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Penetration of Multi-Layered E-Glass Armors by Small Projectiles

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ABSTRACT

Ballistic targets were designed based on Multilayer E-glass fabrics with different layer structures. The fabrics were almost designed according to a base of constant weights/ area of square meter for each multilayer category. The main fabric constructions used were the Plain and satin 4 weave. Each type of Fabric samples were tested for their mechanical properties; tensile strength, tearing resistance, in addition to ballistic test for armor. The ballistic behavior was studied based on the individual fabric layer construction in addition to the summation of the multilayer layers structure and the construction of the armor. Impact energy measuring was performed based on 9mm caliber projectile. The relation between the fabric parameters of the construction were studied with respect to number and total areal density of layers, and the ballistic proof property. Compact structure of fabrics (very small spaces between yarns) showed good results and fabrics without any additional reinforcement polymers had no ability to prevent the projectile. E-glass fabrics had smoothly yarns which slip over each other that made the projectile penetrate the fabric and layers very easy and made failure of primary yarns.
KEYWORDS: Fiber glass- armor – Anti-ballistic – Multilayer

1. INTRODUCTION

Significant research and development effort had led to the development of ballistic fabrics –based armors which protect against ballistic threats [1]. Most of light armors are designed and produced of multilayer fabrics; based on different materials and structures.[2].

The Next generation of body armor must be light and in many cases flexible for general wear and in order to provide full body protection [2].The threat velocity has a critical effect on the armor weight required to defeat the projectile. [3].

Possible energy absorbing mechanisms during ballistic impact are: cone formation on the back face of the target, deformation of secondary yarns, tension in primary yarns, delamination, matrix cracking, shear plugging and friction between the projectile and the target. [4]

The armor structure comprises a plurality of sheets of two-dimensional woven fiberglass fabric, and a plurality of sheets of three-dimensional woven fiberglass fabric. A composite laminated armor structure for absorbing and dissipating kinetic energy from a projectile fired at the armor structure was used.[5]

Actual mechanisms will depend on such variables as material properties, impact velocity, projectile shape, method of target support, and relative dimensions of projectile and target. [4]

Projectile impact velocity would just cause perforation. At the ballistic limit, the kinetic energy of the projectile is consumed completely in target deformation and damages associated with the projectile penetration process. The ballistic limit represents a target's ability to resist projectile perforation because it provides a quantitative measure of the maximum amount of kinetic energy the panel can absorb before it is perforated by the projectile. [5]

The ballistic resistances of aramids and its composite targets are relatively greater than the corresponding E-glass targets having the same number of layers and weight. Increasing the number of layers of E-glass targets has a limited effect on increasing their ballistic resistances. Moreover, the used epoxy has a great effect on increasing their ballistic resistances. [6]

2.The Concept of design

Armored Steel is almost used in armoring against bullets but steel is very heavy so scientist trend to use high performance fibers and composites to overcome the increase in weight compared with steel inmost armors against small and medium calibers.

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E-glass type was chosen to be used in the production of the armor as it has good tensile strength, chemical resistance, low density, low cost, good mechanical performance, and good corrosion resistance. Fiberglass [E-glass] is more available in local market and its price compared with aramids is lower, but on other hand the areal density of E-glass is higher than the aramids. Moreover the tenacity of aramids is higher than that of fiber glass so the number of layers used in fiberglass targets will be more than these used by aramids target.

Revealing to the properties of aramid, the multilayer armors produced from Aramid material ranges from25 to 30 layers [detex from 670-1100], giving effective proof test result. In the case of fiber glass through our research, the number of layers is about 50 layers[500gm/m^2]. Keeping into consideration some design aspects depending on the fiber used, the concept of designing this armor was based on using high tenacity E- glass multi-layer fabrics, with no epoxies, and according to the literature and the other products of aramid, it was found that fiberglass target will be formed from 50 layers from high tenacity fiberglass to match25 layers of aramid. [Aramid tensile was higher than E-glass [almost twice]]. Epoxies were not used to adhere the layers, in order to study the ability of fiberglass to absorb energy alone without the effect of the epoxy. Instead of epoxies resins, Stitching were used with settled pattern for holding the layers. In some other samples a flexible coating polymer was used for the back layers and a comparison study was done with the other samples.

3.Experimental work:

This work was based on designing multi-layer E-glass woven fabrics with defined parameters, using stitching with a pattern to binding these layers, with no epoxies used. Part of these layers was coated.

Moreover the research samples were designed on the base of almost a constant weights per unit area, regardless the density of the materials.

In order to determine the protective capability of target materials, the tensile strength and tearing strength were measured; In addition to the ballistic test for the obtained armor [armor was made of 50 layers bonded by stitching].

3.1.Materials:

Two types were selected from about 10 types of E-glass fabrics which were used because of its construction and its properties : first one was satin 4 weave with 1300 Denier yarn count and the other one was plain weave with 4000 denier yarn count, the weight for one square meter of the two types was approximately 500g/m^2. The layers were collected by stitching used yarn 30/3 En count; some samples were coated from the back by flexible polymer named [LINE-X XS-350 which was a two-component spray-in-place flexible 100% solids Polyuria/Polyurethane system].[7]In order to study the effect of flexible polymer on absorbing kinetic energy and study its efficiency as a backing material.

The materials were tested for their specifications like weight according to [ES 0758/2005][8], its yarn count according to[ES 0391/ 2007][9] and defined number of warp and weft per cm^2 according to [ES 0294/2008][10]in laboratory of Kader factory. The sample size was 20cm×20cm. Table [1] shows the specification of the used E-glass fabrics for single layer of target materials. Then the layers were collected in multi-layered samples, the total weight of each collected sample approximately was 1300 gm. Table [2] shows the specification of multilayered samples

Table 1: Main specification of single layer fabric of target materials

Single layer	Type	Weight g/m^2	Warp Count denier	Weft count denier	Warp /weft density	Weave construction
Sample 1	E-glass	500	1300	1300	20/12 yarn /cm	Satin 4
Sample 2	E-glass	430	4000	4000	6 yarn /cm	Plain weave

Table 2: Main specification of multi layered target materials

Samples	Areal density for sample [Ad][kg/m^2]	Number of layers	[Ad] per layer [g/m^2]	Weave density [count/cm]	Fiber liner density [denier]	notes
Sample 1	1.205	50	500	20	1300	No resin
Sample 2	1.100	50	430	6	4000	No resin
Sample3	1.220	50	430	6	4000	Line-x in back
Sample4	1.300	50	430	6	4000	0,90,+60,-60 Line-x in back
Sample 5	1.555	36	430	6	4000	Line-x in first –middle –back

3.2. Method of making samples:

E-glass fabrics were cut in small pieces, the area of each layer was 20×20cm, the layers were collected as multi-layer samples, each sample consists of 50 layers or else according to its areal density, stitched on a diagonal stitching machine with diagonal pattern and the distance of stitching is 1.5 inch [4.5cm].

Some samples which were coated from the back with flexible polymer coating, processed through dispensing equipment. It is fast cure for service at ambient temperature after 24 hours. It has low density and relatively high abrasion resistance, impact strength, tensile strength, and high resistance to severe weather conditions.[6]

3.3. Experimental tests

In this study parameters studied were the effect of density of yarn on ballistic test, the effect of yarn count and yarn tenacity on ballistic test, the effect of bullet [small caliber projectile] on the secondary and primary yarn and the effect of the coating by flexible polymer on ballistic test.

3.3.1. Mechanical tests

The E-glass fabrics were tested for its mechanical properties; tensile strength [ES 1506-01/2007][11]and tearing strength [ES-0390-02/2007][12]in the textile lab of The National Institute of Standards and Calibration [NIS], the tests were done on SDL tensile strength apparatus and fig [1] show the apparatus of tensile strength and tearing strength tests.

Fig 1: Tensile strength and tearing tests

3.3.2. Ballistic testing

The Ballistic test was done according to NIJ standard[10][protection level IIIA], where the samples were clamed tightly from all four sides, bulletswere shooted froma 5m distance. A backing clay material was used to determine the depth of trauma.The clay had to be refixed and re-leveled after each shot in order to meet the requirements, where each shot should impact the sample at the same condition with 9mm caliber projectile with mass 8gm and velocity [400 m/sec] on HPI test rifle and the test was done in one of militarian factories.figure [2]show the expermental setup and figure[3]show HPItest rifle of 9mm caliber projectile.

Figure[2]Experimental setup

Figure [3] HPI test rifle of 9mm caliber projectile

4. RESULTS AND DISCUSSIONS

The E-glass fabrics were tested for its mechanical properties; tensile strength and tearing strength, table [3] illustrates the mechanical properties of single layer of E-glass fabrics.

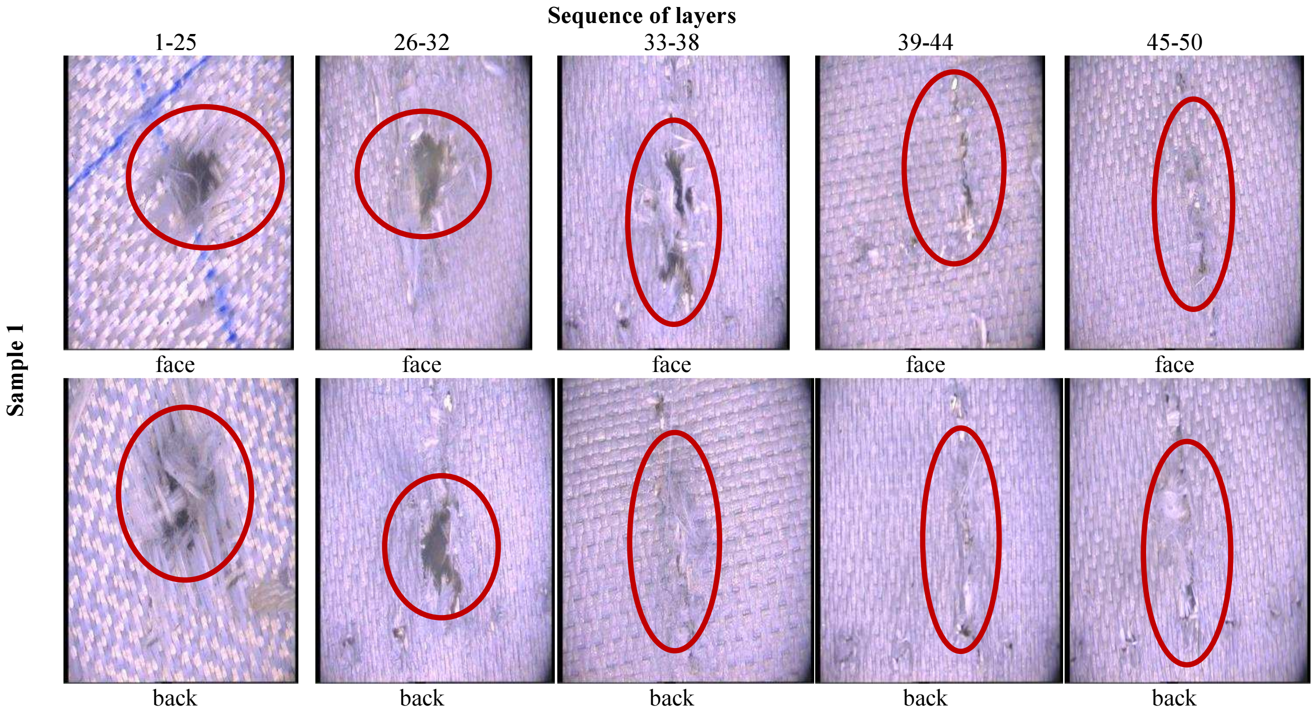
Table 3: mechanical properties of single layer fabric of target materials

Single layer	Warp Stress [Mpa]	Weft Stress [Mpa]	Warp Tearing strength [N]	Weft Tearing Strength [N]
Sample 1	293	222	163	181
Sample 2	75	64	356	158

The samples were measured for their tensile and tearing strength for each individual layer. In addition the multi-layered samples were tested for penetration resistance property. It was revealed that the yarn properties considering; its strength, tearing, number of twists, in addition to its count contribute with a high percentage to the total properties of the fabric produced.

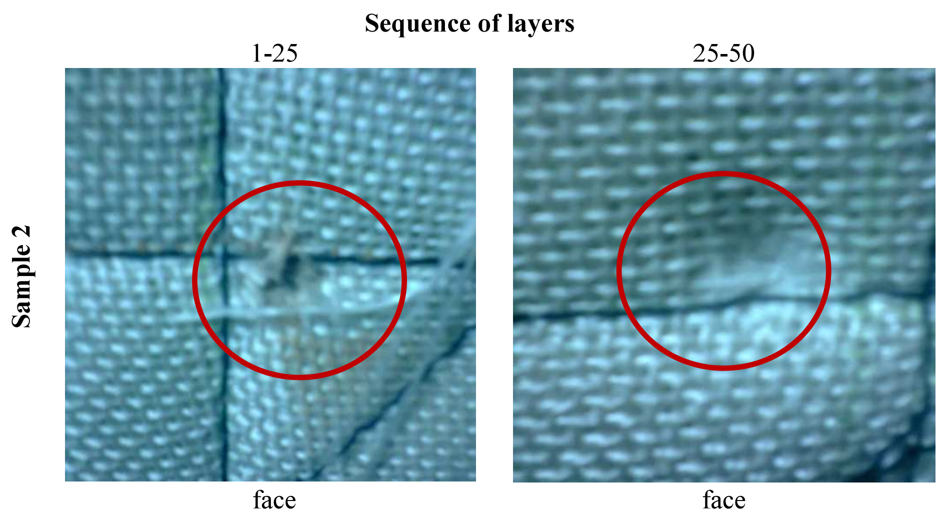
As mentioned before Plain and Satin weaves were used for the woven E-glass fabrics. Tests proved that compact weave constructions revealed in better results for penetration resistance [Bullet passage through the fabric] rather than open constructions. This was due to the summation parameters of the yarn counts and number of yarns per unit area, in addition to the construction of the weaves.

The five multilayered samples were tested for their ballistic behavior for protection **level IIIA according to NIJ** standard with 9mm caliber projectile with velocity 400m/sec and there were full penetration of all samples, the tested samples were examined after firing to study the behavior of penetration of the E-glass armors without resin, figure [4] illustrate the penetration behavior of sample [1] after ballistic test and post firing examination. Figure [5] illustrate the penetration behavior of sample [2] after ballistic test and post firing examination. Figure [6] illustrate the penetration behavior of sample [3] after ballistic test and post firing examination. Figure [7] illustrate the penetration behavior of sample [4] after ballistic test and post firing examination. Figure [8] illustrate the penetration behavior of sample [5] after ballistic test and post firing examination.



Fig[4]Sample 1 after ballistic test and post firing examination: the projectile penetrated the layers from [1-38] then the projectile got out from weak point from stitching in layers[39-50]

Sample [1] in fig [4] was made from compact fabric coated with silicon polymer which resist bullet and absorb kinetic energy from the result of ballistic test, which showed that the v50 of this armor is 400m/sec because the bullet stopped in in clay, post firing examination of this sample showed that the stitching had a bad effect on fiberglass yarn and stitching break the fiberglass which lead to weakness in the fiberglass fabrics and the yarn lost its tenacity and the bullet did penetrate the target to the layer number 38after that layer the bullet broke the fabric at the weak points of stitching on fabric and went out through it.



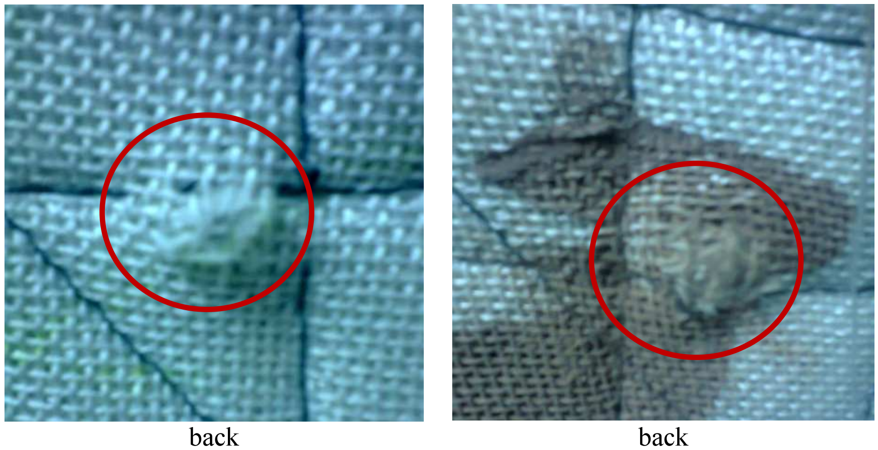


Figure [5] Sample 2 after ballistic test and post firing examination: the projectile penetrated the layers from [1-50] the fabrics without any reinforcement polymers

Sample [2] in fig [5] was made from plain weave and non-compact fabrics (open structure), the sample was fully penetrated, that mean the compact fabric structure is better than non-compact fabrics (open structure) in ballistic applications because the relations between fibers and yarns and the entire area with respect to the fabric are very important in absorbing the chock and the kinetic energy of the bullet. Open structure fabrics are not recommended in armors, as open constructions ease the permitting of the bullets, due to the inter spaces between the yarns, and this is obvious from the hole in clay, which was very big in this case as the yarns of fabric were free to move (slip) upon any releasing force .

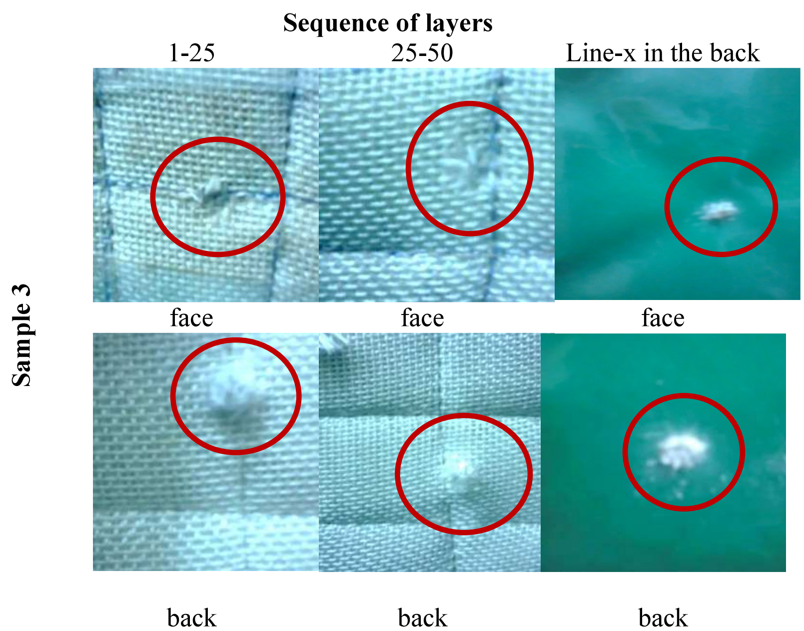


Figure [6] Sample 3 after ballistic test and post firing examination: projectile penetrated the layers [1-50] and the back from flexible polymer made the projectile sharper

Sample [3] in fig [6] was made from 50 layers of E-glass (3layers were coated) with the flexible polymer (line-x) in the back, the sample was fully penetrated in the ballistic test and the post firing examination showed that the hole in the clay was small while the hole in sample [2]was bigger than the hole in case of sample [3] which mean that the line-x had no effect on stopping the projectile but if we increase the number of layers which coated with Line-x it may be give different results .Meanwhile it could attribute in fixing/holding the fabric network (weaving construction yarns) thus decreasing their ability of movement, thus the hole was narrower.

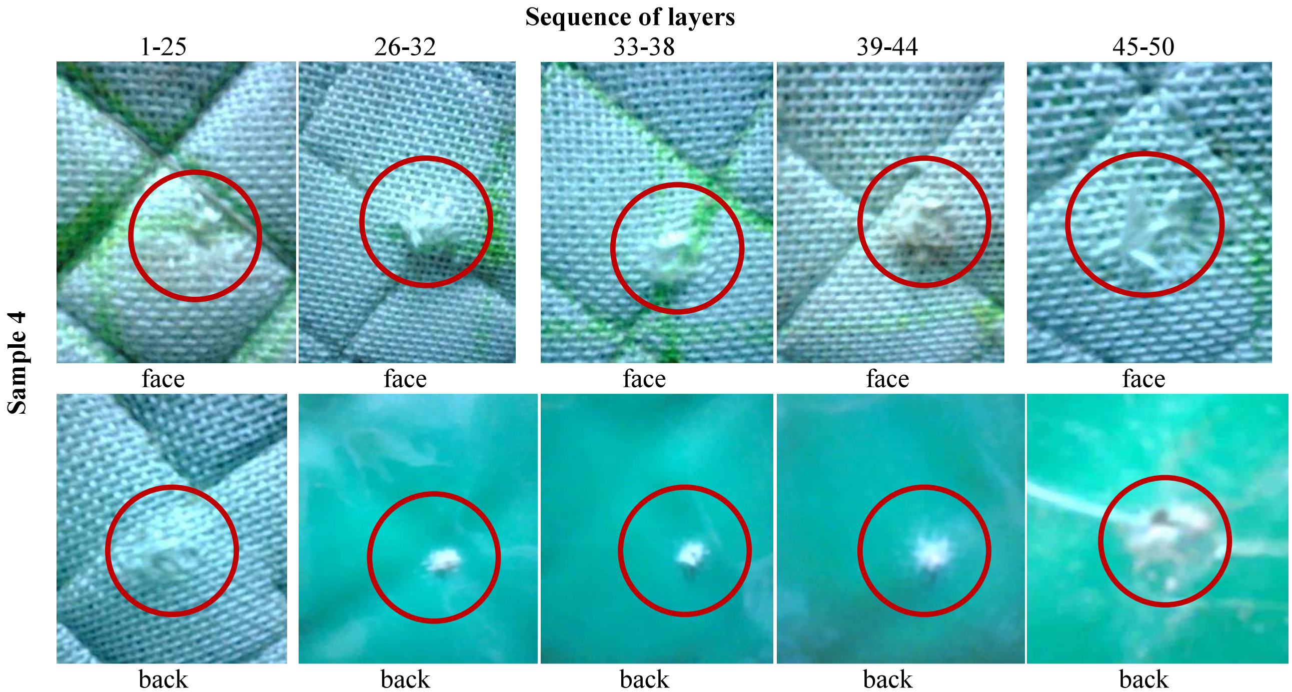


Figure [7] Sample 4 after ballistic test and post firing examination: projectile penetrated the layers [1-50] and the back from flexible polymer made the projectile sharper

Sample [4] in fig [7]was made from 25 layers of fiberglass stitched together divided into four groups each group consisted of 6 layers coated with line-x in back, In the ballistic test the sample was completely penetrated and the hole in the clay was small like the hole in case of sample [3] that means the line-x prevented the slippage (movement) of yarns.

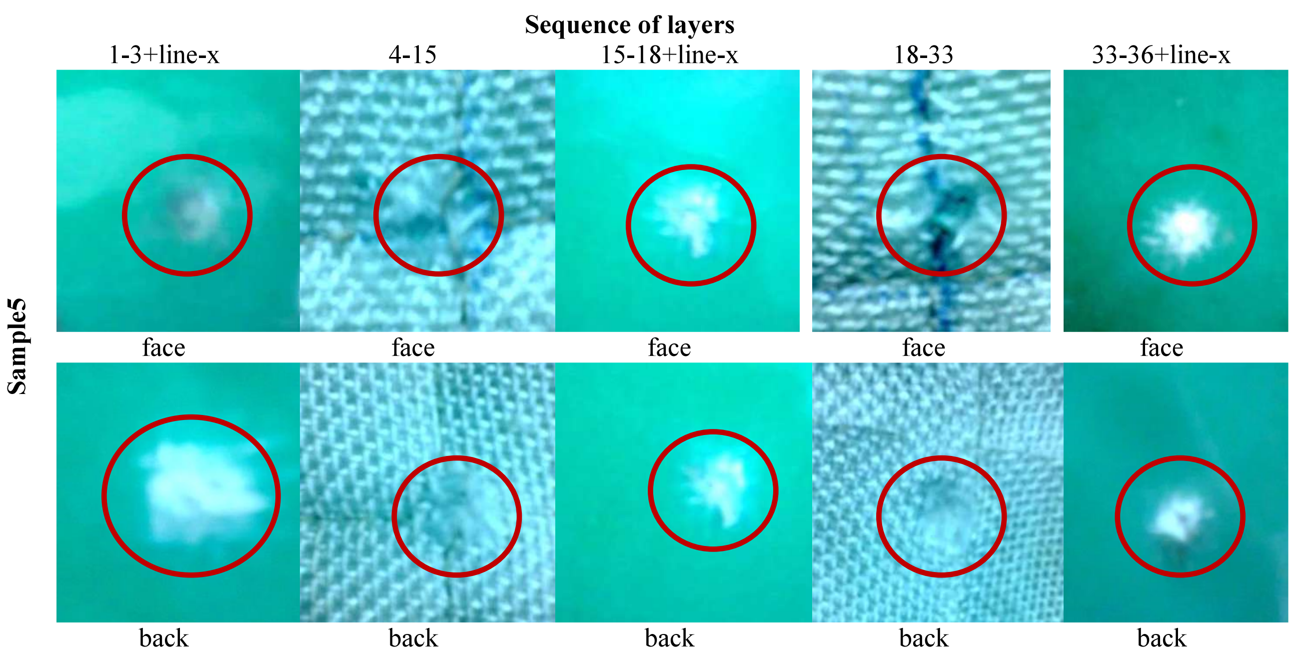


Figure [8] Sample 5 after ballistic test and post firing examination: projectile penetrated the layers [1-36] and the flexible polymer made the projectile sharper

Sample [5] in fig [8] was made from fiberglass layers which coated with flexible polymer line-x in the front and middle and back of sample to determine if the line-x has effect in defeating the bullet or not and the result of ballistic test showed that the line-x don't have ability in impact test that's mean the line-x has no effect in stopping the projectile.

5. Conclusion:

Compact fabrics[compact tight structures] showed to be better than open structure weaves in ballistic resistance behavior, even when yarns count in compact fabrics were lower and not twisted. The spaces in-between the warp yarns and the weft (warp and weft density), in addition to the total number of yarns in unit square area, decrease the movement of the yarns, especially with the back-coating of the fabric that prevent the slippage of the smooth fiberglass yarns thus opposing the bullet, absorbing its kinetic energy. Stitching had a bad effect on fiberglass fabrics and causing weak points, thus breaking the yarns.

Moreover different trends were clarified; Flexible polymer coating (line-x)may give other results in case of increasing the number of layers which coated with it on stopping or opposing the penetration of the bullet in fiberglass armors or absorbing kinetic energy. Open woven structures are not recommended in case of bullet proof textiles as the interspaces between the yarns ease the penetration of the bullets, due to the free movement/ slippage of the yarns. Fiberglass multilayered armor without polymer reinforcement has no ability to prevent the bullet or absorbing kinetic energy due of the slippage of smooth fiberglass yarns over each other and their free movement especially in open structure fabrics, but the advantages of using E-glass was its low cost and availability in local market but it is not recommended to use E- glass fabrics in armors without reinforcement polymers.

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