Woven Fabric for Protection against Stabbing

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Abstract

Today's law enforcement personnel are regularly spotted with body protection vests. These vests assist them in coping with a variety of threats like from small firearms and others originating from the edge of a sharp metal piece. Light weight and ability to offer better mobility to the wearer, have made soft body armour a preferred choice. The work here presents a numerical study of low velocity impact response on one such soft body armour, prepared as a woven fabric. A multi-layered dimension-wise graded woven fabric is developed using CAD software SolidWorks 2020 and its performance against stab threats is investigated using impact simulations on commercially available FE tool ABAQUS CAE 2019. The investigation involved subjecting the fabric to the standardized energy level E1 (24J) - defined as per the National institute of justice (NIJ) standard 0115 - for a range of attack angles and observing dissipation of energy brought in by the impactor into different forms. The material for yarns is Kevlar 29 while the impactor is considered as a perfect rigid body. There are *three* key observations: *first*, in case of oblique angle impacts, stress and strain distributions are observed to be asymmetric as compared to normal impacts and with increase in obliquity, tendency of yarn slippage increased. *Second*, for energy dissipation, at higher oblique angles, lower plastic dissipation of energy is observed whereas for frictional energy dissipation, higher oblique angles resulted in higher frictional energy dissipation. *Third*, the frictional dissipation energy has a non-linear relationship with inter-yarn coefficient of friction. The simulation depicted that the frictional dissipation energy rose with smaller μ, reached a peak value, in this case, at $\mu = 0.45$, and then decreased with further increase in μ. This is attributed to the fact that high inter-yarn friction could lead to premature yarn breakage, reducing the energy absorption capacity of the fabric. This highlights the importance of administering the inter-yarn coefficient of friction, especially for refining the energy dissipation.

Keywords. Graded woven fabric, Body protection vest, Low-velocity impact, NIJ standard 0115.00, ABAQUS/Explicit

1. Introduction

Wars have been around since the beginning of the humankind, trying to protect oneself and to keep others at bay, humans looked towards weapons. Initially the weapons were made from wood clay and stones, but as the time progressed and other materials started to surface, humans started using them in upgrading their weapons like after discovery of metals, the spearheads and arrowheads which were made from stones were upgraded to one's made from metals, similar upgradation happened throughout. With wars and weapons evolving, the need for a body protection shield was felt.

Initial body protection clothing was made from basic materials like wood, clay etc., it all changed once the metals were discovered. With properties like malleability, the metals could be rolled and hammered into body armour suits which provided decent protection to the wearer. It all again changed when gunpowder was discovered, all the earlier developments made for protection against threats like swords, spear and arrows were left useless against these new high-speed firearms. Now the body protection industry again pivoted, the armour developed were in shape of a vest which supplemented the protection by guarding the ribcage and back, by a solid metal plate. This continued till the 1970's until p-aramid materials like Kevlar were developed. These newly developed synthetic fibres showed strength to weight ratio 4-5 times higher than that of steel. So, because of all these properties, also coupled with light weight, these became an epicentre of body protection research industry(Nayak *et al.*, 2017).

Protection clothing can be classified in 2 categories, hard body armour and soft body armour. Hard body armours are supplemented using metal or other ceramic material plates, which comprise different piles in protective clothing. They are used by personnel in operations for protection where high-speed high-calibre bullets are involved. These are bulky and hinder the wearer's mobility. On the other hand, soft body armour is developed by bringing together different plies formed of p-aramid fabric, making it light and comfortable for the wearer, these soft body protection vests compliment mobility of the person wearing it. Police personnel, prison guards etc., prefer these soft armours against threats from small firearms like handguns or from any edged object. Soft body armour can be developed using various techniques like knitted, woven, non-woven etc, and each technique can be implemented with help of different patterns. The study here focuses on stab resistant behaviour of one such soft body armour prepared as woven fabric. Woven fabrics are widely accepted for body protection clothing. Woven fabric provides, when compared to non-woven and knitted structure, better packing of yarns. With their advantages, they also possess certain shortcomings, as they are formed due to interlacing arrangement of warp and weft yarns because of this arrangement crimp is formed. This crimp is the wavy nature of yarns, because of this crimp, yarns develop buckling tendencies when put under compressive loads such as during the action of stabbing, it may happen that the yarns might slip during such an event and can result in injury to wearer. This problem of slipping can be overcome by tightly stacking the yarns into the weave, when the weave is finer it improves the stab resistance behaviour but also can't be too tight as flexibility will be compromised. Soft body armour prepared as woven fabric have shown to be implemented with many techniques like with modification of yarn surface and using different weave patterns (Usman Javaid *et al.*, 2019; Hameed *et al.*, 2021), but Abhijit majumdar *et al*., (2014) research work focused on the impact performance of soft composite with Kevlar-STF. It was noted that the STF coating improved the energy absorption of the soft composite. Similar findings were made by M. J Decker et al. (2007), this research work focused on Kevlar fabric and nylon cloth, impregnated with shear thickening fluid of equal area density for stab resistance. The standard drop tower test was performed and it was noted that the STF addition significantly boosted the stab resistant performance of fabric. Rajesh Mishra *et al*. (2014), prepared a model of woven Fabric in SolidWorks and then simulated the impact on Ansys workbench, the parameters of deformation, strain and stress were noted on the fabric it was observed that the deformation in the 3D Kevlar epoxy composite was maximum when compared to others. The literature available on protection against threats be it low or high velocity, clearly indicates the body protection clothing available for protection against ballistic impacts may not necessarily perform when subjected to stab threats or vice versa (Nayak *et al*., 2017).

After going through the literature, factor influencing stab resistant behaviour can be listed under following categories as below.

a. Impactor related characteristics like geometry, size, point of impact, angle of impact etc.,
b. Fabric related characteristics like material property, friction, weave pattern, fabric density etc.

Upon going through the literature, it was observed that most of the research carried out related to this low velocity impact study, has been done with impactor positioned to attack at perfectly normal to the target area, but in actual scenario the probability of perfect normal impact is very slim. Also, it was noted that even though a lot of research is available on 2D fabric weaves but the performance a multi-layered fabric is yet to be explored in details. In the study here, an attempt has been made to address these, the study focuses on development of a multi-layered plain-woven fabric and a P1 knife impactor according to the National institute of Justice (NIJ) standard 0115.00, and investigation of the stab resistant behaviour of the prepared woven fabric when subjected to oblique angles of attack by the knife at E1 energy level according to the NIJ standard 0115.00. It was also noted that friction between yarn-yarn and knife-yarn plays an important role in dissipation of kinetic energy brought in by the impactor, an attempt has been made here to study the change in frictional energy dissipation by varying coefficient of friction in model.

2. PREPARATION OF MODEL

2.1 Preparation of geometry of woven fabric and knife

The geometry of both the woven fabric and knife were prepared on commercially available CAD tool SolidWorks 2020. Impactor was developed in accordance with the specifications provided in NIJ standard 0115.00 for single cutting-edge impactor (i.e., P1 type).

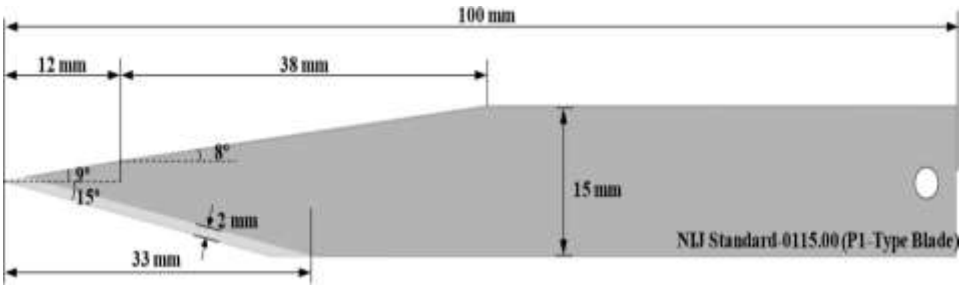

Figure 1. P1 type impactor

Preparation of woven fabric was done with fabric thread density of 7.5 per centimetres for both weft and wrap and linear density is taken as 158 tex. For calculation of strength parameters, a single yarn is taken and tested experimentally. It is important to note that when the yarn is tested it has a circular shaped cross section but when this same yarn is weaved into a fabric the compression forces make the cross section into lenticular shaped. For this study same arcs of curvature are assumed for lenticular cross section. All geometrical parameters are calculated using equations.

$$L = \frac{2}{thread\ density} \tag{1}$$

$$b = \frac{Fabric\ thickness}{4} \tag{2}$$

$$x = \frac{L}{4} \tag{3}$$

$$R_m = \frac{x^2 + y^2}{2b} \tag{4}$$

$$R_i = R_m - b \tag{5}$$

$$a = (2bR_i - b^2)^{1/2} \tag{6}$$

Where L is yarn path wavelength, Rm is radius of the arc of yarn path, Ri is radius of the arc of yarn cross section, a is half of the width and b is half of the height of cross section of yarn. Based on equation 1- 6 following geometrical parameters are calculated for development of woven fabric geometry.

Table 1. Geometrical parameters for woven fabric development

Layer no.	L	b	x	R_m	R_i	a
1	6	0.255	1.50	4.4400	4.1850	1.40
2	6	0.235	1.50	4.8129	4.5779	1.40
3	6	0.215	1.50	5.2383	5.0233	1.40
4	6	0.195	1.50	5.7707	5.5757	1.40
5	6	0.175	1.50	6.4468	6.2718	1.40

Kevlar 29 is considered for the material assignment of the yarns with properties listed in Table 3. The yarns are modelled with the assumption that they are comprised of homogenous material and rather than being orthotropic, they are considered to be isotropic in nature, the reason behind this is that when energy absorption was considered, there was only a slight difference due to orthotropic nature and this difference was incomparable with other energies being absorbed upon impact.

2.2 Description of Finite element model

The geometric model created as described above, was imported into ABAQUS CAE 2019 for further analysis. The problem was solved using the explicit dynamic solver of the ABAQUS 2019. The fabric (yarns) was meshed with the help of a user defined mesh (Fig 4) with 8 node brick C3D8R type elements whereas the knife was considered as a discrete solid and was meshed using R3D4.

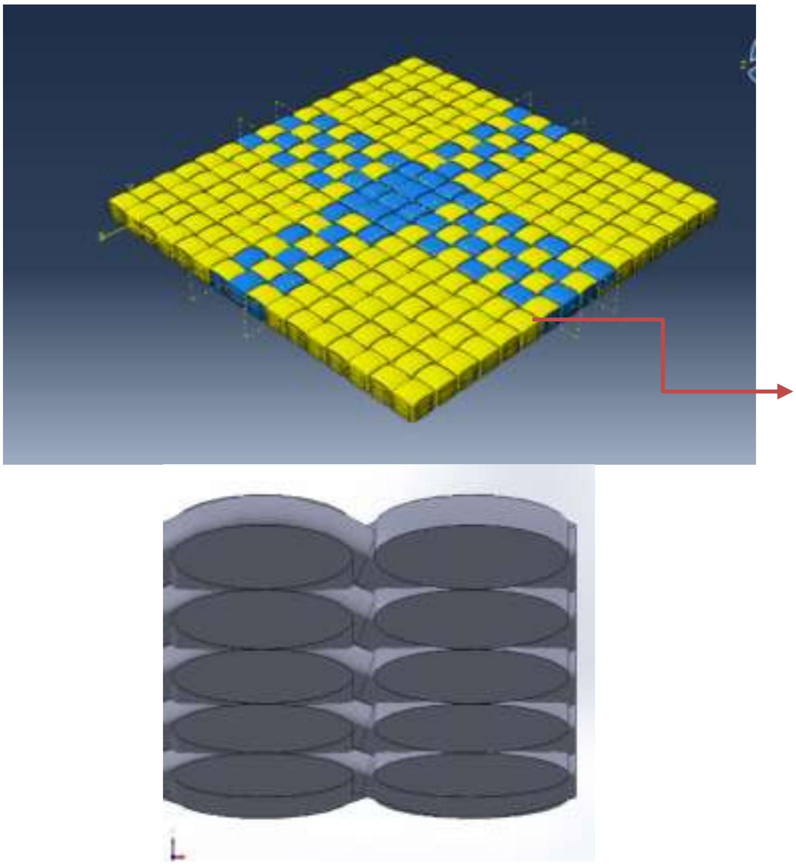

Figure 2. Iso-metric view and cross section of prepared Woven fabric

A) Impactor

It's important to note that this study is carried out at E1 energy level according to the NIJ standard 0115.00, which is 24 $\pm$0.5 Joules. Now the kinetic energy can be considered as

$$K.E = 0.5\, m\, V^2 \qquad (7)$$

Where m is the mass of the P1 type knife used here, which is considered to be 1.8 kgs and V is magnitude of velocity, which upon simple calculation comes up to be nearly 5.164 m/s.The knife is assumed to be rigid solid and since this analysis involves oblique impacts, the velocity is defined as a vector as shown below

$$\vec{V} = V_x\hat{\imath} + V_y\hat{\jmath} + V_z\hat{k} \qquad (8)$$

Where V_x, V_y and V_z are components in x, y and z axis respectively.

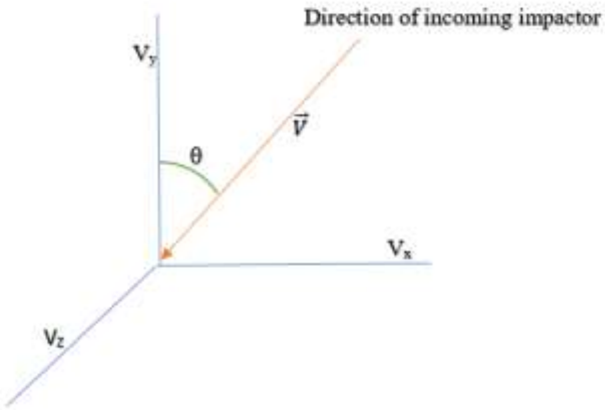

Figure 3. Orientation of components of velocity vector

Where θ is angle of obliquity, based on above orientation, values of components of velocity for different oblique angles of impact is listed below

Table 2. Components of velocity of impactor

θ	V_x	V_y	V_z	$\lvert \boldsymbol{V} \rvert$
0°	0	-5163.98	0	5163.98
15°	0	-4988.02	1336.54	5163.98
30°	0	-4472.11	2581.99	5163.98
45°	0	-3651.49	3651.49	5163.98

*All values are in mm/s

(B) Fabric

Friction plays an important role in energy dissipation in these kinds of woven fabrics, two kinds of friction are considered in the above model, 1 between yarn and yarn the other being between yarn and knife surface, this study also carries out an investigation with variation of coefficient of friction to see how the energy absorption is affected by this variation. This study proceeds further by ignoring inter fibre friction because, as generally yarns are made of multiple fibres but in this study the yarn is considered to be made up of a continuous and isotropic material, also the inter fiber friction contributes to very negligible amount of energy being absorbed, so it is not considered here. For plastic behaviour of yarns and failure modelling, Johnson-cook model is considered after ignoring the effects of temperature softening on material with total elongation being 4%, along with tensile strength of 3.5 GPa taken as a failure criteria for a yarn. All parameters of J-c model are listed in table 3.

Table 3. Material properties

volumetric density	1440 kg/m^3
Young's modulus	93.5 GPa

Poisson ratio	0.35
A	3500 MPa
B	3560 MPa
n	1
m	0
Melting temperature	0 K
Transition temperature	0 K
Fracture strain	0.04
Stress triaxiality	-0.333
Strain rate	2000 s^{-1}
Fracture energy	74.674 N/mm

To facilitate the friction between yarn-yarn and knife-yarn, a penalty-based contact algorithm is provided by ABAQUS/Explicit finite element package and effect of friction on stabbing performance of woven fabric using analysed by different coefficient of friction. Referring to boundary condition of the problem, all degrees of freedom are constrained at all the four edges of the fabric and a fixed edge boundary condition is modelled, in ABAQUS this is done using encastre condition.

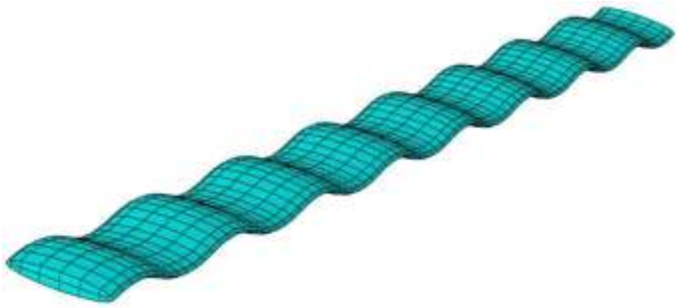

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Figure 4. Represents the meshed view of yarn with C3D8R element

3. RESULTS AND DISCUSSIONS

3.1 Effects of obliquity of stabbing impact on woven fabric

When knife is attacked normal to fabric, the deformation shape XYZ, surrounding the impact area stay symmetrically. This deformation leads to strains which in turn leads to stresses, it's easy to conclude both stresses and strains in case of a normal impact would be same on both the sides i.e., XY and YZ sides. But in case of angle of attack being at any oblique angle the deformation shape becomes X'Y'Z'. It can be noted that X has moved to X', Y to Y' and Z to Z', it can be easily understood that with high oblique angle the asymmetry will also be higher.

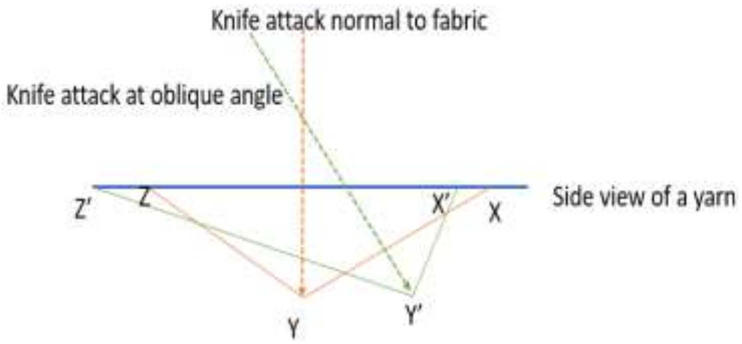


Figure 5. Comparison of knife attack on a yarn at normal and oblique angles of impact

In case of a normal impact, strains on both sides will be symmetric hence would cause a normal reaction to pass through knifes reference axis. This will not be the case when angle of attack is anything expect normal, because with obliquity some asymmetry in deformation will be observed. It can be understood that $\varepsilon_{X'Y'} < \varepsilon_{Y'Z'}$, where ε represents strain. This translates to a stress asymmetry with side Y'Z' experiencing higher stress when compared to X'Y', finally this induces a non-uniform force which is experienced by the knife.

(A) Effect on displacement (slippage) of warp and weft yarns with changing θ

The investigation performed here focuses on considering different angles of attack i.e., θ, to study the slipping of warp and weft fibres. This was done by selecting surrounding nodes of both warp and weft yarns in close proximity of impact zone and tracing their path throughout the simulation. The results obtained (Figure 6) show that with higher obliquity angle θ the slipping increases, as discussed earlier when the impactor impacts the yarn vertically, the strains generated in the surrounding of the impact point are symmetric and the reaction force experienced by the knife is along its axis of travel, but when the impact angle changes the strains are no longer symmetric, which create different stresses in nearby by region.

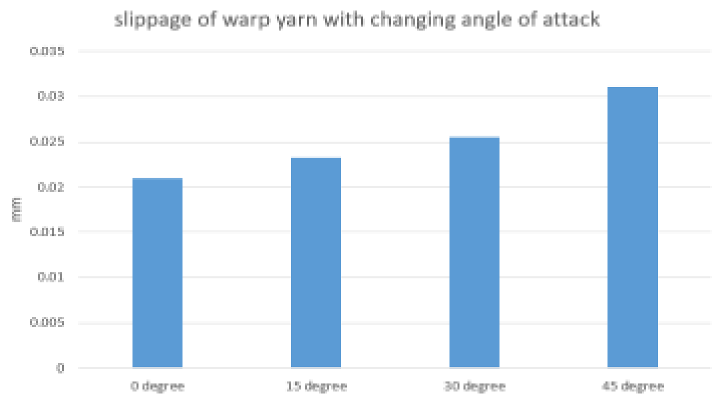
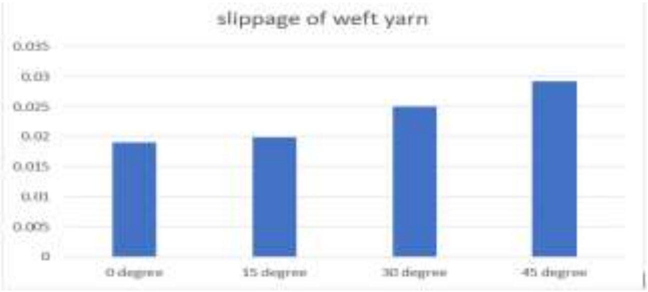


Figure 6(a). Slippage of warp and weft yarns



. Figure 6 (b). Slippage of warp and weft yarns

Moreover, initially the primary yarns do not perforate immediately they try to move in the direction of the projectile. This creates a tendency in the secondary yarns present underneath the primary ones to slip, which is countered by the presence of friction between the yarns. As the angle of attack that is the angle of obliquity is increased, the strain and stress distribution's asymmetric character increases, so at high oblique angles knife drives yarns without perforating, causing them to slip by overcoming inter-yarn friction, and hence it can be concluded that, if obliquity is increased the tendency to slip will also increase.

(B) Effects on energy dissipation

The kinetic energy brought in by the impactor has to be dissipated as soon as possible to improve performance of the fabric, dissipation of energy is a phenomenon which involves a lot of variables. Here energy dissipation in fabric is mainly categorised as Elastic Strain energy absorbed by the fabric, the plastic strain dissipated and energy dissipated because of friction.

- ***Effect of elastic strain energy absorbed and plastic energy dissipated***

During impact the primary yarns experience a stretching because of this stretching elastic strain energy starts getting absorbed by the fabric, when this phenomenon continues there comes a point when the yarns enter plastic deformation and depending upon the material property, the fracture happens. The amount of strain energy stored within the fabric is majorly decided by the number of yarns participating in the impact.

It can be noted that plastic energy dissipation in the beginning would be zero (Fig 7) it would continue to be zero for some time, until the yarn enters plastic deformation zone once the yarn enters plastic deformation zone the plastic energy dissipation starts rising it will continue to rise until the yarns fail. Upon failure the plastic energy becomes constant. It can be noted that the plastic energy dissipation is lowest for high oblique angles like 30° and 45° this is because plastic energy dissipation will be higher if the impact involves more number of yarn in impact, as more yarn to store energy, as discussed in the previous section where the displacement of warp and weft yarn is shown, it was evident that at impact angle of 45°, the maximum displacement (slippage) of warp and weft occurred, so those yarns got away from the zone and were not strained till later and hence the plastic dissipation is lower. Similar reasoning can be applied for others to understand the trend of graph (Fig 7).

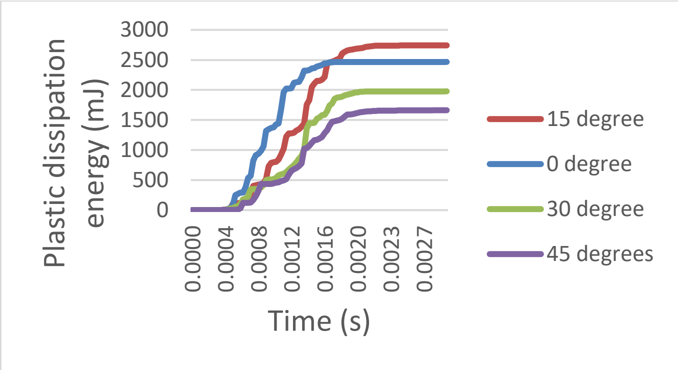


Figure 7. comparison of plastic dissipation at various θ

- ***Effect of frictional dissipation energy***

When the impact occurs in the primary yarns longitudinal wave fronts and transverse wave fronts are generated longitudinal wave travel within that same plane and transverse wave travel out of the plane i.e., in the direction of impactor. Because woven fabric is formed due to interlacing arrangements of yarns at crossovers, frictional contact is higher and in ABAQUS, tangential contact and hard normal contact properties are given in interaction section to accommodate this. Majorly in this model two types of friction are responsible for frictional energy dissipation

a) yarn and yarn and b) between yarn and impactor.

When angle of attack θ is 0° the chances of impactor sliding over yarn are very slim, but when the obliquity is introduced this changes. In the plot (Fig 8) it can be seen that for 45° the frictional energy dissipation is maximum this can be attributed to the fact that was explained earlier frictional energy depends upon yarn-to-yarn friction and also on yarn to and knife fiction so as 45° impact involves slipping of yarn at maximum, this shows the friction induced will be higher that is why frictional energy dissipation can be seen as maximum.

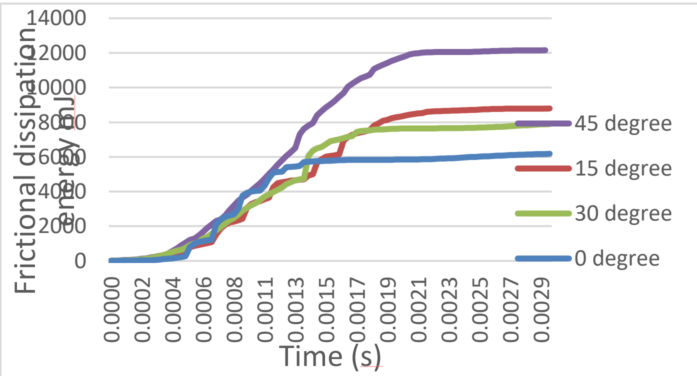


Figure 8. Comparison of frictional energy dissipation at various θ

(C) Knife travel and penetration into the fabric

The knife travel and penetration into the fabric is the most important parameter in determining the stab resistant property of the fabric. The knife travel here was calculated by selecting a node at the tip of the knife and plotting its journey through the entire simulation process. Knife penetration is a complex phenomenon and is dependent on a lot of factors like the energy dissipation, yarn slippage discussed in previous sections.

Because of the minimum dissipation of energy in the case of 45°, it is quite evident that fabrics performance at an obliquity of 45° impact of the knife is the poorest. The results obtained (fig 9) after plotting of the curve are in accordance with our hypothesis.

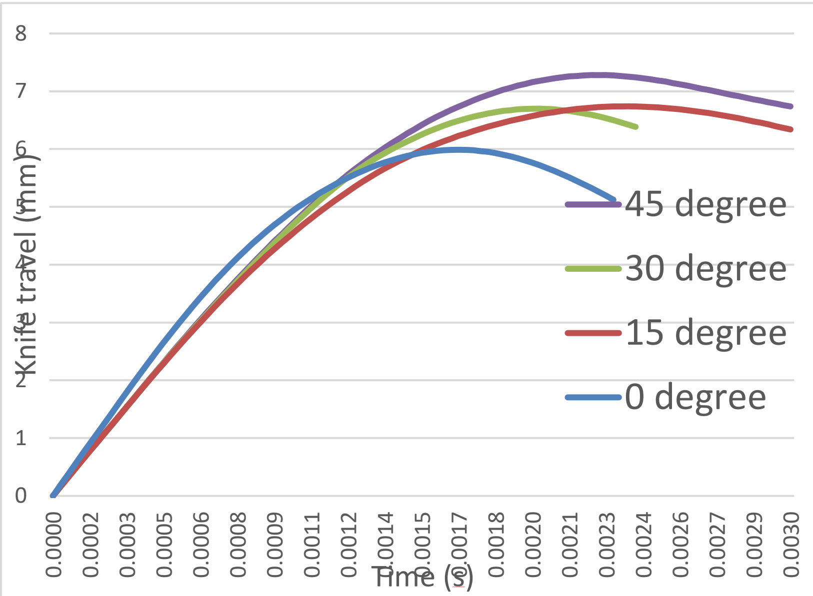


Figure 9. Comparison of Knife travel

3.2 Effect of coefficient of friction on energy dissipated by fabric

The performance of a protective clothing is substantially affected by its frictional behaviour. Factors influencing textile friction behaviour can be divided into fiber friction, yarn friction and fabric friction. As discussed earlier the fibre friction is not considered here, the other two factors are explored here.

Upon impact in woven fabric two kinds of wavefronts are generated longitudinal and transverse, the longitudinal wavefront is the fast-travelling wavefront, travelling in primary yarns, is responsible for stretching of yarns and it travels away from the impact zone i.e. within the plane, at a wave speed $\sqrt{(E/p)}$, where E is young's modulus and p is the density of material, it can be noted it is independent of speed of the impactor whereas the transverse wavefront travels along the projectile, it is the slower wavefront and takes impact out of the plane. Now as woven fabric is formed because of interlacing arrangement of the yarns, there are crossover regions present, where warp and weft yarns overlap, this is where inter yarn friction comes into play majorly. When the impact occurs, primary yarns are stretched and tensile stresses are induced in them, at crossover region these interact with secondary yarns, present orthogonal to these, secondary yarns are deformed and are subjected to stresses and strains, which results in stress distribution to a large extent and more energy is dissipated. In ABAQUS tangential contact and hard normal contact properties are given in interaction section to accommodate this frictional contact. This study used the developed woven fabric with impactor positioned at θ=0° for observing the changes in frictional dissipation energy when coefficient of friction is varied between yarn-yarn. The simulation results (Fig 10) shows that initially frictional dissipation energy rose with smaller μ, reached a peak value and then came down with further increase in μ. This can be attributed to the fact that, high inter-yarn friction can lead to premature yarn breakdown, reducing the energy absorption capacity of the fabric. So as a result, good control of inter-yarn frictional coefficient is crucial to improve the energy dissipation capability of the fabric. When the μ between yarns surpasses a certain level, the energy dissipated by the fabric will come down, in this case the peak value for max dissipation is $\mu = 0.45$

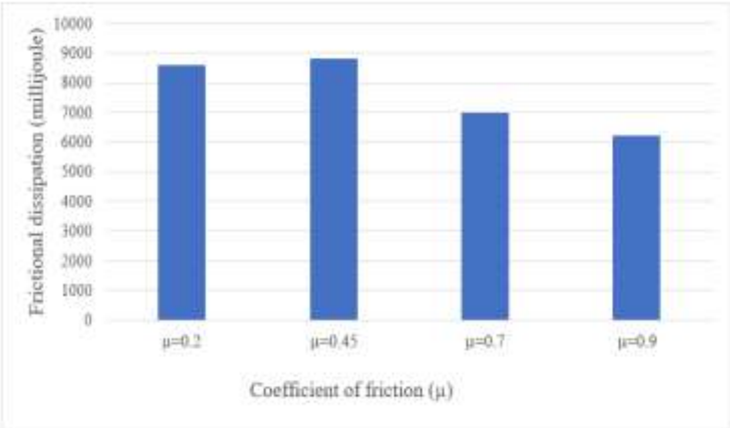


Figure 10. Frictional dissipation for different value of coefficient of friction

4. CONCLUSION

The stab resistant behaviour of the fabric was simulated and studied for effects of impact at oblique angles, the material assigned during simulation was Kevlar 29 for yarns, while impactor was considered as rigid. Along with effects at oblique angle impacts, the stab resistant behaviour of the fabric was also closely observed with variation of inter yarn coefficient of friction. It was noted that in case of oblique angle impact, stresses and strains were not symmetrically distributed as they were in case of normal impact. For different angles of impact, the phenomena of warp and weft yarn slippage was examined, it was noted that higher oblique angles caused higher slippage. The energy coming in through the impactor was considered as kinetic and its dissipation was mainly observed as elastic strain energy absorbed, plastic energy dissipation along with frictional energy dissipation. It was noted that for higher obliques angles plastic dissipation of energy was lower whereas for frictional energy dissipation, it was seen that for high oblique angles frictional energy dissipation was higher. It was also concluded that among all the cases of oblique angle impacts simulated here, highest knife travel within the fabric i.e., penetration, was observed at θ=45°, yarn slippage was considered a major factor for it. Similarly, when the frictional dissipation energy was observed, with different inter yarn coefficient of friction, simulation results showed that initially frictional dissipation energy rose with smaller μ, reached a peak value and then came down with further increase in μ. This was attributed to the fact that, high inter-yarn friction can lead to premature yarn breakdown, reducing the energy absorption capacity of the fabric, in this case the peak value for maximum dissipation was $\mu = \mathbf{0.45}$. This stressed the importance for good control of inter-yarn frictional coefficient to improve the energy dissipation capability of the fabric. It is important to note that this work was carried out during covid 19 lockdown on a relatively limited capable workstation, improved results maybe obtained on a highly capable workstation.

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