

(43) International Publication Date
20 May 2010 (20.05.2010)(10) International Publication Number
WO 2010/056614 A2(51) International Patent Classification:
D03D 13/00 (2006.01) *F41H 1/02* (2006.01)
D03D 1/00 (2006.01)(US). KEEFE, Michael [US/US]; 305 Manubay Court,
Bear, DE 19701 (US).(21) International Application Number:
PCT/US2009/063667(74) Agents: DONNELLY, Rex, A. et al.; RatnerPrestia, P.O.
Box 980, Valley Forge, PA 19482 (US).(22) International Filing Date:
9 November 2009 (09.11.2009)(81) Designated States (unless otherwise indicated, for every
kind of national protection available): AE, AG, AL, AM,
AO, AT, AU, AZ, BA, BB, BG, BH, BR, BW, BY, BZ,
CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO,
DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT,
HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP,
KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD,
ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI,
NO, NZ, OM, PE, PG, PH, PL, PT, RO, RS, RU, SC, SD,
SE, SG, SK, SL, SM, ST, SV, SY, TJ, TM, TN, TR, TT,
TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/113,412 11 November 2008 (11.11.2008) US
12/579,945 15 October 2009 (15.10.2009) US(71) Applicant (for all designated States except US): UNI-
VERSITY OF DELAWARE [US/US]; 112 Hullihen
Hall, Newark, DE 19716-1551 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): NILAKANTAN,
Gaurav [IN/US]; 93 Amstel Avenue Apartment #1,
Newark, DE 19711 (US). GILLESPIE, Jr., John, W.
[US/US]; 106 East Bridle Path, Hockessin, DE 19707(84) Designated States (unless otherwise indicated, for every
kind of regional protection available): ARIPO (BW, GH,
GM, KE, LS, MW, MZ, NA, SD, SL, SZ, TZ, UG, ZM,
ZW), Eurasian (AM, AZ, BY, KG, KZ, MD, RU, TJ,
TM), European (AT, BE, BG, CH, CY, CZ, DE, DK, EE,
ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV,
MC, MK, MT, NL, NO, PL, PT, RO, SE, SI, SK, SM,

[Continued on next page]

(54) Title: BALLISTIC RESISTANT FABRIC ARMOR

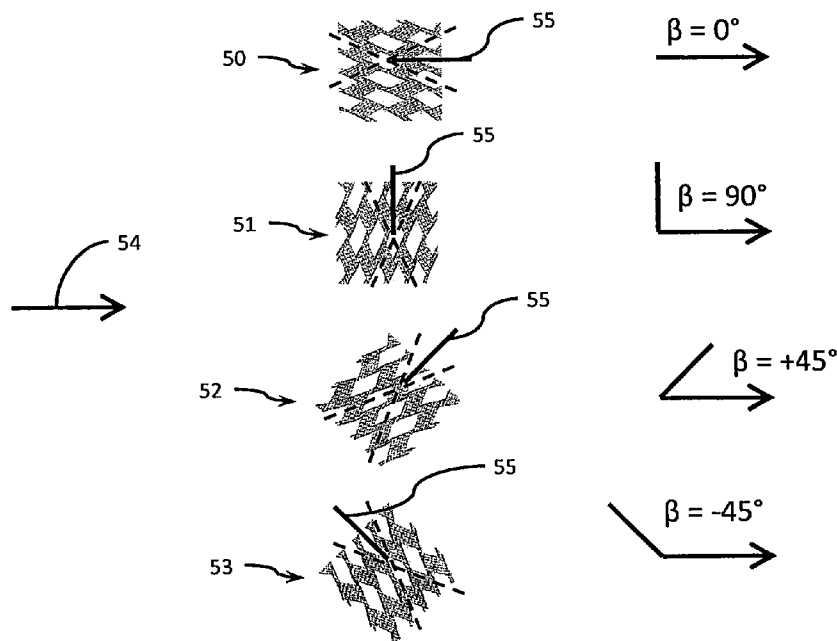


FIG. 5

(57) Abstract: A woven ballistic resistant fabric armor system comprising at least one ply having a yarn-yarn angle between the warp and fill yarns of less than 90°, with each ply oriented relative to an axis along the thickness of the plies such that adjacent plies have a different yarn-yarn angle, a different orientation, or both. The armor system may feature materials of different stiffness, strength, and strain-to-failure in each ply or a filler between selected plies, including a filler comprising discrete pieces of fabric ply that fit within the cell periphery of a stitching pattern.



TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG). **Published:**

— *without international search report and to be republished upon receipt of that report (Rule 48.2(g))*

Declarations under Rule 4.17:

— *as to applicant's entitlement to apply for and be granted a patent (Rule 4.17(ii))*

BALLISTIC RESISTANT FABRIC ARMOR

CROSS-REFERENCE TO RELATED INVENTIONS

This invention claims priority to U.S. Provisional Application Serial No. 61/113,412, filed November 11, 2008, and to U.S. Application Serial No. 12/579,945, filed October 15, 2009, both titled "BALLISTIC RESISTANT FABRIC ARMOR," and both incorporated in their entirety herein by reference.

FIELD OF INVENTION

The present invention relates, generally to an energy dissipating system, broadly to an armor arrangement, and specifically to a filament-based, woven fabric arrangement used in protective clothing against ballistic projectiles. Applications of the present invention include, but are not limited to personnel body armor, turbine fragment containment systems in airplane fuselages, and spall liners in military vehicles.

BACKGROUND OF THE INVENTION

Protective clothing or armor is needed by personnel whose line of work involves being directly subjected to impact by high velocity projectiles that include bullets, pellets, and shrapnel. Penetration by these projectiles into the human body causes fatality by massive internal bleeding and organ failure. The primary goal of the protective clothing is to retard the projectile's motion without the projectile being able to completely penetrate through the protective clothing. One important constraint that must be satisfied while accomplishing this goal is to ensure the dynamic deflection or back face deformation of the protective clothing is kept to a minimum to prevent blunt force trauma injuries. Such injuries can also be fatal. The limit of back face deformation is set forth in the National Institute of Justice (NIJ) Standards to be a maximum of 1.73 inches or 44 millimeters. Protective clothing should also be kept to a minimum thickness so that it is flexible enough to be comfortably worn on the human torso, especially around the extremities, without restricting any motion of the limbs, and that if needed, it can be concealed underneath regular clothing. Further, it should be as lightweight as possible so that it does not exhaust or diminish the performance of the personnel in the line of work. Finally, it should be able to dissipate heat and moisture and allow for ventilation to keep the human body cool and prevent dehydration.

Many arrangements for flexible ballistic resistant fabric armor comprised of high strength and high stiffness woven yarns are known. Non-limiting examples of such high performance materials include aramid fibers, such as KEVLAR® aramid fibers, manufactured by E. I. du Pont de Nemours and Company, of Wilmington,

- 2 -

Netherlands; PBO (poly (phenylene benzobizoxazole)) fibers, such as ZYLON® PBO fibers, manufactured by Toyobo Co. Ltd. of Japan; UHMWPE (ultra heavy molecular weight poly ethylene) fibers such as SPECTRA® UHMWPE fibers, manufactured by Honeywell International of Morristown, NJ and DYNEEMA® UHMWPE fibers,
5 manufactured by DSM High Performance Fibers B.V. of the Netherlands; PIPD (poly{2,6-diimidazo[4,5-b:4',5'-e]-pyridinylene-1,4(2,5-dihydroxy)phenylene}) fibers, such as M5® PIPD fibers, manufactured by Magellan Systems International, LLC of Bethesda, Maryland. Other non-limiting examples of suitable materials include VECTRAN® aromatic polyester fiber (Kuraray Co. Ltd. of Japan), TECHNORA® aramid
10 fiber (Teijin Techno Products Limited, of Japan), and NEXTEL® ceramic fiber (3M Ceramic Fiber Products). All of the fibers listed above are characterized by high stiffness and high strength-to-weight ratios.

There still exists much opportunity in the current state of the art to enhance the ballistic resistance of fabric systems comprised of the aforementioned high
15 performance yarns. The improved performance may be realized, for example, by creating lighter fabric systems by using less material and fewer number of plies, by reducing back face deformations, and by increasing the V_{50} velocity (velocity at which there is a 50% probability of penetration) and V_0 velocity (highest velocity at which there is a 0% probability of penetration), as compared to equivalent systems comprised
20 of the conventional arrangements addressed in the prior art.

SUMMARY OF THE INVENTION

One aspect of the invention comprises a woven ballistic resistant fabric armor system comprising a plurality of plies that together define a thickness, at least one ply comprising warp yarns and fill yarns having a yarn-yarn angle between them of
25 less than 90°. Each ply has a warp and fill orientation relative to an axis along the thickness of the plies such that adjacent plies either have different yarn-yarn angles, different ply orientations, or a combination thereof. The minimum yarn-yarn angle is typically greater than the locking angle of the yarns. Each ply may have the same yarn-yarn angle or the plies may have different yarn-yarn angles, for example, wherein
30 the yarn-yarn angle of each successive ply beneath a topmost ply is less than an adjacent ply above.

At least two plies, and in one embodiment, all plies, may be stitched together. The stitching pattern may comprise parallel unidirectional lines, or a square, rectangular, or diamond shape. A first plurality of plies, including a topmost ply and all
35 plies above a mid-plane of the armor thickness, may be stitched together in a first stitching pattern, with remaining plies below stitched together in second stitching pattern that differs in shape or size.

In one embodiment, an upper plurality of plies, such as comprising no more than a quarter of the total thickness of the armor, may be separated from a lower plurality of plies by a filler material. The filler material may comprise a plurality of fabric ply pieces, each piece sized and positioned to fit completely within a cell periphery created by a stitching pattern, wherein at least adjacent plies directly above and directly below the filler material are stitched together using the stitching pattern.

All or less than all of the yarns in all of the plurality of plies may comprise a same single high strength and high modulus material. The materials of construction in the upper plurality of plies may comprise a first material characterized by greater absorption of energy during high energy impacts that cause failure by a shearing mechanism and the lower plurality of plies may comprise a second material characterized by greater absorption of energy during low energy impacts that cause yarn failure by a tensile elongation mechanism. The stiffness of the yarn materials used in the plies may change, such as by progressively increasing, through the armor thickness and/or the strain-to-failure may change, such as by progressively decreasing, through the armor thickness.

The armor may comprise a flexible, dry fabric armor system, or a flexible fabric armor system comprising one or more plies partially or fully impregnated with resin. The armor may comprise a body armor wearable by a user, or an armor for another use, such as but not limited to use in an engine casing, a lining for an airplane fuselage, or a spall liner for a vehicle.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a schematic view of a '*normal*' plain weave fabric showing the warp and fill yarns;

FIG. 2 is a schematic view of a '*sheared*' plain weave fabric showing the warp and fill yarns;

FIG. 3 is a schematic view of the upper portion of the human body;

FIG. 4 is a schematic view of a ballistic resistant fabric armor system applied to the upper portion of the human body shown in FIG. 3 according to an exemplary embodiment of the present invention;

FIG. 5 is a schematic view of an exemplary layup of the fabric plies in a ballistic resistant fabric armor system according to an exemplary embodiment of the present invention;

FIG. 6A is a schematic side view of the impact of a spherical projectile on a single ply of a plain weave fabric;

FIG. 6B is a perspective view of the projectile impacting the single ply of plain weave fabric of FIG. 6A;

FIG. 7 is a schematic view of the various mechanistic zones of interactions and energy dissipations of a '*normal*' plain weave fabric system as seen from the top;

FIG. 8 is a schematic view of the various mechanistic zones of interactions and energy dissipations of a '*sheared*' plain weave fabric system as seen from the top;

FIG. 9 is a schematic view of the various zones of deformation of a multiple ply fabric target resting against a backing material and transversely impacted by a projectile;

FIG. 10 is a schematic view of the same system shown in Fig. 9, but with a filler material included between the fabric plies;

FIG. 11 is a schematic view of a system with filler comprising a plurality of cut ply material pieces, each of which is located entirely between the stitches of a stitching pattern;

FIG. 12A is a schematic view of an exemplary ballistic testing arrangement as known in the prior art;

FIG. 12B is a perspective view of an exemplary rectangular ballistic testing fixture holding two sides of single ply fabric.

FIG. 12C is a perspective view of an exemplary rectangular ballistic testing fixture holding two sides of double-ply fabric.

FIG. 13A depicts an exemplary rectangular ballistic testing fixture holding two sides of a sheared fabric;

FIG. 13B depicts an exemplary rectangular ballistic testing fixture holding two sides of a normal fabric;

FIG. 13C is a plot generated from Modeling Case 2 showing predicted projectile velocity over time for the impact of a projectile on a single layer of woven fabric having different yarn-yarn angles;

FIG. 13D is a plot generated from Modeling Case 2 showing predicted internal energy over time for the impact of a projectile on a single ply of fabric for different yarn-yarn angles;

FIG. 14A is a front exploded view depicting exemplary fabric layers schematically depicted within rectangular ballistic testing fixtures each holding two opposite sides of a two ply sheared fabric with identical ply orientation.

FIG. 14B is a front exploded view depicting exemplary fabric layers schematically depicted within rectangular ballistic testing fixtures each holding two opposite sides of a two-ply normal fabric with identical ply orientation.

FIG. 14C is a front exploded view depicting exemplary fabric layers schematically depicted within rectangular ballistic testing fixtures each holding two sides of a two-ply sheared fabric with rotated ply orientation.

FIG. 14D is a front exploded view depicting exemplary fabric layers
5 schematically depicted within rectangular ballistic testing fixtures each holding two sides of two-ply normal fabric with rotated ply orientation.

Fig. 14E is a scatter plot generated from Modeling Case 2 of the time taken to arrest the projectile and maximum dynamic deflection for several weave and ply configurations.

10 Fig. 15A is a scatter plot generated from Modeling Case 3 of the time taken to arrest the projectile and maximum dynamic deflection for several weave and ply configurations.

FIG. 15B is a plot generated from Modeling Case 3 showing predicted projectile velocity over time for the impact of a projectile on fabrics of various weave
15 and ply orientations.

FIG. 15C is a plot generated from Modeling Case 3 showing predicted internal energy over time for the impact of a projectile on fabrics of various weave and ply orientations.

FIG. 15D is a plot generated from Modeling Case 3 showing predicted
20 fabric layer to layer contact force over time for the impact of a projectile on fabrics of various weave and ply orientations.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a flexible ballistic resistant fabric armor system that can be used for both human torso and extremity protection. It can also be
25 used as a subsystem in other armor arrangements such as stiff armor that is comprised of fabrics with resin impregnation and composite inserts. Multiple plies of fabric may be stitched together. These multiple plies may also be oriented in different directions and/or may be comprised of different high performance fibers.

The present invention uses various material and/or architectural
30 modifications to increase the performance of a fabric armor system over the prior art. Such architectural modifications include changing the angle between the warp and fill yarns in each plain weave ply to an angle less than the conventional 90°, and systematically varying the ply orientation of successive plies through the thickness. Such material modifications include using materials of different stiffness and strain-to-
35 failure in each ply. The enhanced performance of such a fabric armor system may be realized through an increased V_{50} velocity, an increased V_0 velocity, a reduced back face

deformation, and a lighter fabric armor system compared to conventional arrangements in the prior art.

Although the invention is illustrated and described herein with reference to specific embodiments such as body armor for law enforcement and military personnel, the invention is not intended to be limited to the details shown. Rather, various modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention. The invention may be modified to encompass any fabric-based, protective, energy-dissipating system and composite structures, including but not limited to, engine casings and airplane fuselages, spall liners in armored vehicles and infantry carriers, and any other casing that requires ballistic, shrapnel, or fragment containment. Thus, as used herein, the term "ballistic resistant" refers to resistance to penetration from any type of projectile, including but not limited to bullets, shrapnel, fragments, and the like.

Fig.1 illustrates a plain weave fabric with the warp yarns 10 oriented at 90° to the fill yarns 12 and vice versa. This is henceforth referred to as a '*normal*' plain weave fabric or simply "normal fabric." Dotted line 11a represents the direction of warp yarn 11 and dotted line 12a represents the direction of fill yarn 12. The angle between the yarns, henceforth referred to as '*yarn-yarn angle*' is represented by the symbol ' θ '. The shape of the cross section of the yarns changes from an approximately circular shape before weaving to an approximately elliptical shape after weaving, wherein the final shape closely depends on the architectural parameters of the fabric such as crimp (measure of undulations) and span (reciprocal of the number of yarns per unit linear dimension) and the weaving parameters such as yarn tension. The normal plain weave fabric arrangement of Fig. 1 forms the basis of much of the arrangements of fabric body armor disclosed in the prior art.

Fig. 2 illustrates a plain weave fabric with warp yarns 13 oriented at $\theta < 90^\circ$ to the fill yarns 14 and vice versa. This is henceforth referred to as a '*sheared*' plain weave fabric or simply "sheared fabric". Dotted line 13a represents the direction of warp yarn 13 and dotted line 14a represents the direction of fill yarn 14. The minimum angle possible between the yarns is the locking angle, which is defined as the angle at which yarns jam in a picture frame or shear test, which is well known in the art, accompanied by a sharp rise in the in-plane fabric shear modulus. For the same planar area of a fabric, a sheared plain weave fabric has a higher areal density than a normal plain weave fabric because of the smaller span or smaller gaps between the yarns. The sheared plain weave fabric forms the basis of the ballistic resistant fabric armor disclosed in this invention.

Fig. 3 illustrates the upper portion of the human body 20 consisting of the torso 22 and extremities 21. The lower extremities (legs) have not been shown but are relevant to the following statements. When the human body 20 is subjected to direct impact by high velocity projectiles or high energy impacts, penetration of the projectiles into the human body can cause internal bleeding and organ failure leading to fatality. However for non-penetrating high energy impacts, blunt force trauma injuries can lead to fatality. Therefore a light weight protective armor is required to protect the body against impact by projectiles such as bullets, pellets, fragments, and shrapnel.

Fig. 4. illustrates a ballistic resistant fabric armor system 100 worn by the human body 20 according to an exemplary embodiment. Multiple plies of sheared plain weave fabric are used over the torso 22. This includes a generic upper ply 23 and generic lower ply 24. The yarn-yarn angle θ may be the same or different in each ply. Further each ply has been rotated in the counter clockwise direction by some angle β from a vector normal to the fabric plane (in the direction of the thickness of the assembled plies), illustrated later. The multiple plies of fabric armor 100 may be stitched together, however, stitching is not essential to the core working of fabric armor 100. Further, the multiple plies of sheared fabric used to protect torso 22 may be dry and flexible, or impregnated partially or wholly in resin, and may also comprise composite or ceramic inserts. As before, however, these are not essential to the core working of fabric armor 100. As used herein, the term "partially impregnated" refers to plies having some impregnation with resin but that remain somewhat flexible, whereas "fully impregnated" refers to plies impregnated with a sufficient amount of resin such that they are completely rigid. Multiple plies of sheared plain weave fabric are also used to protect the extremities 21 which include the forearms not shown in Fig. 3. This includes a generic upper ply 25 and generic lower ply 26 which again are rotated about the normal to the fabric plane by some angle β . The portion of the fabric armor used to protect the extremities must be both flexible and light weight not to impede the performance and functionality of the human in the line of work. Furthermore, the vital human organs are located within the torso 22. Therefore, fewer fabric plies are typically used in the part of the fabric armor 100 that protects the extremities 21 as compared to the torso 22.

Armor 100 is usually encased in some flexible outer cover that shields it from light and abrasion, as well as to provide a camouflage design to the armor. This outer cover, however, is not essential to the core working of the fabric armor 100.

Fig. 5 illustrates a preferred embodiment of the stacking sequence of the multiple plies of sheared plain weave fabric in fabric armor 100. The line that bisects the yarn-yarn angle θ is henceforth referred to as the '*angle bisector*' 55. Consider

some arbitrary vector 54 to be used as a reference. The topmost fabric ply 50, which is the first impacted ply, is oriented along the 0° direction since angle bisector 55 is along the same direction as reference direction 54. Consequently the angle β , which is the angle counter clockwise between the reference direction 54 and the angle bisector 55, is 0° . The next ply below top ply 50 is the second ply 51. Ply 51 is oriented along the 90° direction as ' β ' for this ply, is 90° . Proceeding in a similar manner, the third ply 52 is along the $+45^\circ$ direction and the fourth ply 53 is along the -45° (i.e. a β value of 135°). The orientation of the fifth ply and so forth will restart with the pattern used from the first ply to the fourth ply. In another embodiment of the stacking sequence, only β values of 0° and 90° are used. However, the fabric armor 100 is not limited to these two embodiments. The stacking sequence may follow some stepwise increment of β in the clockwise or counter clockwise direction. In yet another embodiment, with regard to the preferred embodiment, the fifth ply may have a β of 22.5° , the sixth ply may have a β of -22.5° , the seventh ply may have a β of 67.5° , the eighth ply may have a β of -67.5° , and the ninth ply onwards will restart the pattern from the first ply onwards, and so forth. The appropriate choice of stacking sequence may be affected by the choice of boundary conditions which may be fixed, free, or no boundary conditions present as a backing material is present. It may also be affected by the maximum number of plies permissible, choice of high performance materials used in each ply, and other design considerations apparent to someone skilled in the art.

To better understand the enhanced performance of fabric armor 100 over conventional arrangements in the prior art, the basics of the mechanics of energy dissipations and interactions in a fabric system are briefly discussed: Fig. 6 illustrates the impact of a spherical projectile 60 on a single ply of a normal plain weave fabric 62 gripped on all sides. The primary modes of energy dissipation by such fabric systems subjected to ballistic impact are (a) internal energy (b) kinetic energy (c) frictional energy. Component (a) is the fabric internal energy and is created by the elastic straining of the yarns upon elongation.

Upon impact, a longitudinal strain wave propagates through the yarns in a direction pointing outwards from the impact zone with a velocity approximately equal to the square root of the ratio of the longitudinal elastic modulus to the material density of the yarn. The yarn material within the front of this longitudinal strain wave is subjected to elongation and correspondingly develops an elastic strain energy. It is commonly assumed that most high strength and high stiffness yarns used in ballistic applications are elastic until failure. Thus a part of the kinetic energy of the projectile is converted into the internal energy of the fabric. Component (b) is the fabric kinetic

energy and is created through momentum transfer between the impacting projectile and the fabric system.

Depending on the orientation of the plain weave plies in the fabric system, the locus of the fronts of the transverse displacement wave in all yarns creates a deformation that has a pyramidal shape that grows in time as it propagates outwards from the impact zone. The transverse wave propagates outwards with a velocity orders of magnitude lesser than the longitudinal strain wave velocity in a yarn.

Referring to Fig. 6 this pyramidal deformation has a general height h and a width d that vary with time during the impact event. The height h also provides a measure of the back face deformation or dynamic deflection of the fabric system. The shape of the base of the deformation pyramid 61 is a diamond for normal plain weave plies. This diamond shape is obtained by joining the fronts of the transverse displacement wave in each yarn with a straight line. If the transverse displacement wave propagates with the same velocity in both the warp and fill directions, then all four sides of the diamond will be of the same length. The fabric mass within the fronts of the longitudinal strain wave in all yarns but outside the deformation pyramid 61 is drawn inwards towards the region of impact while the fabric mass inside the deformation pyramid is accelerated in the direction of the projectile. Thus a part of the kinetic energy of the projectile is converted into the kinetic energy of the fabric.

If any sides of the fabric are left free, the component of fabric momentum caused by the inward pulling of the fabric towards the impact zone will be higher than if the sides of the fabric were gripped. Component (c) is the frictional energy that is dissipated when two or more entities slide past one another. The amount of frictional energy dissipated is related to the product of the normal contact force and the coefficient of friction between the sliding surfaces. Component (c) is further divided into four sub components depending on entities that participate in the sliding interactions: (i) filament-filament interactions within a yarn, (ii) yarn-yarn interactions within a single fabric ply, (iii) ply-ply interactions within the fabric system, and (iv) projectile-fabric system interactions during penetration. These interactions however not only contribute to component (c) but also to components (a) and (b). In addition to these three main components, there are other modes of energy dissipation.

Fig. 7 illustrates the diamond shaped deformation pyramid of Fig. 6 as seen from the top. Elliptical shape 70 is the smallest elliptical shape that can enclose the periphery of the base of the deformation pyramid 71 and pass through all its four corners. If the base of the deformation pyramid is a diamond with all sides of equal length, then the elliptical shape 70 is a circle. The normal plain weave fabric is depicted by a hatched region which is further comprised of a series of parallel straight

lines, one set for the warp yarns and one set for the fill yarns, oriented at 90° to each other. We are only considering the area of the fabric that lies within the base of the deformation pyramid 71 and accordingly only that region has been depicted by the hatched region of normal fabric 73. Region 73 represents the region where the maximum fabric kinetic energy is developed (i.e. maximum momentum transfer from projectile to fabric).

If Fig. 7 represented multiple plies of normal plain weave fabric with all plies having the same orientation, then region 73 would represent the transverse deformation pyramid of all plies. Clearly the amount of inter-ply interactions in terms of relative ply frictional sliding and inter ply deformations wherein each upper ply tries to deform the lower ply, are at a minimum in region 73. The region 72 outside region 73 but within region 70 is the region of negligible or no interactions, henceforth referred to as the '*unaffected region*' 72. For such an arrangement of the fabric plies, there is little to no yarn reorientation leading to negligible inter yarn rotational frictional energy dissipation. Further the inter ply contact pressure is maximum only at the impact location, which is at the center of region 73, and quickly decreases with distance away from the impact location, within region 73.

Fig. 8 illustrates a four ply fabric system with sheared plain weave fabric plies, each ply from the top to the bottom oriented at 0° , 90° , $+45^\circ$, and -45° respectively. Region 80 is the smallest elliptical shape that encompasses the bases of the deformation pyramids 83 of all plies. Only the region of transverse deformation for each ply has been depicted by hatched lines. Here each set of lines in the hatched region 83 that represent the warp and fill yarns are oriented at some yarn-yarn angle θ since this corresponds to a sheared fabric. The base of the transverse deformation pyramid for each ply is now rectangular in shape. The larger the angle θ , larger is the width of the base of the transverse deformation pyramid in Fig. 8, wherein the width refers to the smaller of the two dimensions of the rectangular shape.

Because of the varying orientation of each ply, unlike in region 72 of Fig. 7, region 82 of Fig. 8 is now a region of high inter ply interactions. Region 82 depicts that region of each ply outside that own ply's deformation pyramid base. In all parts of region 82, the upper ply has a different orientation of its deformation pyramid than the lower ply, and as the upper ply deforms, it induces an additional deformation in the lower ply, that is different from the usual pyramidal deformation shape of the lower ply. Thus the total deformation induced in a lower ply is the sum total of two components. The first component is the deformations induced in that lower ply by the upper plies outside of the usual pyramidal deformation shape of that lower ply, or region 82 of that ply. The second component is usual pyramidal deformation shape of that ply, or the

hatched region 83 of that ply. Further, the inter ply sliding interactions that contribute to the frictional sliding energy dissipation are increased. This is because of increased inter ply contact pressures due to the differential deformation shapes.

While region 72 in Fig. 7 remained unaffected by any significant interactions or deformations, region 82 in Fig. 8 represents a region of increased interactions and deformations. Thus the total affected area 80 of the sheared fabric multiple ply system that contains deformations and interactions is higher than the corresponding affected area 71 of the normal fabric multiple ply system. This is true even when each ply of the normal plain weave fabric is rotated in such a manner so as to create a quasi-isotropic system. The greater the affected area (i.e. the greater amount of fabric that takes part in the energy dissipation process) the better the performance of the fabric armor system.

In addition to the effect of orienting each sheared fabric ply in a differential manner, there is a significant effect of altering the yarn-yarn angle on fabric armor performance, as discussed earlier. The angle between the warp and fill yarns in a plain weave fabric is reduced from the conventional 90° such that $\theta_{lock} < \theta < 90^\circ$. Here, θ_{lock} refers to the locking angle which is the minimum angle permissible between warp and fill yarns, such that during a biaxial tensile test of a plain weave fabric, the fabric in-plane stiffness shows a sharp rise when the angle between the yarns reaches the locking angle. This is also caused by yarn jamming in a picture frame test where the fabric in-plane shear modulus shows a sharp rise at the locking angle.

Depending on the chosen yarn-yarn angle, even a single ply of sheared fabric under transverse impact may outperform an equivalent normal plain weave fabric that is gripped on two opposite sides or on all four corners, since in addition to usual modes of energy dissipation of a fabric as discussed earlier, the sheared fabric also utilizes the rotational interactions between the warp and fill yarns within a ply, termed as '*yarn reorientation*'. This accounts for an increased frictional energy dissipation due to yarn reorientation. Further, if the locking angle is reached before penetration, the sharp increase in fabric stiffness will lead to an increased fabric in-plane tension which provides the necessary retarding contact force against the projectile.

According to the Impulse-Momentum equation, the greater the contact force, the larger the deceleration of the projectile. Increasing the coefficient of friction between the warp and fill yarns through additives, surface treatments, or interfacial treatments known in the art may further enhance the rotational frictional energy dissipated, as well the sliding frictional energy dissipated by yarn pullout. Known treatments include but are not limited to polymeric film coatings including a polypyrrole, as described in U.S. Patent No. 6248676, treatment with a pyrrole

- 12 -

compound and an aniline compound as described in U.S. Patent No. 5225241, a combination of elastomer and plastic film coatings, as described in U.S. Patent No. 6846758, and corona or scouring treatments with or without fiber coatings, all of the foregoing patents incorporated by reference for their teachings with respect to

5 increasing of frictional coefficients of ballistic fabric yarns. As mentioned above, because of the increased inter-ply sliding and deformation interactions in a sheared fabric multiple ply system, the impact on total frictional sliding energy of increasing the friction coefficient is greater for sheared fabrics than for normal fabrics. Also, for the same in-plane dimensions, a sheared fabric ply has a larger areal density (mass per

10 unit fabric area) than a normal fabric ply, because of the decreased span or larger cover factor, which implies smaller gaps between the yarn cross over regions. This areal density increases with decreasing yarn-yarn angle θ . A higher areal density implies greater kinetic energy of the fabric system through momentum transfer, which further translates to enhanced performance. The smallest yarn-yarn angle permissible will be

15 constrained by the drapability of the fabric armor, however, since it must remain flexible enough to conform to the shape of the human extremities.

SIMULATED EXPERIMENTAL RESULTS

The improvements of the present invention over the conventional prior art are illustrated by specific embodiments of the invention as discussed herein. The

20 components of a typical experimental fabric ballistic impact test are illustrated in Fig. 12A, which is a schematic illustration depicting a fixture 120 to support fabric 122, a gas gun 124 to shoot projectile 126, and instrumentation, such as high speed cameras 128, to record the results. Fig. 12B depicts a perspective view of fixture 120 supporting a single ply fabric 122, and Fig. 12C depicts a perspective view of fixture

25 120 supporting a double-ply fabric consisting of plies 122A and 122B.

The advanced commercial dynamic finite element code LS-DYNA®, made by Livermore Software Technology Corp, of Livermore, California, was used to simulate this experimental ballistic impact event. The finite element analysis, in general, and this code, in particular, have been well-established for such purposes in the scientific

30 community and open literature. Using the simulation environment to highlight the superior performance of exemplary embodiments of the present invention was chosen to minimize human or operator interference that may introduce variability in the test set-up from one test to another, as well as to remove experimentally-induced uncertainties and errors into the test, that include but are not limited to: uneven fabric clamping pressures; non-alignment of the fabric within the grips; projectiles of varying

35 shapes, masses and impact velocities; calibration errors in the recording instrumentation; damaged fabric samples; variation in impact location around the

fabric dead center, et cetera. The simulation environment provides an unbiased, repeatable, and deterministic approach that also provides for the extraction of in-depth results and information not possible through experimental testing.

For example, the energy dissipated during the experimental ballistic impact of a fabric is often quantified using the simple equation:

$$\frac{1}{2}m_p(v_i^2 - v_f^2) = E$$

where m_p is the mass of the projectile assumed to remain constant, v_i is the initial or impact velocity, v_f is the final or residual velocity, and E is the energy dissipated by the fabric. Using only experimental instrumentation and analysis techniques, however, the quantity E cannot be easily partitioned into its various components, such as the fabric strain energy, fabric kinetic energy, and fabric frictional energy. These are the dominant components of energy dissipation, and an increase in any component can cause drastic improvements in ballistic performance. Such an aforementioned partition is possible, however, through the simulation environment. Components of the quantity E are very important in comparing the performance of fabric systems, in addition to other parameters, such as the V_{50} velocity and back face deformation.

For purposes of the simulation, a generic high strength plain weave fabric of in-plane dimensions 50.8 mm x 101.6 mm, having an areal density of 47 g/m² and a longitudinal elastic modulus of 62 GPa was chosen. The material properties were arbitrarily chosen and are not necessarily indicative of actual or desired material properties.

An event comprising a 5.334 mm diameter rigid spherical projectile of mass 0.63 gm at 106.3 m/s impacting at the center of the fabric was simulated. The fabric was modeled within the finite element code as a homogenous membrane using fully integrated shell elements with two through-thickness integration points. An orthotropic elastic material model was assigned to the shells. No failure criterion was incorporated, resulting in only non-penetrating impact scenarios. The two integration points of each shell represent the material directions, or more specifically, the warp and fill yarn directions. For a normal fabric, the two integration points were aligned along the warp and fill yarn directions by assigning angle values of 0° and 90°. For a sheared fabric, two integration points were assigned different angle values based on the specific examples used in this case study, such as ±15°, ±26.5°, ±35°, and so forth. The fabric boundary conditions were varied between gripping the two shorter sides and gripping all four sides. For multiple layers of fabric, the fabric was modeled as stacked identically in all layers (henceforth referred to as '*Identical*') or systematically rotated in each layer through the thickness (henceforth referred to as '*Rotated*'). Thus, for two

layers of fabric, the second layer was typically rotated by 45° or 90° in the counter-clockwise direction with respect to the first layer. The fabric velocity history, time at which the projectile is stopped, maximum fabric dynamic deflection or back face deformation, and fabric internal or strain energy history were recorded and used to compare the present invention against prior art.

Levels of fabric back face deformations are an important consideration in protective human torso applications, since large back face deformations can result in traumatic or fatal injuries classified as BABT or behind armor blunt trauma. Similarly, the V_0 velocity is an important consideration, which is defined as the highest velocity at which there is a zero percent probability of projectile penetration. This quantity can indirectly be assessed by considering non-penetrating impact cases and measuring the time taken to arrest the projectile completely. Limitations of this particular implementation of the simulation approach include (1) the homogenizing assumption that precludes yarn-yarn frictional interactions and (2) inability to account for yarn through-thickness compression and yarn reorientation effects. Other advanced simulation techniques are available that capture more detailed levels of interactions and mechanisms. For the limited purpose of presenting selected improvements of the present invention over prior art, however, the presently incorporated simulation technique was deemed sufficient. The use of more advanced simulation techniques may report further net improvements in ballistic performance over the prior art.

Modeling Case 1: Single layer fabric gripped on the two shorter sides

In simulated tests modeling a single layer of fabric held on the two shorter sides, for a sheared fabric as depicted in Fig. 13A and for a normal fabric as depicted in 13B, the model predicted that the sheared fabric would decelerate and stop the projectile faster than the normal fabric, as shown in Fig. 13C. The model predicted that the superior performance of the sheared fabric would increase with a decrease in the angle between the warp and fill yarns of the sheared fabric for this type of gripping condition. The model also predicted that sheared fabrics would develop greater magnitudes of internal or strain energies at faster rates than normal fabric, as shown in Fig. 13D.

Modeling Case 2. Two layers of fabric gripped on the two shorter sides

A second simulated experiment was modeled as two layers of fabric gripped on the two short sides, with one set of fabric layers sheared with identical ply orientation as depicted in Fig. 14A, one set normal with identical ply orientation as depicted in Fig. 14B, one set sheared with rotated ply orientation as depicted in Fig. 14C, and one set normal with rotated ply orientation as depicted in Fig. 14D. The

model predicted that the sheared fabric with identical ply orientation would decelerate and stop the projectile faster and have lower maximum fabric dynamic deflection or back face deformation as compared to the normal fabrics, as shown in Fig. 14E. The model also predicted that the sheared fabric with identical ply orientation would
5 develop a higher rate and magnitude of fabric internal energy than the normal fabrics (graphical results not shown).

Modeling Case 3. Two layers of fabric gripped on all four sides

Another simulated experiment was run comparing sheared and normal fabric with rotated and with identical second ply layers, similar to the Modeling Case 2
10 with the same relationships between fabric plies as illustrated in Figs. 14A-D, but this time with a boundary condition in which the fabric was gripped on all four sides instead of only on the shorter sides. The model in this case predicted that sheared fabric with the rotated ply orientations would stop the projectile faster, with greater deceleration, and with lesser maximum dynamic deflection or back face deformation than the normal
15 fabric, as shown in Fig. 15A. With the boundary condition of four gripped sides, the model also predicted that the sheared fabric with rotated plies would outperform the sheared fabric with identical ply orientations, in contrast to the simulation assuming two gripped sides, in which sheared fabric with identical plies outperformed the sheared fabric with rotated plies. In most practical applications of high strength fabrics, the
20 fabrics either have boundaries on all sides, or are left free on all sides (infinite domain assumption). Therefore, the sheared fabric case with varying ply orientations is expected to be the most effective predictor of ballistic fabric results in real world applications. The working of the invention may be better understood with reference to the graphical results shown in Figs. 15B, 15C, and 15D.

As shown in Fig. 15B, the model predicts that 15° sheared fabric with
25 rotated ply orientations decelerates and stops the projectile much faster than the 15° sheared fabric with identical ply orientations. To understand one source of this improvement, the individual fabric strain energies of each layer were partitioned for further analysis. For the case where the ply orientation is the same in both layers, the
30 model predicts that the strain energies of both layers is almost the same in magnitude during the entire time event, as shown in Fig. 15D. This is expected because the deformations of both layers are alike. For the case of the 15° sheared fabric with rotated ply orientations, however, the bottom layer is predicted to develop strain energy at a much faster rate and reach a higher magnitude. This is believed to be
35 because, in addition to the deformation pyramid that grows within this bottom layer due to its own warp and fill yarn orientation, added deformation is induced in this layer due to the top layer, whose deformation pyramid is non-aligned, at right angles to, the

deformation pyramid of the bottom layer. This is believed to cause increased inter-layer interactions, increased bottom layer deformations, and increased inter-layer pressures, which directly translates into a faster deceleration and stopping of the projectile, as predicted by the model. This is further understood by Fig. 15D, which
5 illustrates the inter-layer contact forces developed due to layer-layer interactions during the fabric impact event. The highest magnitudes and rates of growth of inter-layer contact forces are observed for the sheared fabric case with rotated ply orientations. For the normal and sheared fabric cases with identical ply orientations, since the deformations are alike in both layers, the inter-layer contact forces remain
10 smaller in relative magnitude.

While the improvements of the present invention were demonstrated using simulated experiments at a yarn-yarn angle of 15° for a generic fabric, with one to two layers, and with fixed-fixed or fixed-free boundary conditions, the final yarn-yarn angle that yields optimal performance over a normal fabric may vary depending
15 on the type of fabric weave architecture and material properties of the yarns. The yarn-yarn angles and ply orientations chosen in these examples are in no way meant to limit the overall scope or applicability of the invention, and are not indicative of the magnitudes of yarn-yarn angles and ply orientations that may yield significant improvements over conventional arrangements in prior art. Rather a broad range of
20 yarn-yarn angles below 90° and many different ply orientation patterns may lead to significant improvements over conventional arrangements. Finally, the relatively small in-plane dimensions and few number of fabric layers chosen for the simulations are merely for illustrative purposes and are in no way indicative of the actual overall size or shape of a ballistic fabric system. In fact, the significant improvements predicted for
25 the present invention over small in-plane fabric dimensions and only a few number of fabric layers, is only expected to scale further upwards with the size of the fabric and number of layers in a typical commercial ballistic fabric system.

OTHER MODIFICATIONS

In addition to the architectural modifications discussed so far, several
30 material modifications may be used in fabric armor 100 through varying the high performance material used in each sheared plain weave fabric ply to further enhance performance. During the ballistic impact of multiple plies of a fabric system, it is possible that the first few (impacted) or last few plies fail earlier than the remaining plies, decreasing the performance of the system. This is because once a ply fails, it no
35 longer contributes in any significant way to the fabric system energy dissipation process, even if the plies are stitched together. It is therefore more desirable for all plies to fail together, thereby maintaining structural integrity for as long as possible

until failure and increasing the elastic strain energy and inertial effects of the fabric armor, since a greater mass of fabric plies are involved in resisting the impacting projectile. If the top few plies fail earlier than the remaining plies, by decreasing the stiffness of the plies, or by increasing the strain-to-failure of the plies, or a combination of both, the yarns in the top few plies may fail at a later time during the impact event, and closer to or the same time that the lower plies failed. If however the lower plies fail earlier, then a similar material modification may be made to them. The desired change in material properties may be accomplished by choosing different variants of materials but within the same class. For example, KEVLAR® aramid fibers have many variants such as KEVLAR® 49, KEVLAR® 129, and KEVLAR KM2® aramid fibers, each with distinctive material properties such as denier, stiffness, and strength. Or, completely different materials may be used altogether, such as a mixture of aramid and UHMWPE.

Fig. 9 illustrates a cylindrical projectile 90 impacting multiple plies of a fabric target 91 resting on a backing material 92. At a high impact velocity, the mode of yarn failure for the top few plies may be predominantly by a shearing mechanism. A plug shaped region indicated by dashed lines in Fig. 9. in the top few plies of fabric target 91, further depicted by dimension 95, corresponds to the region where the shear mode of yarn failure is predominant. This region experiences yarn failure very quickly, and the yarns outside this plug do not contribute to further energy dissipation once the yarns within the plug fail. Beyond this, the deformation and corresponding failure mode transitions over dimension 96 from a shearing to a tensile mode. A tensile mode of yarn deformation always dissipates far greater strain energy than a shear mode of yarn deformation. Within the fabric target 91 region indicated by dimension 97, the deformation mode is predominantly tensile, with the formation of the characteristic deformation pyramid. This fabric deformation pyramid causes a deformation in the backing material 92. This is used to measure back face deformation. Clearly the energy dissipated by the fabric target 91 in region depicted by dimension 95 and dimension 96 is much less than that depicted by dimension 97.

While the aforementioned technology improves the projectile resistance of any fabric consisting of any type of yarn material, embodiments of this invention may yield particularly desirable results using a yarn material that has a denier of at least 450, areal density of at least 150 g/m², longitudinal elastic modulus of at least 50 GPa, and strain-to-failure of at least 2.2% and at most 4.0%. Such materials may be referred to as "high strength," "high modulus," or "high performance." The invention is not limited, however, to any particular ranges of denier, areal density, elastic modulus, or strength. In order to prevent the top few plies from failing much earlier, materials

that absorb more energy during high energy impacts that cause yarn failure by a shearing mechanism, such as ultra high molecular weight polyethylene (UHMWPE), may be used in the upper few plies, while a material that absorbs more energy during low energy impacts that cause yarn failure by a tensile elongation mechanism, such as an aramid or PBO material, may be used in the remaining lower plies. Thus a fabric target 100 that is comprised of different high performance materials in different plies may have a superior ballistic resistance compared to fabric targets comprised of the same high performance material in all plies. Specifically, the warp yarn and fill yarn in a topmost ply may comprise a material having a lesser stiffness than the materials used in the lower plies, with the stiffness progressively increasing through the armor thickness. Similarly, the yarn in a topmost ply may have the highest strain-to-failure of all the plies, with the strain-to-failure progressively decreasing through the armor thickness. Likewise, the yarns may have progressively decreasing stiffness and/or progressively increasing strain-to-failure, or may change in a predetermined pattern across the thickness of the armor system.

If the mode of deformation and failure of the top few plies is forced from a shear mode into a tensile mode, however, the overall performance of the fabric target may be further increased. This may be accomplished by using a soft filler material within the top few plies of the fabric target. For example, the filler may be located between an upper plurality of plies and a lower plurality of plies, wherein the total thickness of the plies above the filler constitute less than a quarter of a total thickness of the armor. Referring to Fig. 10, a compliant material 99 is placed between two plies near the impacted face of the fabric target 91. By doing so, the overall transverse stiffness of the fabric target is reduced. Upon impact, the top few plies will preferentially deform under tension since the filler material 99 is compliant and has a very small transverse stiffness, implying it can be easily compressed. In such a case the entire fabric target depicted by dimension 98 will deform in a tensile mode, consequently the overall energy dissipation of such a fabric target in Fig. 10 will be greater than that of Fig. 9. Because it is preferable to keep the total thickness of the fabric armor to a minimum, it is desirable to minimize the thickness of filler material 99, while still having enough filler material to achieve the benefits discussed above. For example, and without limitation, filler material thickness in the range of two to six times the thickness of a single ply, and, in particular, four times the thickness of a single ply may be advantageous. Further, the filler material 99 may be lighter than the high performance material (i.e. its areal density may be less than the equivalent areal density of a fabric ply) so as not to add weight to the fabric armor, since it is preferable that the fabric armor be as light weight as possible. The filler material may typically

have a stiffness and a bulk modulus that are considerably lower (softer) than that of the fabric plies. The filler material may be stitched to either the plies above it, or the plies below it, or to both plies above and below, but the use and location of stitching will not materially affect the general effectiveness of using a filler material.

5 As shown in Fig. 11, the filler material may also comprise one or more single plies of fabric 110 cut into strips or pieces having a shape corresponding to the stitching pattern, such that the cut piece or pieces of the filler fabric ply fit between upper and lower plies (not shown) entirely inside the periphery of one cell 114 of the stitching pattern without being fastened to the upper or lower ply by the stitching.

10 When the projectile reaches the filler ply, the unencumbered cut pieces of fabric 110 are pushed forwards by the projectile and will encapsulate the projectile, should the plies below the filler ply fail. This increases the surface area of the projectile's impacting face which also partially blunts the overall shape of the impacting face. As the projectile penetrates through plies, there is a significantly increased frictional
15 dissipation between the projectile encapsulated with the fabric piece from the filler ply and the fabric plies, compared to the case of the projectile penetrating through the fabric plies without this filler ply piece. The filler ply piece thus further retards the projectile's motion and thereby enhance the performance of the fabric armor.

 Although shown in Fig. 11 with a square or diamond stitching pattern
20 (dependent upon the point of reference), this embodiment is not limited to any particular stitching pattern. Although not limited to any particular cell size, it will be understood that a stitching pattern with cells too small or too large may be less adept at encapsulating the projectile, but standard stitching patterns that have an area of 1 to 4 inches (sides 1 to 2 inches long) are suitable. Also, while the filler ply may be any
25 shape, an ideal shape is one that fills the area created by the stitching pattern as much as possible, with sufficient room to allow for standard tolerances in the precision of the stitching operation to make sure that the filler plies are not captured in the stitching. During manufacturing, a small amount of resin or other sticky substance may be used to keep the filler plies in place on the bottom ply while the top ply is placed overtop and
30 the top and bottom plies are stitched together.

 The yarn-yarn angle θ may also be varied between plies. It may be preferable to increase the yarn-yarn angle from the top ply to the bottom ply, or vice versa, or to vary the yarn-yarn angle in a predetermined pattern along the thickness of the system. It is also possible to combine plies of normal plain weave fabrics with plies
35 of sheared plain weave fabrics in the fabric armor. In such a case it may be preferable to use the normal plain weave fabrics in the lower few plies of the fabric armor. In this disclosure, the mechanisms have been exemplified with respect to a plain weave fabric,

however they are still valid for other architectures such as but not limited to sheared fabric, satin harness, twill weave, basket weave and the like. Thus, a suitable ballistic resistant armor of this invention may comprise a plurality of plies all comprising a plain weave architecture, which may be balanced or unbalanced, all of the plies may be a
5 satin harness or some other architecture, or the plies may comprise a mixture of plain weave and other architectures.

While stitching is not necessary to the working of the fabric armor, it is preferable to hold the various fabric plies together. Furthermore, by varying the pattern of stitching, the performance may be enhanced. This includes unidirectional
10 stitching, or using patterns of rectangular or diamond shape. All the layers may be stitched together, or only selective plies may be stitched together. In high velocity impacts where the top plies fail earlier, a smaller or tighter pattern of stitching may be used so as to couple the top few layers to the remaining plies below, so that even after the top few layers fail, they still contribute in some part to the overall energy
15 dissipation process. However a bigger or looser pattern of stitching may be used for the lower plies.

Finally, it should be understood that a number of architectural and material variations are discussed herein, each of which may comprise an improvement over the prior art standing alone, and each of which may be used in some combination
20 with one another. For example, improvements may be effected simply by using a yarn-yarn-angle of less than 90°, by using different yarn-yarn angles in different plies, by varying the materials of construction from ply to ply as described herein, by using fillers and/or filler pieces as discussed herein, by varying the stitching as discussed herein, and so on. Accordingly, while combinations of the various aspects discussed herein
25 may provide better performance than use of any one alone, the invention is not limited to any particular combination of features.

This presented invention disclosure and exemplary embodiments are meant for the purpose of illustration and description. The invention is not intended to be limited to the details shown. Rather, various modifications in the illustrative and
30 descriptive details, and embodiments may be made by someone skilled in the art. These modifications may be made in the details within the scope and range of equivalents of the claims and without departing from the invention.

What is Claimed:

1. A woven ballistic resistant fabric armor system comprising a plurality of plies together defining a thickness, at least one ply comprising warp yarns and fill yarns having a yarn-yarn angle between them of less than 90° , each ply having
5 a ply orientation of the warp and fill yarns relative to an axis along the thickness, wherein adjacent plies have (a) a different yarn-yarn angle, (b) a different ply orientation, or (c) a combination of (a) and (b).
2. The woven ballistic resistant fabric armor system of claim 1, wherein the minimum yarn-yarn angle is greater than a locking angle of the yarns.
- 10 3. The woven ballistic resistant fabric armor system of claim 1, wherein:
each ply has (a) an angle bisector that bisects the yarn-yarn angle for that ply and (b) a reference vector that is parallel to corresponding reference vectors for each other ply, and
15 successive fabric plies are rotated relative to one another in a rotation pattern in which the angle bisectors for the first, second, third and fourth plies are aligned relative to the reference vectors at angles of 0° , 90° , $+45^\circ$, and -45° respectively, and the angle bisectors of any additional successive plies repeat the same rotation pattern as the first through fourth plies.
- 20 4. The woven ballistic resistant fabric armor system of claim 1, wherein
each ply has (a) an angle bisector that bisects the yarn-yarn angle for that ply and (b) a reference vector that is parallel to corresponding reference vectors for each other ply, and
25 successive fabric plies are rotated relative to one another in a rotation pattern in which the angle bisectors for the first and second plies are aligned relative to the reference vectors at angles of 0° and 90° , respectively, and the angle bisectors of any additional successive plies repeat the same rotation pattern as the first and second plies.
- 30 5. The woven ballistic resistant fabric armor system of claim 1, wherein:
each ply has (a) an angle bisector that bisects the yarn-yarn angle for that ply and (b) a reference vector that is parallel to corresponding reference vectors for each other ply, and
35 successive fabric plies are rotated relative to one another in a rotation pattern in which the angle bisectors for the first through eighth plies are aligned relative to the reference vectors at angles of 0° , 90° , $+45^\circ$, -45° , $+22.5^\circ$, -22.5° ,

+67.5°, and -67.5°, respectively, and the angle bisectors of any additional successive plies repeat the same rotation pattern as the first through eighth plies.

6. The woven ballistic resistant fabric armor system of claim 1, wherein none of the plurality of fabric plies have the same yarn-yarn angle.

5 7. The woven ballistic resistant fabric armor system of claim 1, wherein all of the plurality of fabric plies have the same yarn-yarn angle.

8. The woven ballistic resistant fabric armor system of claim 1, comprising a topmost ply relative to a potential projectile impact, wherein the respective yarn-yarn angles of plies beneath the topmost ply are progressively less than an adjacent ply above, progressively greater than an adjacent ply above, or different from one another in a predetermined pattern.

9. The woven ballistic resistant fabric armor system of claim 1, wherein at least two plies are stitched together.

10. The woven ballistic resistant fabric armor system of claim 1, wherein all plies are stitched to at least one other ply.

11. The woven ballistic resistant fabric armor system of claim 9, wherein the at least two plies are stitched together in a stitching pattern comprising parallel unidirectional lines, or a square, rectangular, or diamond shape.

12. The woven ballistic resistant fabric armor system of claim 10 having an armor thickness, comprising:

a first plurality of plies stitched together in a first stitching pattern, the first plurality including a topmost ply relative to a potential projectile impact, an intermediate ply above a mid-plane of the armor thickness, and all plies between the topmost ply and the intermediate ply, and

25 remaining plies below the intermediate ply stitched together in second stitching pattern, wherein the second stitching pattern differs from the first stitching pattern with respect to shape or size of the stitching pattern.

13. The woven ballistic resistant fabric armor system of claim 1, comprising a topmost plurality of plies relative to a potential projectile impact separated from a bottommost plurality of plies by a filler material, wherein the topmost plurality comprises fewer plies than the bottommost plurality and the topmost plurality has a thickness that is not more than a quarter of a total thickness of the armor.

14. The woven ballistic resistant fabric armor system of claim 13, wherein the filler material has a thickness in a range of two to six times a single ply thickness, has an areal density less than an equivalent areal density of a single fabric ply, and has a stiffness and a bulk modulus less than a single fabric ply.

15. The woven ballistic resistant fabric armor system of claim 13, wherein the filler material is stitched to plies above, plies below, or a combination thereof.

16. The woven ballistic resistant fabric armor system of claim 13,
5 wherein the filler material comprises a plurality of fabric ply pieces, each piece sized and positioned to fit completely within a cell periphery created by a stitching pattern, wherein at least adjacent plies directly above and directly below the filler material are stitched together using the stitching pattern.

17. The woven ballistic resistant fabric armor system of claim 1,
10 wherein all warp yarns and fill yarns in all of the plurality of plies comprise a same single high strength and high modulus material.

18. The woven ballistic resistant fabric armor system of claim 1, wherein less than all warp yarns and fill yarns in all of the plurality of plies comprise a same single high strength and high modulus material.

19. The woven ballistic resistant fabric armor system of claim 18,
15 wherein the warp yarn and fill yarn in an upper plurality of plies relative to a potential impact comprise a first material and the warp yarns and fill yarns in a lower plurality of plies comprise a second material, the first material relative to the second material characterized by greater absorption of energy during high energy impacts that cause
20 failure by a shearing mechanism, the second material relative to the first material characterized by greater absorption of energy during low energy impacts that cause yarn failure by a tensile elongation mechanism.

20. The woven ballistic resistant fabric armor system of claim 1 having an armor thickness, wherein the warp yarns and fill yarns in a topmost ply
25 relative to a potential impact have a first stiffness, and lower plies beneath the topmost ply each comprise warp yarns and fill yarns having a corresponding stiffness, wherein the corresponding stiffness progressively increases through the armor thickness, progressively decreases through the armor thickness, or varies throughout the armor thickness in a predetermined pattern.

21. The woven ballistic resistant fabric armor system of claim 1
30 having an armor thickness, wherein the warp yarns and fill yarns in a topmost ply relative to a potential impact have a first strain-to-failure, and lower plies beneath the topmost ply each comprise warp yarns and fill yarns having a corresponding strain-to-failure, wherein the corresponding strain-to-failure progressively increases through the
35 armor thickness, decreases through the armor thickness, or varies throughout the armor thickness in a predetermined pattern.

22. The ballistic resistant armor of claim 1, wherein the warp yarn and fill yarn comprise one or more surface treatments, additives or interfacial treatments that increase a coefficient of friction between the warp and fill yarns relative to yarns without such treatments or additives.

5 23. The ballistic resistant armor of claim 1, wherein the warp yarn and fill yarn comprise a material having a denier of at least 450, an areal density of at least 150 g/m², a longitudinal elastic modulus of at least 50 GPa, and a strain-to-failure of at least 2.2% and at most 4.0%.

10 24. The ballistic resistant armor of claim 1 comprising a flexible, dry fabric armor system.

25. The ballistic resistant armor of claim 1, comprising a flexible fabric armor system comprising one or more plies partially impregnated with resin.

26. The ballistic resistant armor of claim 1, comprising a rigid fabric armor system comprising one of more plies fully impregnated with resin.

15 27. The ballistic resistant armor of claim 1, wherein the armor comprises body armor wearable by a user.

28. The ballistic resistant armor of claim 1, wherein the armor comprises an engine casing.

20 29. The ballistic resistant armor of claim 1, wherein the armor comprises a lining for an airplane fuselage.

30. The ballistic resistant armor of claim 1, wherein the armor comprises a spall liner for a vehicle.

31. The ballistic resistant armor of claim 1, wherein each of the plies comprises a plain weave architecture.

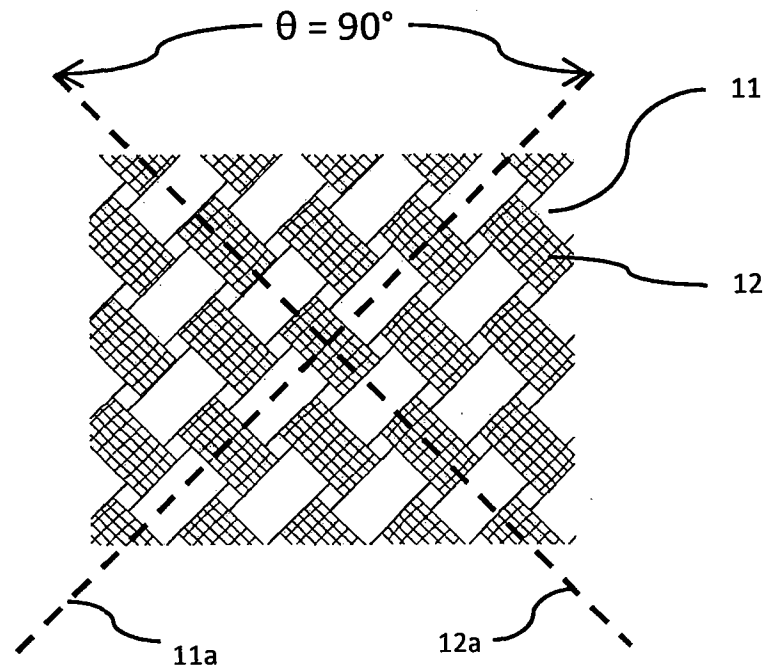


FIG 1

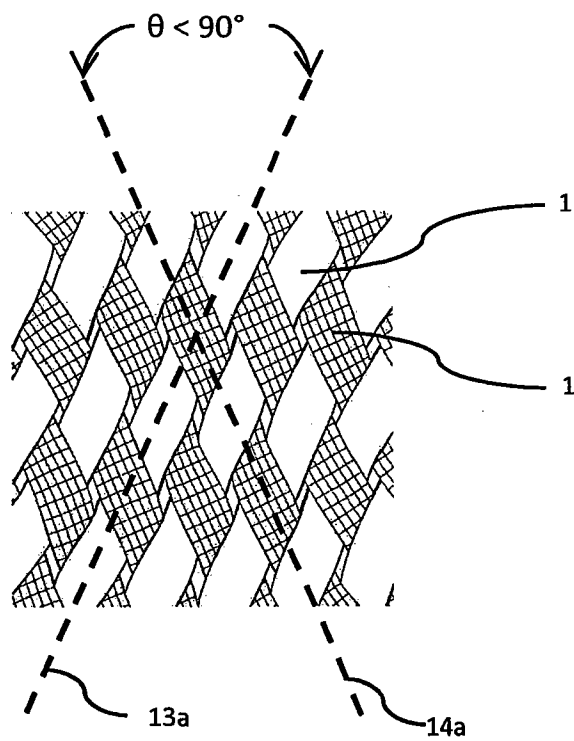


FIG. 2

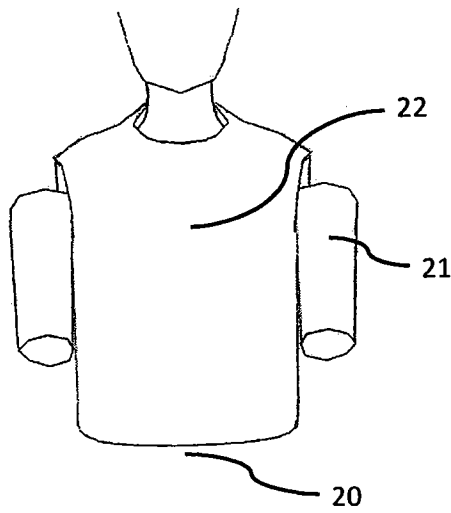


FIG. 3

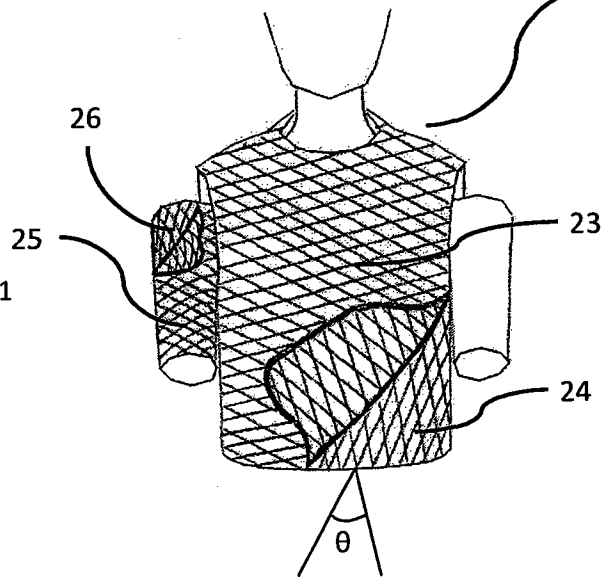


FIG. 4

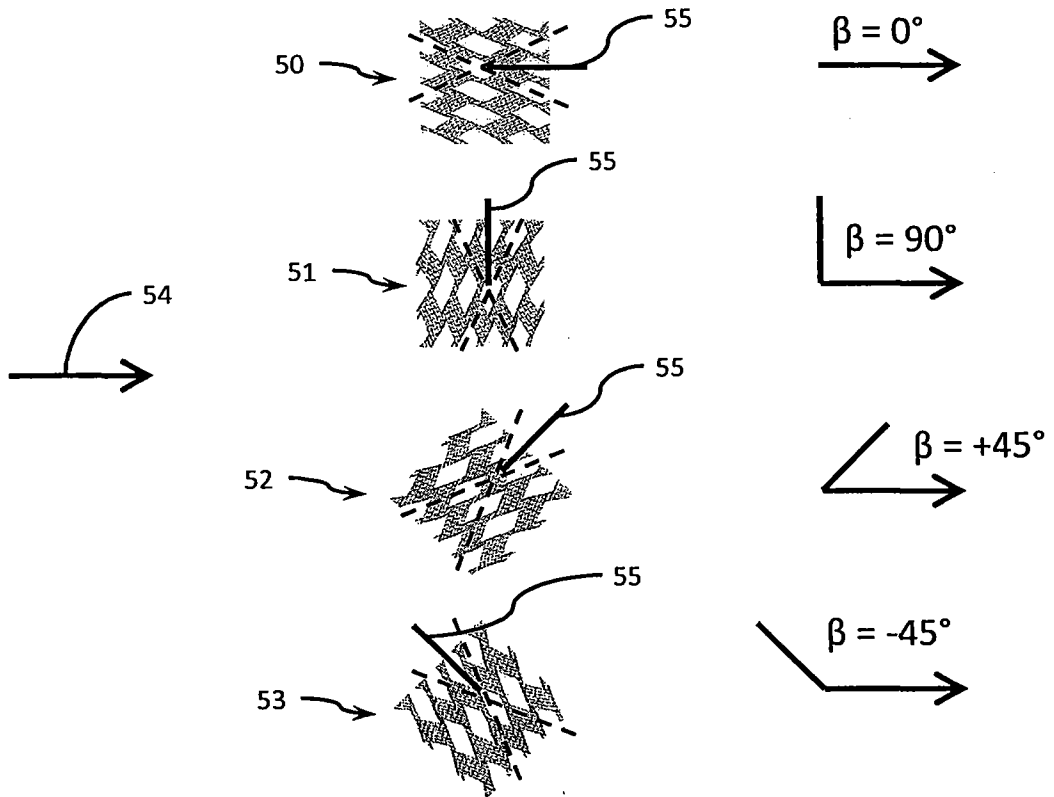


FIG. 5

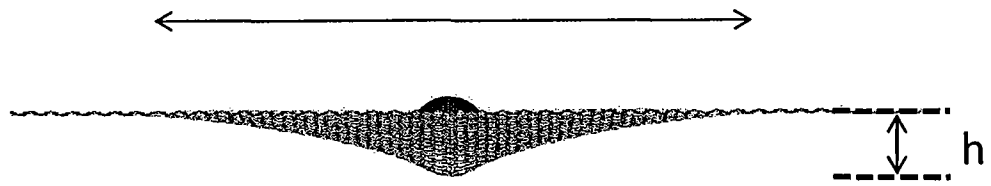


FIG. 6A

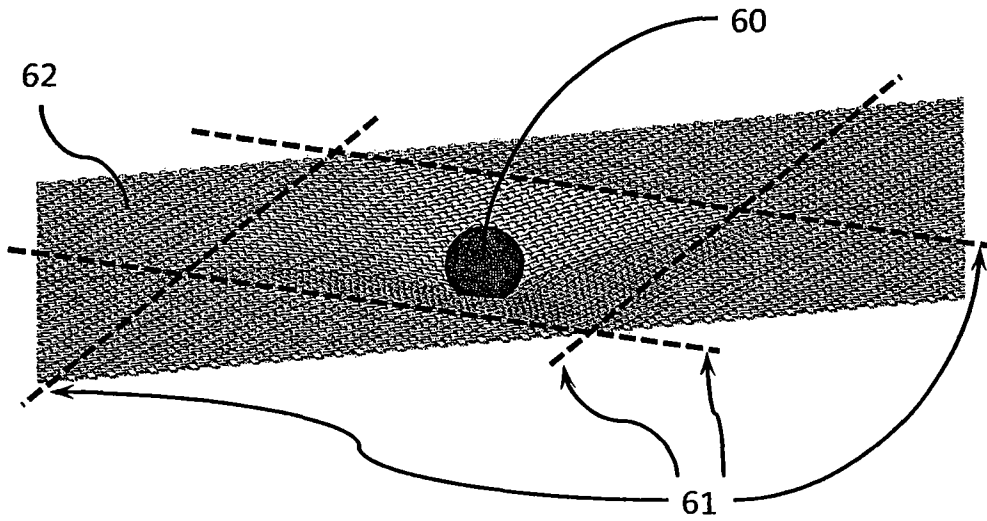


FIG. 6B

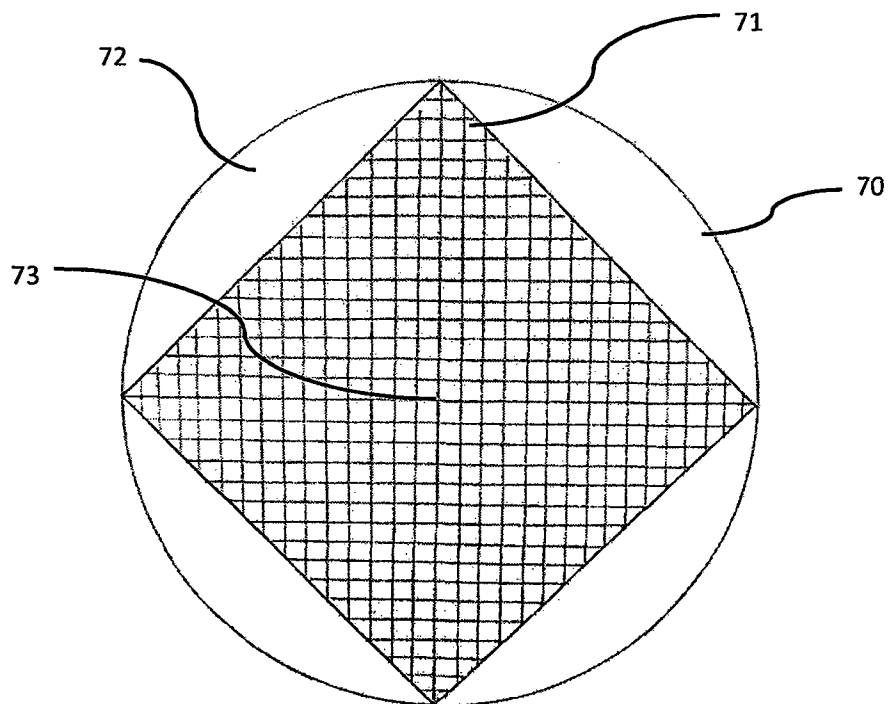


FIG. 7

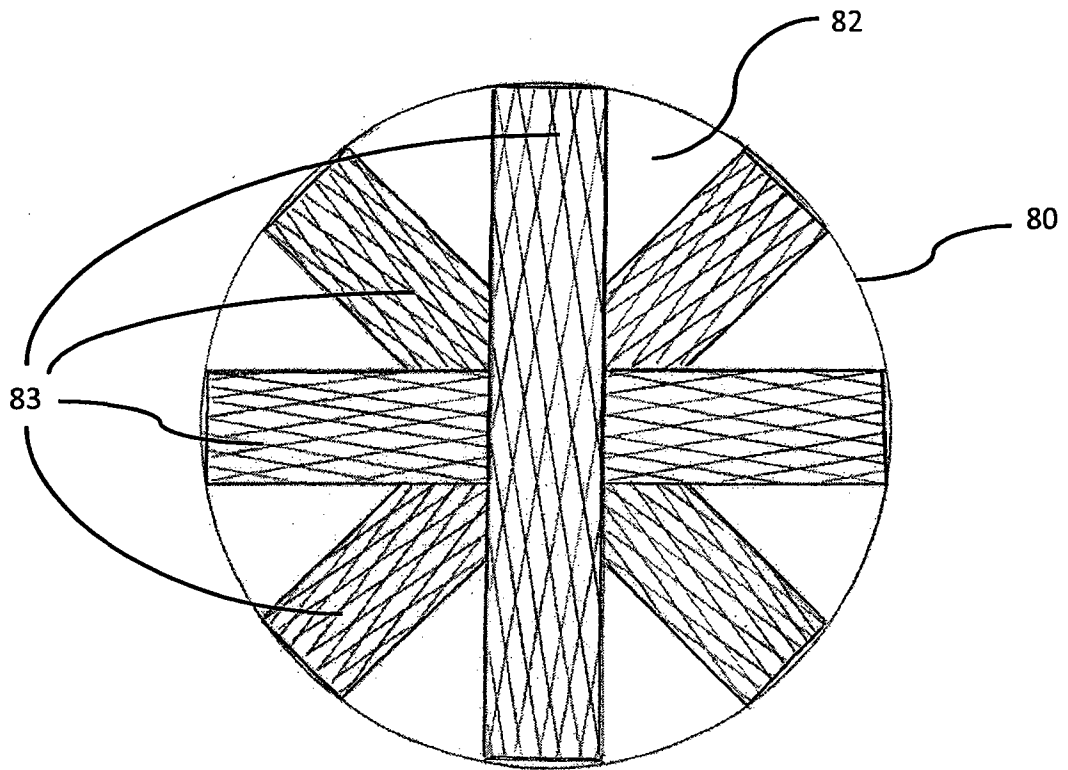


FIG. 8

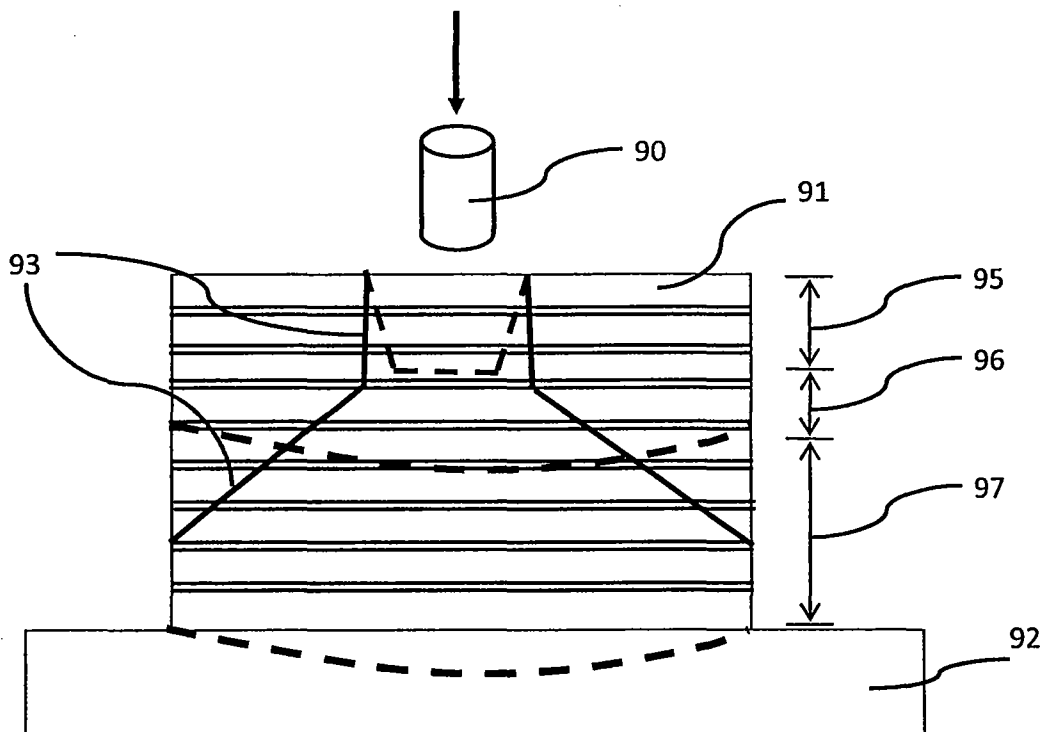


FIG. 9

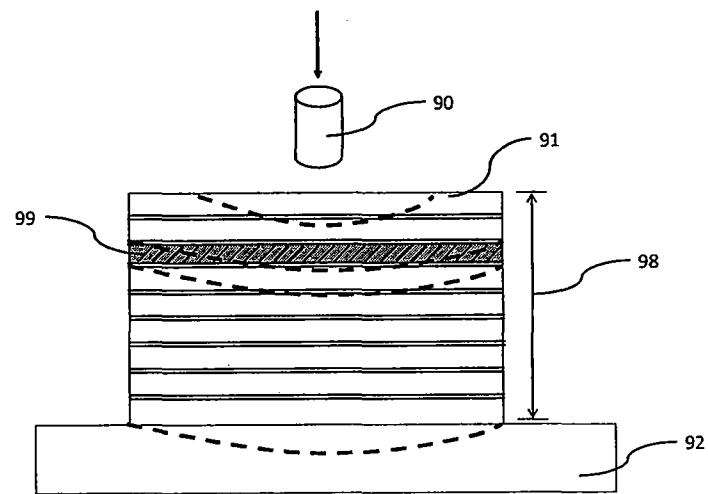


FIG. 10

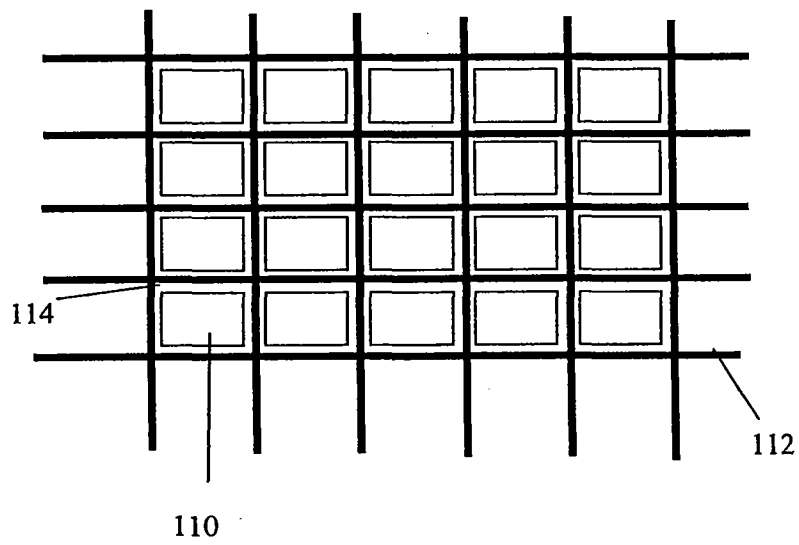


FIG. 11

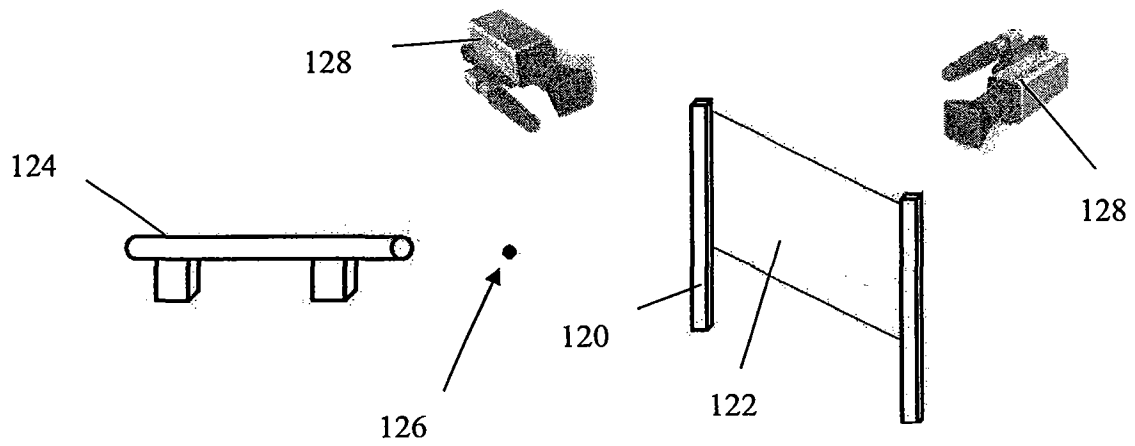


FIG. 12A
(PRIOR ART)

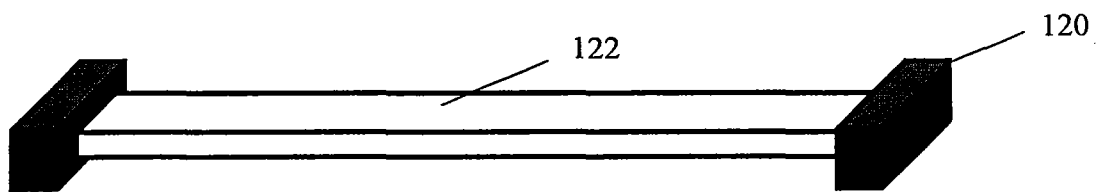


FIG. 12B
(PRIOR ART)

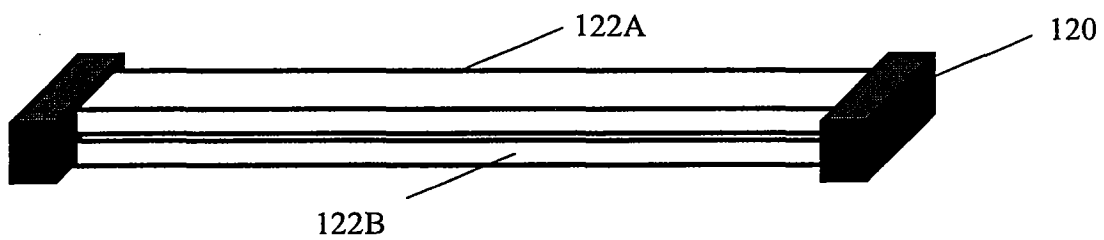


FIG. 12C
(PRIOR ART)

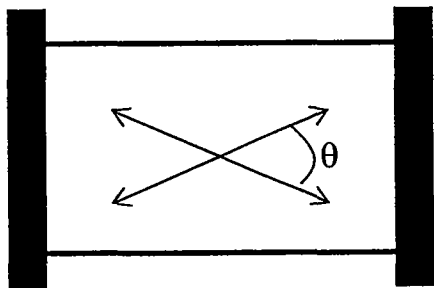


FIG. 13A

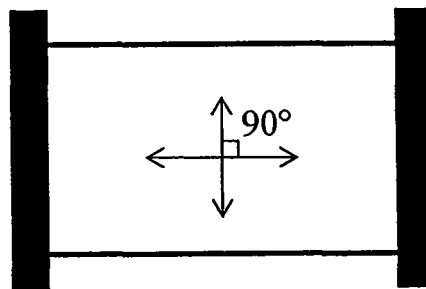


FIG. 13B

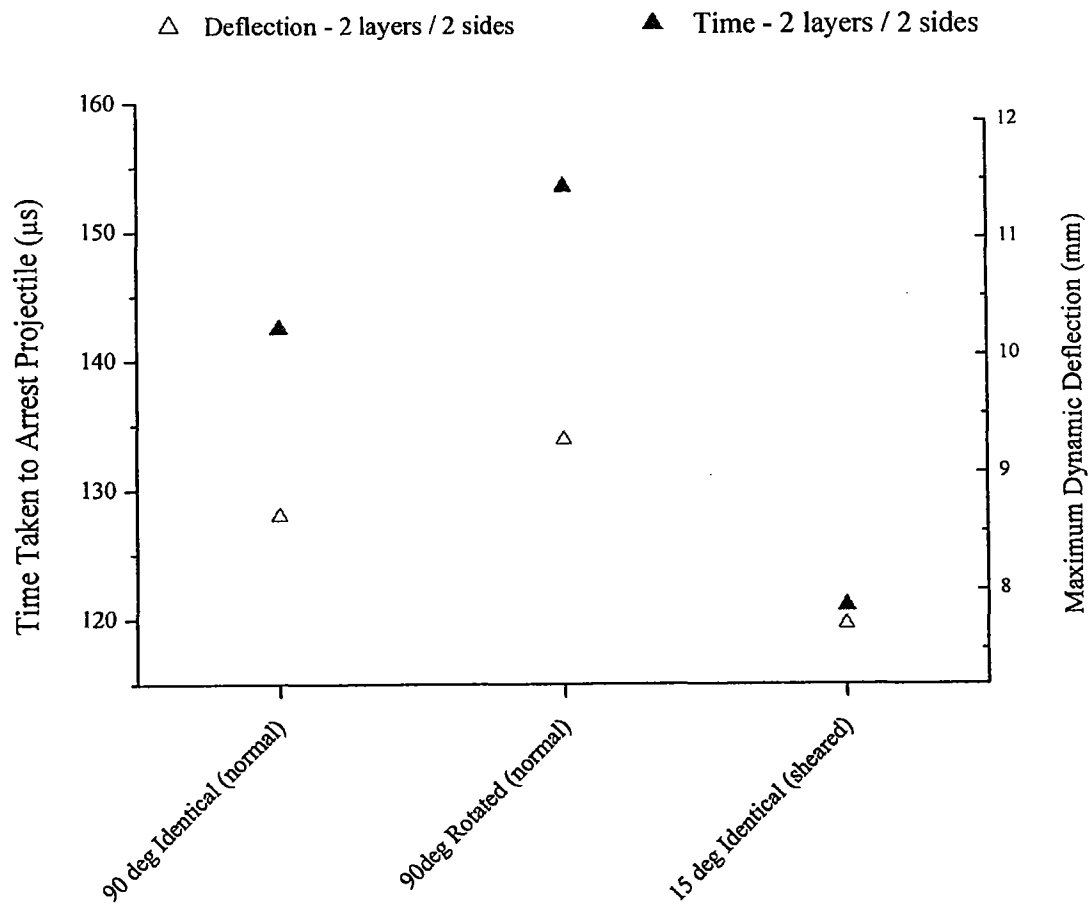


Fig. 14E

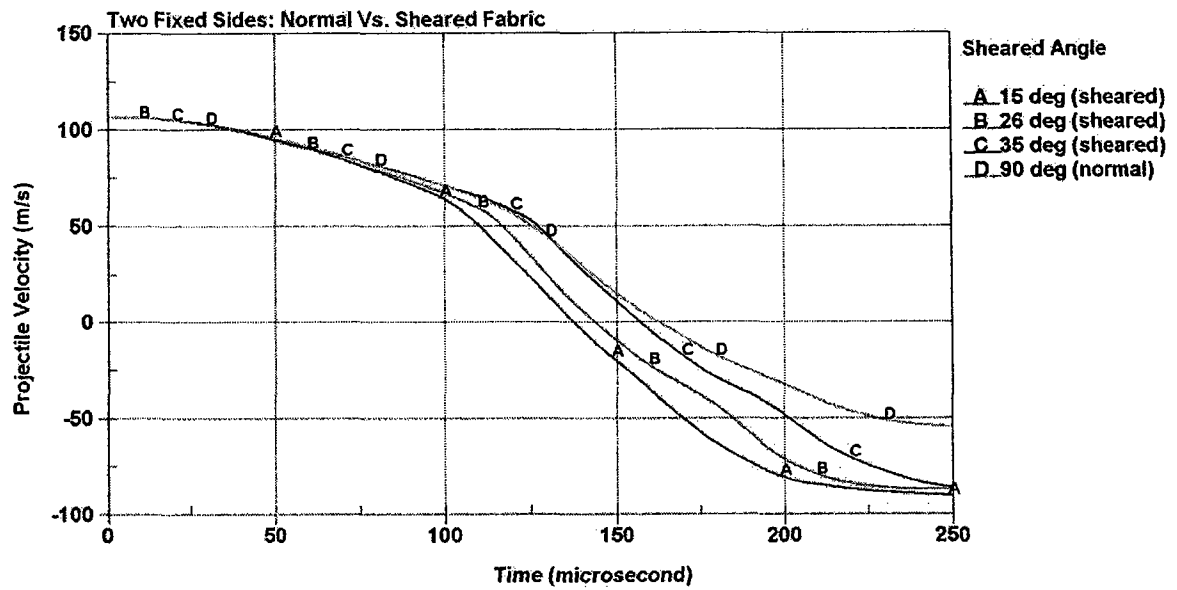


FIG. 13C

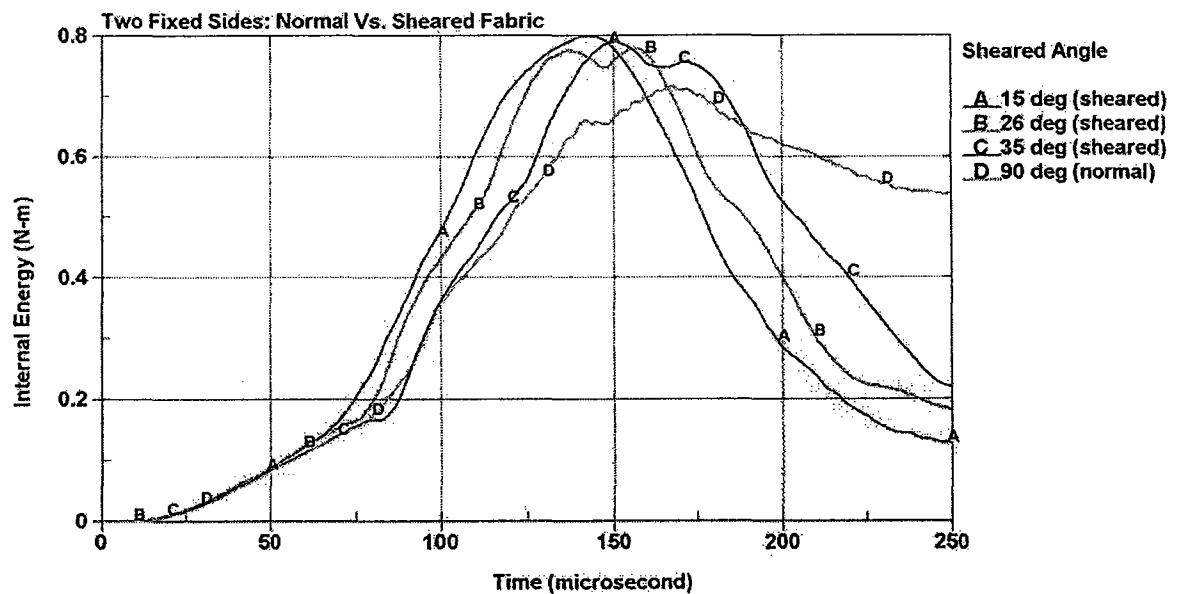


FIG. 13D

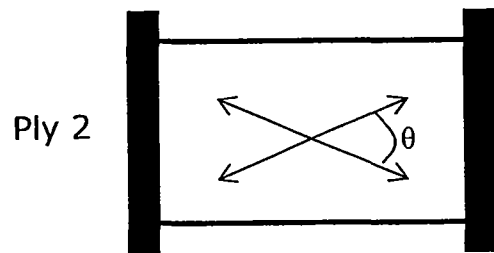
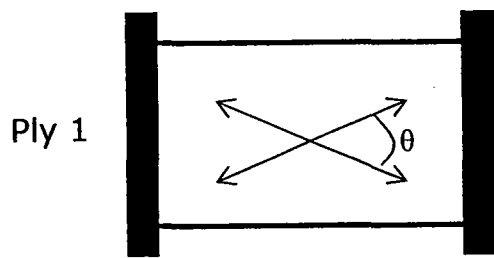


Fig. 14A

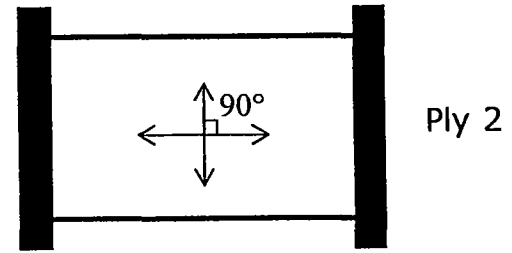
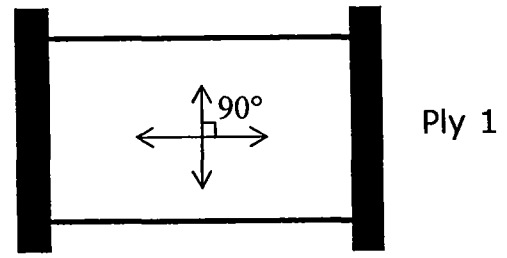


Fig. 14B

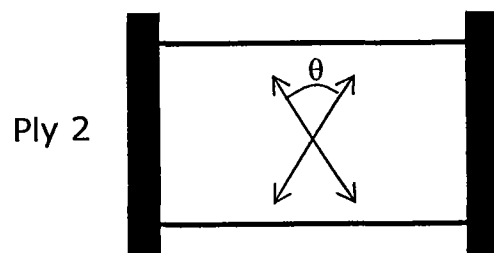
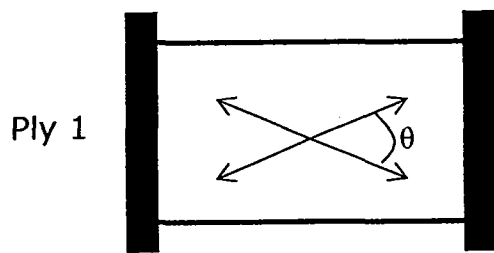


Fig. 14C

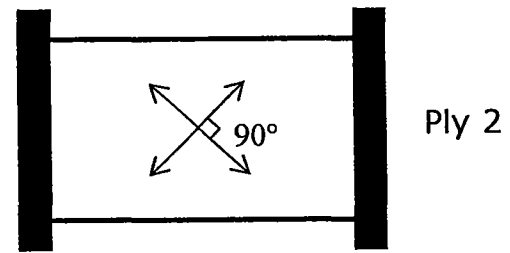
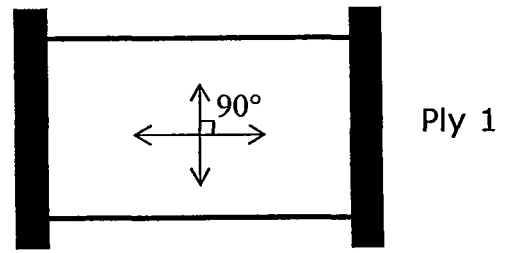


Fig. 14D

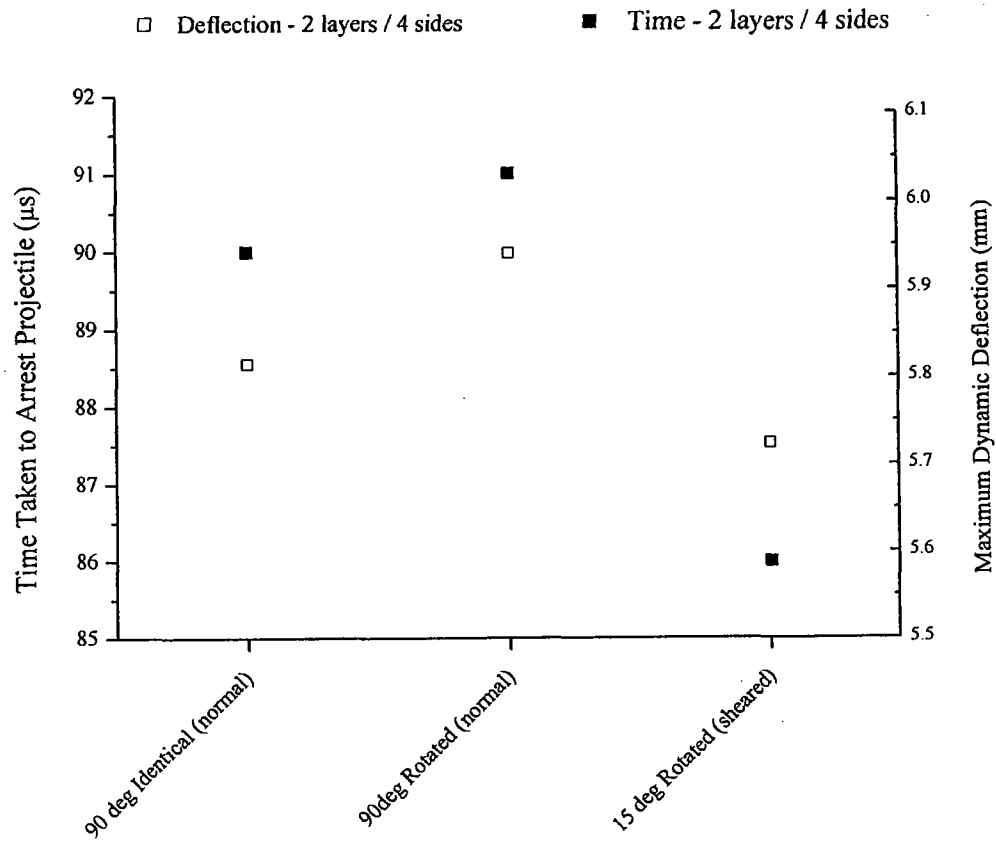


FIG. 15A

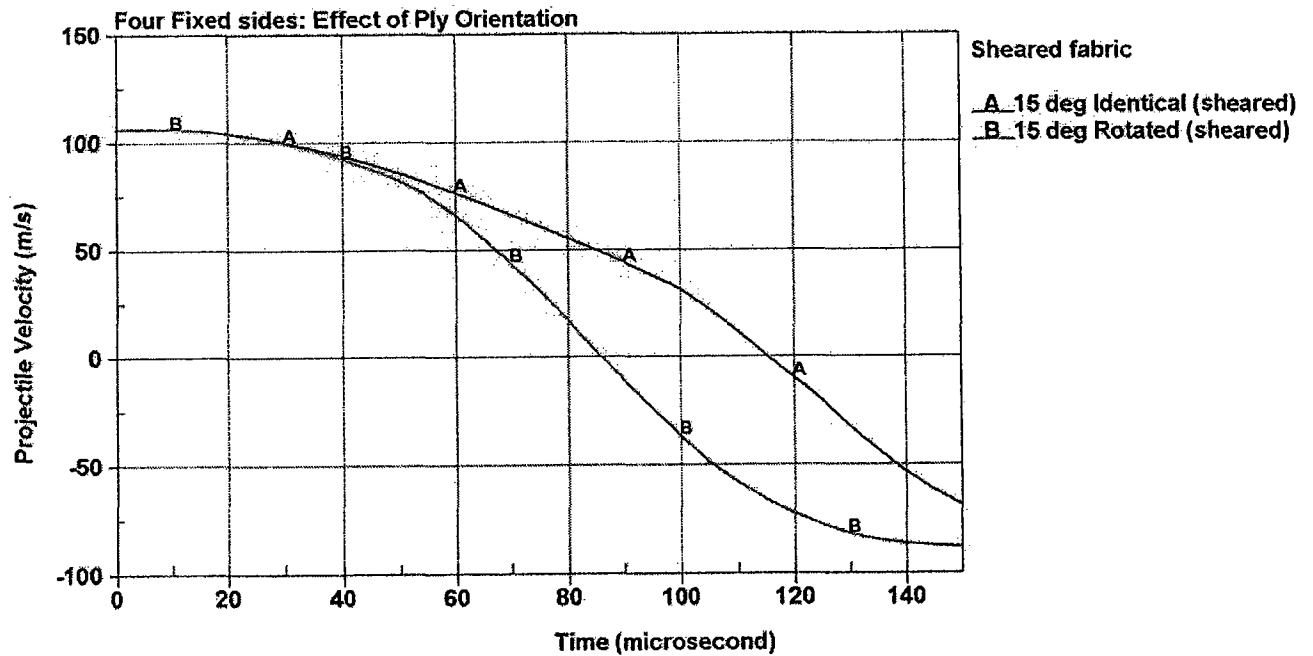


FIG. 15B

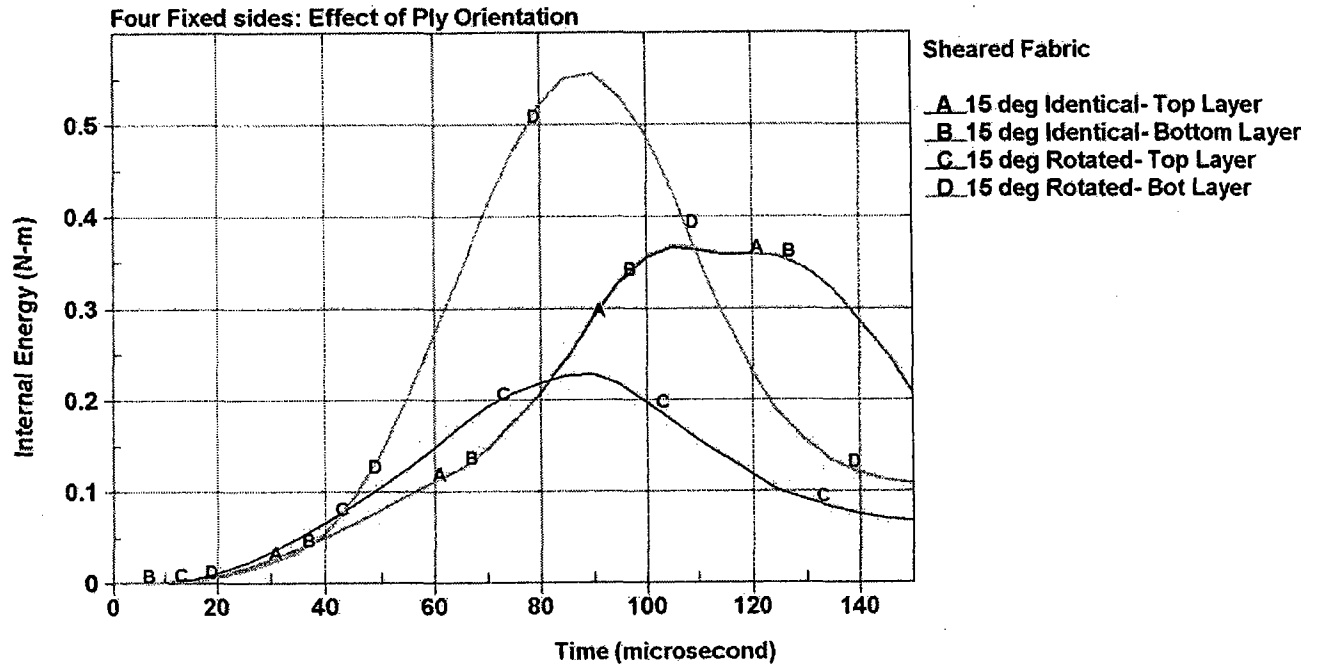


FIG. 15C

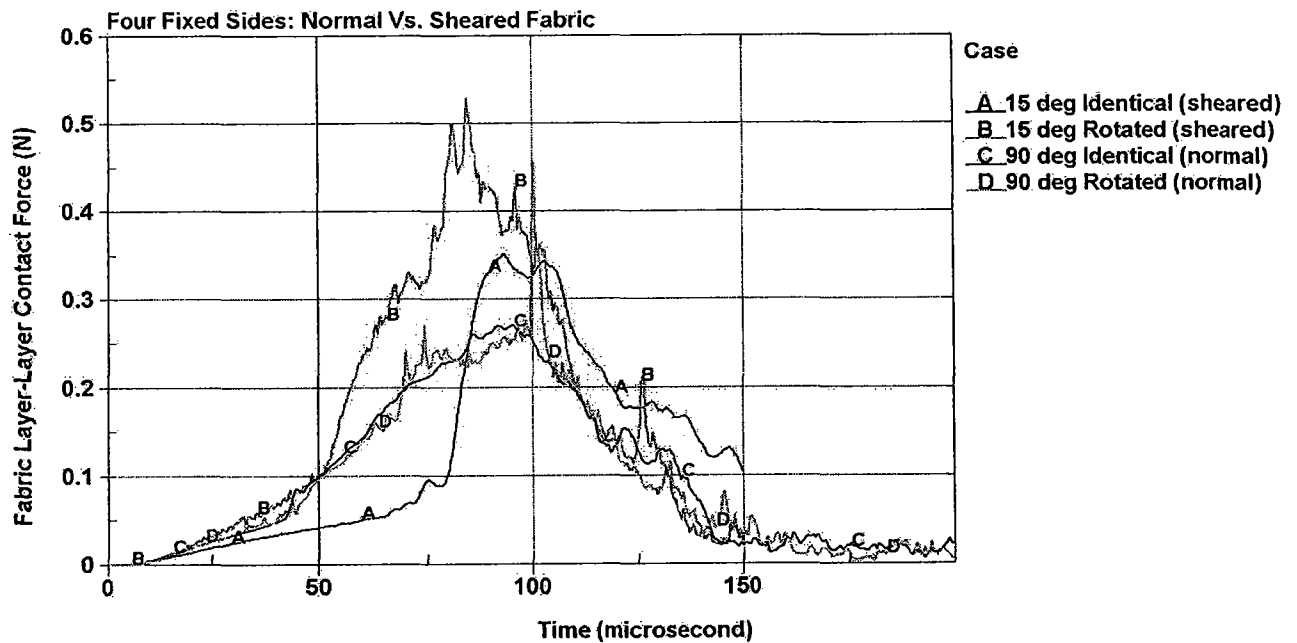


FIG. 15D