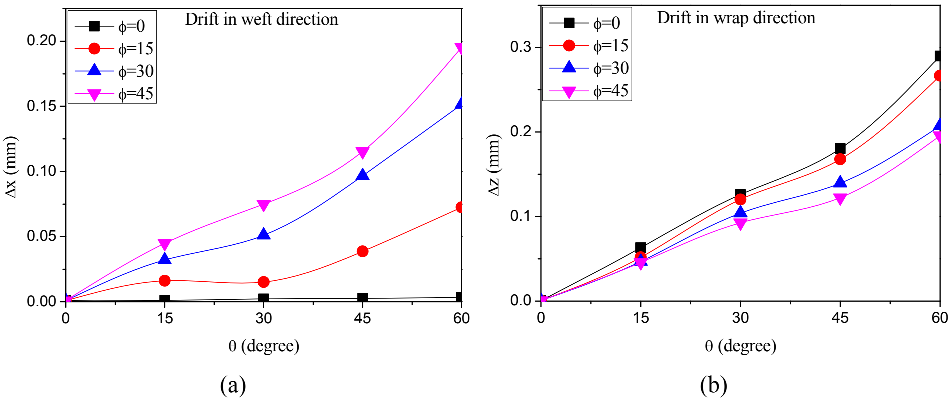
(c)

When a yarn is impacted by a projectile travelling in a normal direction to the fabric at point O, the shape of deformation curve is similar to ABC after some instance of time which is symmetric about both vertical weft yarn and wrap yarn- perpendicular to the plane of the diagram. During the normal impact, both AB and BC portion of the yarn are subjected to the same magnitude of strain and as a result of which stresses generated in both portions are also same. When this yarn is subjected to an oblique impact at point O, the shape of transverse deflection would be A'B'C' after some instant of time.

It is noted that the point A has shifted towards the point of impact to A', whereas the point B has shifted away from the point of impact to B', which can be observed from Figure 2(b). It is also noted that when obliquity increases, the asymmetry in deformation about the point of impact also increases.

When a projectile impact the yarn normally, strains generated in both portions would be same resulting in a normal reaction force experienced by the projectile which would pass through its axis of propagation. But when the same yarn is impacted with some obliquity, it shows some strain variation due to asymmetric deformation. It is evident from Figure 2(c), that strain in an upper portion of the yarn ($\varepsilon_{A'B'}$) is lesser as compared to the strain in the lower portion ($\varepsilon_{B'C'}$). This results in higher stresses in portion B'C' compared to the stresses in portion A'B', and ultimately the force experienced by the projectile is also non-uniform. Moreover, it is evident from the geometry that the length of the yarn wrapping the projectile in lower side (QR) is more than the length of yarn wrapping the projectile in the upper side (PQ). Collectively these both factors try to push the projectile in an upward direction. Due to this upward push to the projectile, chances of slipping between projectile and yarns increases, and only friction is there to prevent this drifting in the form of slippage. Therefore, after a critical value of upward push, the drift of projectile in upward direction takes place and that results in a slightly uniform distribution of strains and stresses. Figure 3 graphically represents the variation of projectile drift in weft and wrap directions with obliquity.

Figure 3 Projectile drift w.r.t *θ* for (a) weft direction and (b) wrap direction (see online version for colours)

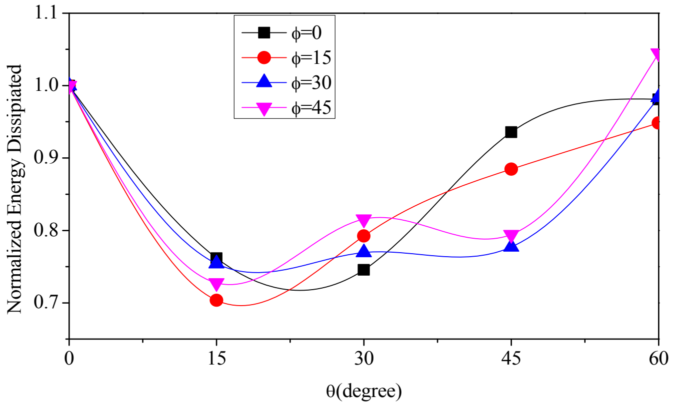


It is observed from the graphical results that with an increase in obliquity '*θ*', the drift of projectile in both weft and warp directions increases which is analogous to the hypothesis discussed above. It is noted that with an increase in the plane offset angle '*ϕ*', drift in weft direction increases whereas in wrap direction it decreases. This observation can be explained by the fact that with an increase in ϕ, V_x increases whereas V_z decreases. Therefore, for a given amount of time, with an increase in ϕ, distance travelled by the projectile in weft direction increases and in wrap direction decreases, resulting in the same effect on the drift of the projectile.

3.2 *Effect of impact obliquity on energy dissipated by the fabric*

When a fabric is obliquely impacted by a projectile, its motion can be described by three mutually perpendicular velocity components, out of which one will be along the normal to the fabric and two would be in the plane of the fabric. In order to avoid perforation of fabric, we need to bring the normal component of velocity to zero. It is to be noted that with an increase in obliquity angle 'θ', the magnitude of normal velocity 'V_y' decreases. Therefore, it is expected that with an increase in the obliquity angle 'θ', ballistic resistance of the fabric should increase. On the other hand, results from the current study suggest that energy dissipation shows a decreasing increasing behaviour, as shown in Figure 4. A similar trend has been obtained by Shim et. al. (2012) for the ballistic limit variation with change in the obliquity angle for a given plane with zero plane offset angle while experimentally comparing the ballistic behaviour of woven and laminated fabrics. The energy dissipated by the fabric is a complex phenomenon constituting the elastic strain energy absorbed by the yarns, plastic strain energy dissipated in the form of plastic deformation and element deletion, frictional energy dissipation between yarn-yarn and projectile-yarn contacts, the kinetic energy carried by the fabric during impact phenomena, etc. It is to be noted that the variation of the energy dissipated by the fabric is shown in a normalised sense. Here normalised energy dissipation is the ratio of energy dissipated by fabric at given obliquity to energy dissipated by fabric when impacted normally. Also, it is interesting to note that irrespective of plane offset angle, the impact is always normal when obliquity angle is zero.

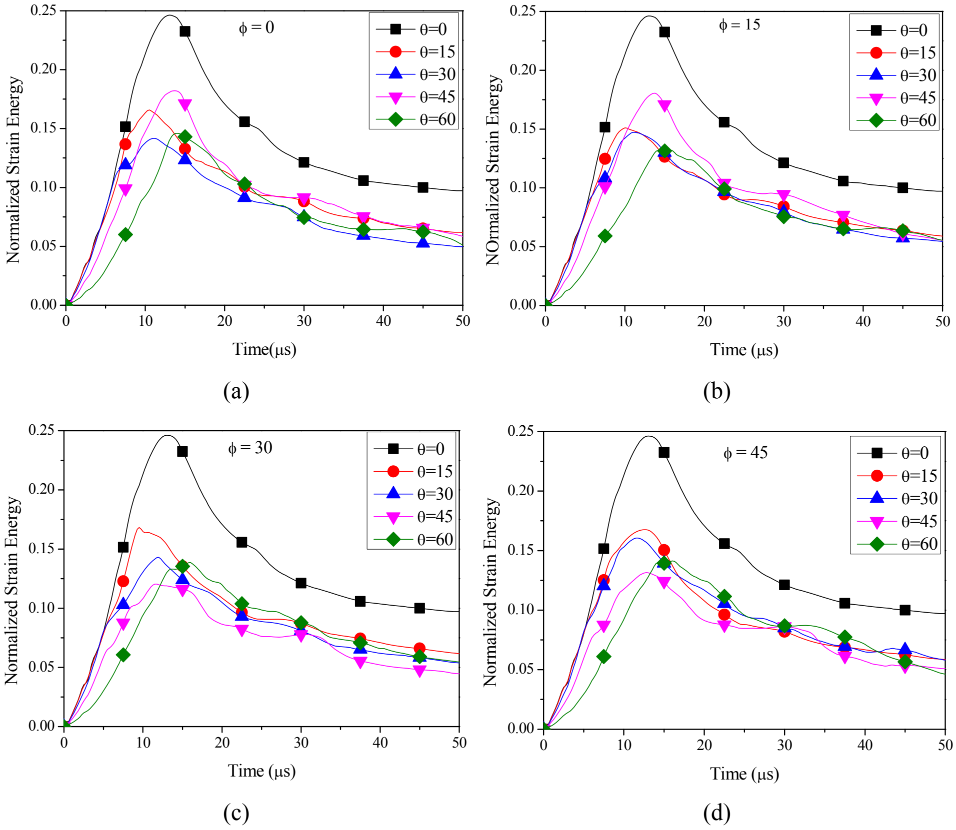
Figure 4 Normalised energy dissipation w.r.t. θ for a given value of ϕ (see online version for colours)



3.2.1 *Effect of obliquity on strain energy absorbed by the fabric*

When a yarn is stretched during impact phenomenon, it absorbs a certain amount of elastic strain energy after which it undergoes the plastic deformation and fracture depending upon the loading and material properties. The total strain energy absorbed by the fabric influenced by the number of the yarns taking part in this strain energy absorption phenomena and the magnitude of strain which every individual yarn faces. When a plain-woven fabric is impacted normally at yarn cross-over or at small obliquity, strain distribution in a yarn is more uniform compared to that of highly oblique impact as explained previously resulting into high strain energy absorptivity near normal impacts which can also be depicted from Figure 5 which shows the variation of normalised strain energy (NSE) with time for a given case. Here normalisation is done with respect to total energy dissipated by fabric when impacted normally.

Figure 5 Normalised strain energy w.r.t. time for a given value of θ and for (a) $\phi = 0$, (b) $\phi = 15$, (c) $\phi = 30$ and (d) $\phi = 45$ (see online version for colours)



(a) (b)

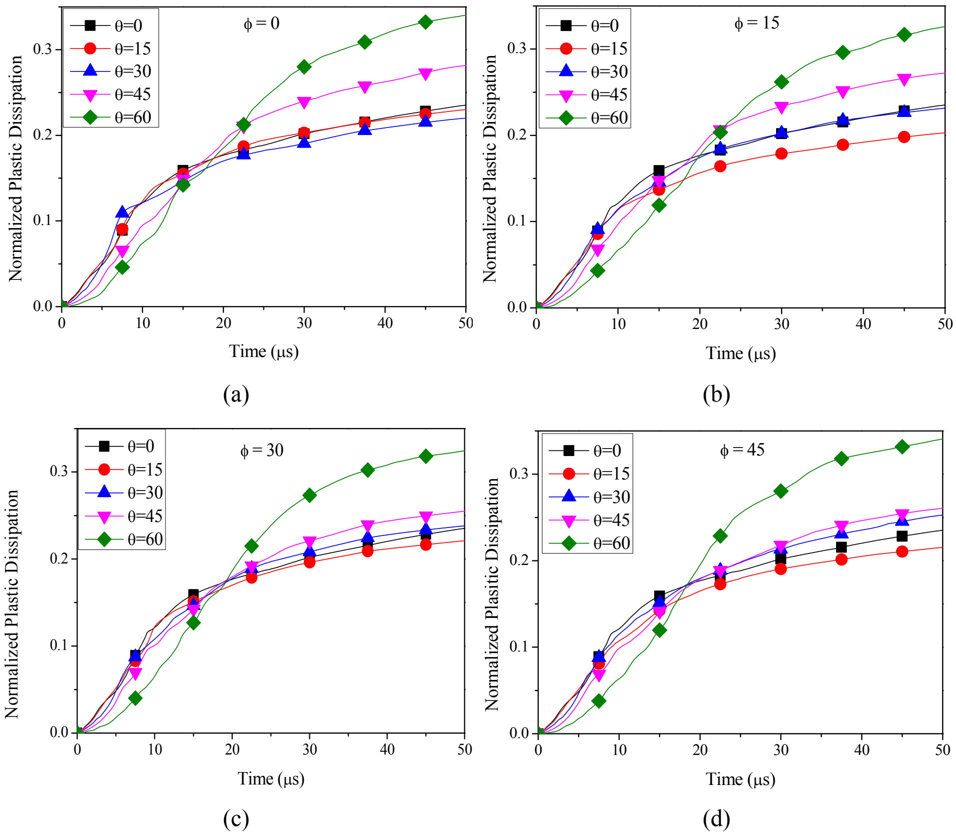
(c) (d)

When a fabric is impacted, its yarns are stretched to their critical limit and then after plastic deformation and absorbing the sufficient energy their fracture occur resulting in the release of absorbed strain energy. A similar behaviour is depicted from the graphical results along with a fact that the maximum normalised strain energy (MNSE) is absorbed just before the first yarn break, which is slightly more than the NSE absorbed at the perforation and is noted down in Table 1 for each case of impact. It is observed from the results that with an increase in obliquity angle the steepness of NSE curve decreases irrespective of any value of plane offset angle, representing that with an increase in obliquity, projectile travel normal to the fabric decreases resulting in less stretch of the yarns for a given time. Another observation from the results is that with an increase in the obliquity, MNSE magnitude decreases which is due to the phenomenon of uneven strain in the yarns as a result of the oblique impact. It is also noted from the results of this current study that with an increase in the plane offset angle ‘ϕ’, both NSE at perforation and MNSE decreases because of a more uneven strain of yarns for a given obliquity.

3.2.2 Effect of obliquity on plastic energy dissipation by the fabric

As followed by the previous discussion it can be concluded that after the yarns are stretched to their critical limit, they deform plastically depending upon the material characteristics. Whereas the elastic strain energy absorbed by the yarns is recovered after the failure as shown in the graphical results of the previous study, plastic dissipation can not be recovered and is seen to be always increasing as shown in Figure 6. Graphical results of this study show the variation of normalised plastic dissipation (NPD) with respect to time. Similar to the previous discussion, normalisation of plastic dissipation is done by the total energy dissipated by the fabric when impacted normally.

Figure 6 Normalised plastic dissipation w.r.t. time for a given value of θ and for (a) $\phi = 0$, (b) $\phi = 15$, (c) $\phi = 30$ and (d) $\phi = 45$ (see online version for colours)



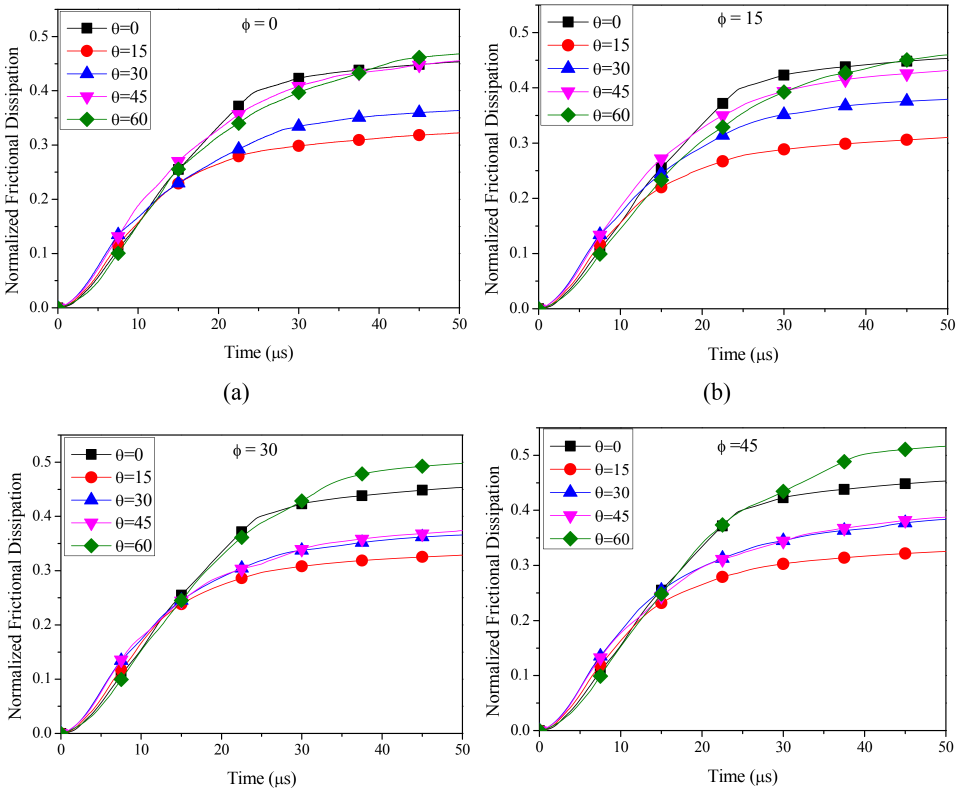
Although the elastic strain energy absorbed by the fabric is more when the strain is uniformly distributed along the yarns, the plastic strain energy is more dependent on the plastic deformation and fracture of the elements occurring in the zone of the impact location. When an element is strained beyond the elastic strain, a permanent change in its geometry takes place, which corresponds to the plastic strain energy absorption that ultimately is revealed as heat dissipation. After some plastic strain, equal to the critical plastic strain of 4%, the element is supposed to offer no resistance to perforation. This feature in ABAQUS v6.16 has been incorporated by default ELEMENT_DELETION algorithm. According to this algorithm, once an element satisfies the failure/damage criteria, its stiffness reduces to zero and it does not offer any resistance to change in shape or loading. So element deleted in this numerical study would have absorbed the sufficient fracture energy and some elements that are deforming plastically but not fulfilled the criteria of element deletion would dissipate the energy in the form of plastic dissipation. From Figure 2(a), it is evident that lower portion of the yarn is more stretched as compared to the upper portion and also deforms plastically earlier than the upper portion resulting into the lesser plastic energy dissipation in the initial phase of impact. When the obliquity of impact increases, the variation in the stretching of yarns along their lengths also increases resulting in lesser absorption of the strain energy at the initial phase of an impact than the normal impacts. However, when the yarns' failure starts after a certain time, the plastic dissipation depends more on the numbers of yarns fractured (NYF). From the results of this study, it is observed that NYF increases with obliquity and has been stated in Table 1 as well. This increase in the NYF results in the more plastic energy dissipation at high obliquity angles and proves that at complete perforation and beyond, plastic dissipation is more for the impacts with high obliquity angles.

3.2.3 Effect of obliquity on frictional dissipated energy

When the longitudinal wavefront propagates in primary yarn in the longitudinal direction and transverse wavefront propagates in the normal direction of the fabric with a projectile, and yarns are subjected to tensile stresses and stretch. When these yarns interacted with the secondary yarns that are orthogonal to respective primary yarns at yarn crossovers, these secondary yarns are also deformed and collectively makes a pyramidal deformation shape for impacts on woven fabrics. At these yarn crossovers, frictional tangential contact and hard normal contact are used as interaction for yarn-yarn and projectile-yarn aiding in the transfer of longitudinal strain wave and transverse deformation waves respectively to the secondary yarns. This frictional contact is one of the causes of the frictional dissipation. Another cause of the frictional dissipation in this study is taken as the sliding of projectile along the yarns.

When an impact is normal or has small obliquity angle, there is no or little possibility of sliding between projectile and yarns, resulting into yarn-yarn frictional contact as the primary cause of the friction. Therefore, when the impact is perfectly normal, due to uniform strain and large extent of deformations in less amount of time, friction between the yarns is higher compared to the impacts with slight obliquity. This high drop in the frictional dissipation between the yarns with induction of obliquity is an effect of non-uniform deformation along the yarn and asymmetrical deformation shape of the fabric. This non-uniform deformation of yarns and asymmetrical deformation of fabric results in the decreases the tangential friction between the yarn-yarn contacts. Along with that, for small obliquity slippage between the yarn and projectile interface is negligible and hence frictional dissipation depends mainly on the yarn-yarn frictional dissipation. Afterwards, with more obliquity after a critical limit, slippage between the yarns and projectile takes place and the frictional dissipation associated with this slippage increases as the obliquity of impact increases. After a certain limit of obliquity, the increased frictional dissipation due to slippage between yarns and projectile balances the decrease in the frictional dissipation between yarn-yarn tangential contacts. Moreover, it is observed that the frictional dissipation at obliquity of 45° for the plane offset of 30° and 45° is higher than the normal impact. Also, for these planes, there is a sudden increase in the frictional dissipation after certain obliquity. This is due to the fact that for low obliquity, chances of trapping the projectile between the gaps between yarns are high, which after certain obliquity vanishes resulting into high sliding of the projectile at the fabric. Results from the Table 1 suggest that the frictional dissipation is the main cause of energy dissipation during impacts, constituting the highest share of energy dissipation. This also explains the fact that behaviour of total energy dissipation is similar to the change in frictional dissipation with obliquity.

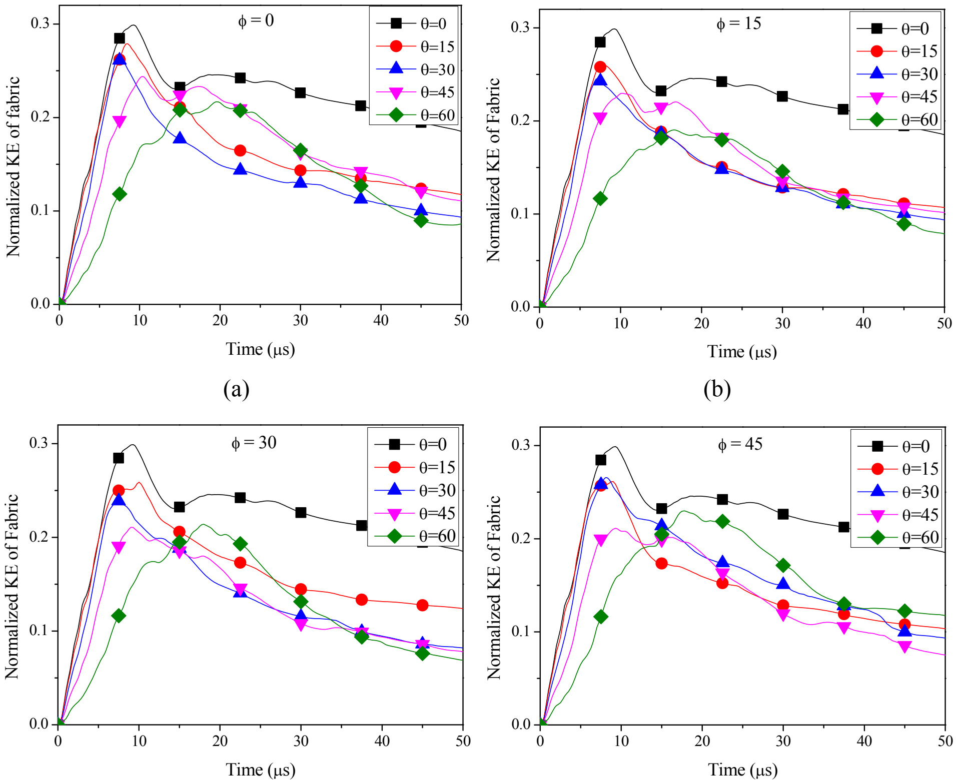
Figure 7 Normalised plastic dissipation w.r.t. time for a given value of θ and for (a) $\phi = 0$, (b) $\phi = 15$, (c) $\phi = 30$ and (d) $\phi = 45$ (see online version for colours)



(a) (b)

(c) (d)

Figure 8 Normalised kinetic energy absorbed by fabric w.r.t. time for a given value of θ and for (a) $\phi = 0$, (b) $\phi = 15$, (c) $\phi = 30$ and (d) $\phi = 45$ (see online version for colours)



(a) (b)

(c) (d)

3.2.4 *Effect of obliquity on kinetic energy absorbed by the fabric*

When a projectile impacts any object, some deformation in target material takes place, which in our study on woven fabrics is pyramidal in shape for normal impacts. As observed, during the initial phase of impact, woven fabrics travel along with the projectile and result in absorption of some portion of total energy dissipation in the terms of kinetic energy. This kinetic energy absorbed by the fabrics depends upon many factors varying from projectile factors like shape, size, mass and velocity of the projectile to the target level factors like material properties and geometrical properties, etc. Results of variation of kinetic energy absorbed by the fabric with time are shown in Figure 8 and Table 1. The results of this numerical study are termed in the normalised kinetic energy (NKE) of fabric where normalisation is done with respect to the total energy dissipation at normal impact. It is observed that in the initial phase of impact phenomena, the velocity of the transverse wave is approximately equal to that of the component of velocity of the projectile in the normal direction. During this phase of impact numbers of yarns subjected to transverse deflection increased with time and so did the kinetic energy absorbed by the fabric up to the maximum limit of the kinetic energy of fabric followed by the breaking of yarns. As the contacts between yarns and projectile break due to yarn failures, the kinetic energy of the respective primary yarns also decrease, followed by the decrease in the kinetic energy of secondary yarns. It is to be noted that the rate of decrease in the kinetic energy of the fabric is not as higher as the rate of decrease in the strain energy absorbed by the fabric after perforation.

Table 1 Results of the numerical study for each case

Case	T_P *(μs)*	*Projectile offset in plane of fabric in(mm)*		*NSE at T_P (%)*	*MNSE (%)*	*NPD at T_P (%)*	*NFD at T_P (%)*	*NKE of fabric at T_P (%)*	*MNKE of fabric (%)*	*NYF*	
		Weft (Δx)	*Wrap (Δz)*							N_x	N_z
$\phi = 0, \theta = 0$	25	0.0009	0.0006	14	25	19	40	24	30	2	4
$\phi = 0, \theta = 15$	26.5	0.0010	0.0631	9	17	20	30	15	28	3	3
$\phi = 0, \theta = 30$	30.5	0.0023	0.1260	7	15	19	33	13	26	4	3
$\phi = 0, \theta = 45$	35	0.0027	0.1804	9	18	25.5	43	15	25	5.5	3
$\phi = 0, \theta = 60$	42.5	0.0035	0.2897	6.5	15	27	45	10	21	8.5	3
$\phi = 15, \theta = 0$	25	0.0009	0.0006	14	25	19	40	24	30	2	4
$\phi = 15, \theta = 15$	25.5	0.0162	0.0518	9	15	17	28	14	26	3	4
$\phi = 15, \theta = 30$	29.5	0.0152	0.1201	8	15	20	35	13	24	4.5	3
$\phi = 15, \theta = 45$	34.5	0.0387	0.1678	8	18	25	40	12.5	23	6	3
$\phi = 15, \theta = 60$	42.5	0.0725	0.2666	7	13	29	42	12	19	8	3.5
$\phi = 30, \theta = 0$	25	0.0009	0.0006	14	25	19	40	24	30	2	4
$\phi = 30, \theta = 15$	25	0.0321	0.0468	9	17	19	30	16	26	3	4
$\phi = 30, \theta = 30$	28.5	0.0510	0.1041	8	13.5	20	34	12	24	4.5	3.5
$\phi = 30, \theta = 45$	33.5	0.0967	0.1394	7	12	23	35	10	21	5.5	4
$\phi = 30, \theta = 60$	39	0.1515	0.2073	7	14	31	48	9	22	7	5
$\phi = 45, \theta = 0$	25	0.0009	0.0006	14	25	19	40	24	30	2	4
$\phi = 45, \theta = 15$	27	0.0449	0.0457	8	17	18.5	30	13	26	3	4
$\phi = 45, \theta = 30$	28.5	0.0750	0.0926	9	16	21	34	15	27	4	4
$\phi = 45, \theta = 45$	33.5	0.1155	0.1224	8	13	23	35	10	20	4.5	4.5
$\phi = 45, \theta = 60$	40	0.1952	0.1957	7	14	32	50	12.5	23	4.5	5.5

Like strain energy absorbed by the fabric yarns, kinetic energy absorbed by the fabric also behaves in an increasing-decreasing behaviour with time, where the steepness of initial phase of energy absorption decreases with increase in the obliquity and the maximum normalised kinetic energy (MNKE) of fabric occurs just before the first yarn break and is having a marginal difference with NKE of fabric. A sharp dip in the NKE of fabric is observed just after MNKE of fabric which depicts that just after the yarn failures, they come to halt for some instant and then they again gain some velocity while the fabric regains its shape. Results of the current study for variation of normalised kinetic energy of the fabric depicts that kinetic energy of the fabric is maximum when the fabric is impacted normally and decreases with increase in obliquity. This is analogous to the phenomenon that with an increase in the obliquity angle 'θ', the velocity of the projectile in the transverse direction of the fabric decreases and results in the decrease in the kinetic energy carried by the fabric. It is also evident from Figure 2 that velocity of the yarns in the upper portion is lesser, where strain is also less than the lower portion, resulting in less kinetic energy absorption with obliquity. This hypothesis is supported by the results in a graphical and tabular form that with an increase in the obliquity angle, kinetic energy absorption capacity of the fabric decreases. However, with the change in the plane offset angle, the change in the kinetic energy absorptivity shows negligible changes.

4 Conclusions

The purpose of this numerical study was to simulate the ballistic response of a plain-woven fabric and study the effect of obliquity on the impact. The study was conducted on Kevlar-29 fabric using a yarn based modelling approach. The obliquity in the impact was controlled by two angles given by ϕ and θ and the change in the obliquity of impact was studied. It was observed that with an increase in the obliquity asymmetric deformation of fabric took place and resulted in the asymmetric stress in yarns about the point of impact. Energy dissipated by the fabric was also affected by the obliquity, showing a decreasing-increasing behaviour with an increase in obliquity. This energy dissipated by the fabric was studied by the means of different energy absorption phenomena: strain energy absorbed by the fabric, plastic dissipation, frictional dissipation and kinetic energy carried by the fabric. Strain energy absorptivity of the fabric showed an increasing-decreasing behaviour where its maximum limit decreased with increase in obliquity as a result of non-uniform straining of yarns. Plastic dissipation of the woven fabric showed a monotonically increasing behaviour with time whose magnitude decreased with obliquity at perforation time. It was also observed that with obliquity, its steepness also decreased. Similar to the plastic dissipation, frictional dissipation also increased with time, which initially decreased with obliquity due to decreased yarn-yarn sliding friction but after certain obliquity, it again increased due to sliding of the projectile over the fabric. Kinetic energy absorbed by the fabric also showed an increasing-decreasing behaviour with time, similar to strain energy absorption. Its steepness and magnitude decreased with increase in the obliquity. Apart from these minute details, it is observed that for a given obliquity angle in impact, fabric response varies with offset angle changes. This can be further used in better designing of armours. As an example, based on the current study we see that for an obliquity angle of 45°, the fabric having offset angle of 0° performs poorest, whereas the fabric with an offset angle of 45° performs best. Therefore, to avoid perforation for a probabilistic impact obliquity, it is better to stitch fabrics together with different angles of orientation.

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