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Citation for published version:
Martínez-Hergueta, F, González, C, Llorca, J, Blanco-Varela, T & Martínez, JJ 2013, 'Multilayer ballistic systems based on dry fabrics', Paper presented at 19th International Conference on Composite Materials, ICCM 2013, Montreal, Canada, 28/07/13 - 2/08/13 pp. 6184-6191.

MULTILAYER BALLISTIC SYSTEMS BASED ON DRY FABRICS

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Keywords: *Dry Woven Fabrics, Non Woven Felt, Ballistic Impact*

1 Introduction

The continous demanding requirements of weight reduction in the armour industry are changing the designs of protection systems and techniques of soft-body armours and the application to non traditional uses as vehicles or aircrafts armouring. Composite materials are promising lightweight solutions due to their inherent low density and the use of high performance fibers. Typically, the composite solution contains a certain percentage of resin to maintain the laminate lay-up configuration and protect the fibers against detrimental environments. However, the lightest configuration corresponds to dry fabrics where the resin is being removed in order to decrease the final areal weight of the armour. It has been demonstrated that for relatively low areal densities, these materials exhibit the best ballistic performance as compared to their fabric/resin laminates counterparts [1].

Dry fabrics manufactured with high strength fibers have an outstanding performance in arresting metallic fragments. The ballistic response of woven dry fabrics has been extensively reported in the literature [2]. For instance, Kevlar fabrics are currently used for barriers [3]. However, arresting small fragments with dry wovens may not be totally useful depending on the relation between the size of the fragment and the fabric architecture [4]. In those cases, nonwoven felts show the best ballistic performance against small fragment impacts. Fibers in nonwovens are randomly distributed in the plane. The structural behaviour is not only due to the specific stiffness and strength of the fibers but on the way the fibers interact which each others. Such bonds can be of different nature, such as simple mechanical entanglement, local thermal fusion or chemical binders, depending on the particular material or the processing technique [5]. Regarding the structural properties, nonwovens posses moderate strength and stiffness than their woven counterparts, but they are superior in terms of energy consumption during deformation.

Different nonwoven felts have been design to increase the absorbed specific energy of shields. In 1995, DSM started to commercialize Dyneema Fraglight, a felt based on ultra-high molecular weight polyethylene fibers (UHMWPE). Their mechanical quasistatic and dynamic properties had been fully characterized [6] and ballistic tests were carried out [7]. A very good performance to stop fragments with a very low areal density was found, although large deflections were necessary to arrest the projectile. Another example developed by Auburn University is ArmorFelt [8], which combines semi-thermoplastics aramids and thermoplastic polyethylene. The main energy dissipation mechanisms corresponded to the high strain velocity propagation, the fibrillation of the aramid fibers, and plastic deformation and phase change induced in the polyethylene fibers.

A big effort is being done to improve the bullet resistance of felts and many patents have been developed in the past. Hybrids shields composed by dry woven fabrics and composites [9] are one of the most common designs to minimize the areal weight of the shields, increase the absorbed energy by the shield and reduce the large deflections observed in the nonwoven fabrics. The mechanical response of hybrid multilayer shields composed by felts and composites tiles have been previously analyzed [10], and for instance, combinations of ballistic material with "ArmorFelt" have shown significant advantages when used against rated soft body armour threats. However more studies are needed to rationale and optimize the performance of ballistic textiles through hybrid laminated systems. It is important to determine the absorbed energy partition between their respective components and the corresponding damage mechanisms.

In this work, the ballistic response of several dry woven fabrics and one nonwoven felt has been evaluated experimentally. Additionally, the combinations of felts and wovens have been also tested against impact to find the optimal configuration. A comparison between the ballistic performance of the different materials and hybrid multilayer shield configurations has been done and the mechanical response of the hybrid shield analyzed. Finally another comparison between a conventional dry woven fabric shield and the proposed hybrid configuration has been also evaluated.

2 Materials and Methods

2.1 Fabrics Characteristics

Two dry woven fabrics and one nonwoven felt were selected to evaluate the ballistic performance against small fragments: woven Kevlar KM2, 3-harness satin (3HS) woven Dyneema (with SK65 Ultra High Weigth Molecular Polyethylene UHWMP) and Dyneema Fraglight Felt, respectively in 'Table 1'. Mechanical properties of the fibers can be shown in 'Table 2'.

2.2 Experimental Setup

A pneumatic launcher was used, with compressed air or helium up to 150 bars to impel the projectile reaching 100J of impact energy at velocities ranging from 270 to 550m/s. The projectile consists of a steel sphere with 5.56mm diameter (caliber 0.22), which implies a mass of 0.706g. A Phantom high-speed camera was used to obtain the initial and residual velocities of the projectile and measure the energy absorption capacity of the fabrics.

Dry fabrics were clamped along their four edges using an aluminum rigid rig. The dimensions of the free surface of the fabrics were 350x350mm^2, while the fabrics dimensions were 500x500mm^2, see 'Fig. 1.a'. A total of 16 steel screws with Ø6 m were used to clamp the fabric.

All the edges of the laminates were previously impregnated with DERAKANE 8084 epoxy vinyl ester resin see 'Fig. 1.b', to inhibit relative frame/fabric sliding. The resin cured at room temperature in approximately 24 hours. The blend is composed by 100g of raw DERAKANE resin, 1.55g of MEKP and 0.3g of CoNap 6% as catalysers.

2.3 Ballistic tests

Ballistic tests have been divided in two different categories. The purpose of the first set is the ballistic characterization of the dry fabrics. In the second set the effect of a hybrid multilayer structure with different dry fabrics has been analyzed.

Configurations are fully described in 'Table 3' (Single fabrics) and 'Table 4' (Multilayer targets). For the sake of clarity, the denomination of each test is composed by the number of layers and the first letter of each material, K for Kevlar, D for Dyneema and F for Fraglight.

3 Single Layer Ballistic Performances

3.1 Kevlar KM2 Woven Fabric

During the first stages of the impact, yarn uncrimping takes place and the yarns start to carry tensile load by elastic deformation. For high initial impact energies, the impacted yarns of the fabric reach their ultimate tensile strength which is followed by the subsequent failure, see 'Fig. 2'. For such kind of fabrics, the elastic energy transferred directly to the impacted and neighbouring yarns was responsible of the behaviour of the material. An enhancement of the yarn-to-yarn sliding could potentially help to increase the total energy dissipation.

Targets with different numbers of layers have been tested. For impacts above the ballistic limit, all the layers present breakage of the yarns while for impacts below the ballistic limit, no breakage of yarns could be appreciated. This could demonstrate that yarn failure occurs almost simultaneously in this thin lay-up, so the final strain level reached in all layers should be similar.

The ballistic curve for a target composed by 4 layers of Kevlar KM2 is presented in ‘Fig. 3’, where the initial velocity is represented against the residual velocity of the projectile after penetration. The ballistic limit for this impact is ≈297m/s, corresponding to 31.14J of initial kinetic energy. The test results were fitted to a Lambert type curve (1) where the exponent was approximately 2.75:

$$V_r=(V_i^n - V_{50}^n)^{1/n} \qquad (1)$$

3.2 Dyneema SK65 Woven Fabric

The absorbed energy of this fabric was negligible as the size of the projectile was similar to the yarn-to-yarn spacing which led to an easy projectile sliding, see ‘Fig. 4’. The low friction coefficient of Dyneema promoted this mechanism. The projectile was, therefore, free to move between adjacent yarns without substantial opposition. Yarn sliding does not cause yarn failure and the energy transmitted to the target during the impact was negligible. It is worthwhile to remark that Dyneema woven fabric was not able to arrest such small caliber projectiles but should be useful for larger projectile sizes.

3.3 Fraglight Felt

The mechanical response of the Fraglight Felt is different to the response of dry woven fabrics due to the anisotropy and random distribution of the fibers on it. The in-plane wave travelling through the felt during the impact makes the felt fibers to stretch radially towards the impact point. At this point, felt fiber radial alignment increases the performance of the material which finally fails in a ductile fashion by tear. Fraglight felt presented the higher specific energy absorption capacity, but in opposition, with the largest deflection level, see ‘Fig. 5’. The behavior of the felt scaled with the number of layers used in the impact tests.

In ‘Fig. 6’, the ballistic limit curve is shown. It has been represented the residual velocity of the projectile *vs* the initial velocity. The ballistic limit for this impact is considered 339m/s, which implies a kinetic energy of 40.6J. The test results were used to fit a Lambert type equation (1) and the corresponding exponent was 7.

4 Hybrid Multilayer Ballistic Performance

The present work is focused not only on the individual performance of each of the presented fabrics but also on the hybrid shield behavior. For instance, the influence of back adding dry woven fabric to the Fraglight felt has been analyzed, ‘Table 4’. The suggested targets are composed by a first layer of Fraglight Felt and dry woven fabrics. The first configuration has one layer of Kevlar KM2 on the rear face and the second configuration has 4 layers of Dyneema SK65.

For all the tests, during the initial stages of the impact, both materials deflect together, but when the woven yarns reach their maximum strength or slide, the projectile passes through this layer although the Fraglight is still deforming. In this configuration, a high percentage of the fibers are totally reoriented in the loading direction, and the elastic, plastic and damage energy became important prior to the final tearing of the felt, see ‘Fig.7 ’.

One of the most important parameters for optimization in these materials is the fabric architecture. It has been observed that increasing the yarn-to-yarn space increase the amount of felt which penetrates the dry fabric and therefore the volume of fibers which are reoriented in the loading direction, see ‘Fig. 8’, so therefore, the absorbed energy increases. For the specific tests carried out the Dyneema SK65 woven fabric with 15 yarns per inch offers an improved impact response than Kevlar KM2 with 31 yarns per inch.

Both configurations have been compared with the single layer tests performed for Fraglight Felt. In ‘Fig. 9’ the absorbed energy vs the initial kinetic energy has been represented. Straight lines represent the 100%, 75% and 50% percentage of absorbed energy. The best results have been obtained by the combination of Fraglight felt layers with Dyneema woven fabrics. The combination with Kevlar presents a lower response due to specific amount of Fraglight felt involved in the projectile arresting mechanisms. The space left by the breakage of Kevlar yarns was smaller than the space left by the slide of Dyneema yarns.

5 Comparing Conventional and Hybrid Solutions

Two different configurations, see 'Table 5', which could be used for a potential solution for a shield with a similar areal weight have been compared. The first solution consists of a conventional ballistic protection composed by 4 layers of Kevlar KM2. The second target consists of a hybrid system composed by the Fraglight Felt and 4 layers of Dyneema SK65 dry woven fabric.

Ballistic limit curves are compared in 'Fig. 10' for such material combinations. The Lambert equation (1) was fitted to the experimental results with an exponent value of $n=2.75$ for Kevlar and $n=2$ for the hybrid shield, respectively. Ballistic limit for the conventional configuration of Kevlar is ≈297m/s corresponding to 31.14J of initial kinetic energy and for the hybrid configuration is ≈368m/s, which implies a kinetic energy of 47.8J. The best results have been obtained by the combination of Fraglight felt layers with Dyneema woven fabrics.

5 Conclusions

The ballistic performance of felts has been improved changing its mechanical response with the addition of a dry woven fabric at the back face of the shield. The global deflection of the target has been reduced as well. The absorbed energy by the hybrid target depends on the architecture and the ratio between the projectile size and the yarn-to-yarn spacing of the dry woven fabric.

The mechanisms responsible of the enhanced response of the multilayer fabric are not totally clear. Nevertheless, it has been considered that the felt penetration into the woven fabric produced the confinement of the felt and the fiber alignment, increasing the energy absorption and delaying the tearing onset of the felt.

Hybrids systems have been compared with a conventional solution based on Kevlar layers. For the analyzed caliber, the best results have been obtained with a hybrid combination of Fraglight Felt and Dyneema SK65 woven fabric. The combination of fabric/felt layers could be useful to arrest a variety of fragments sizes, being the felt used for the smaller and the wovens for bigger size, respectively.

Acknowledgements

This investigation was supported by Airbus Spain Operations within the framework of the TARGET Project (CENIT program funded by the Spanish Center for Industrial and Technological Delvelopement CDTI). The authors are also grateful to M. J. Pérez and F. Gálvez from the Polytechnic University of Madrid for their support during the experimental tests.

Fabric	Weave Pattern	Yarns per inch	Tex	Areal Density (g/m^2)
KM2	Plain	31	94.4	231
SK65	3HS	15	132	180
Fraglight	Felt	--	--	200

Table 1. Characteristics of the fabrics

Fiber	Strength (GPa)	Density (kg/m^3)
Kevlar KM2	3.4	1440
Dyneema SK-65	3.42	970

Table 2. Mechanical properties of the fibers

id	Layers	Mat	Sequence
1K	1	Kevlar KM2	[0]
4K	4	Kevlar KM2	$[0]_4$
1D	1	SK65 Fabric	[0]
3D	3	SK65 Fabric	[0/90/0]
1F	1	Fraglight	[0]
2F	2	Fraglight	$[0]_2$

Table 3. Single fabric test materials

id	Layers	Material	Sequence
F+K	1	Fraglight	[0]
	1	Kevlar KM2	[0]
F+4D	1	Fraglight	[0]
	4	SK65 Fabric	[0/90/0/90]

Table 4. Multilayer hybrid fabric tests

id	Layers	Material	A. Weight (g/m2)
4K	4	Kevlar KM2	922
F+4D	1 4	Fraglight SK65 Fabric	920

Table 5. Areal weight for potential solutions for a shield

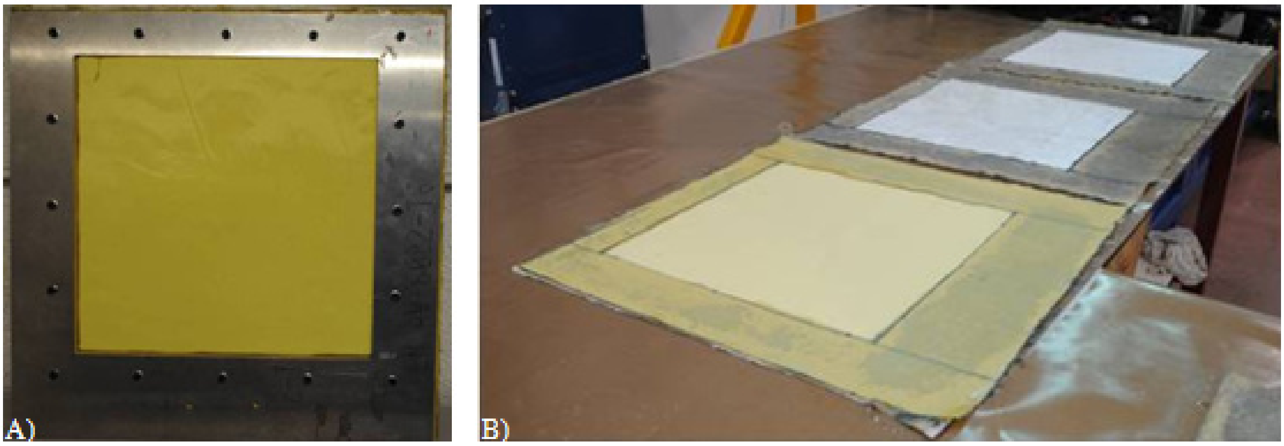

Fig. 1. a) Testing frame used for the impact test of the dry fabrics, b) Impregnated laminates with DERAKANE 8084 resin along the edges

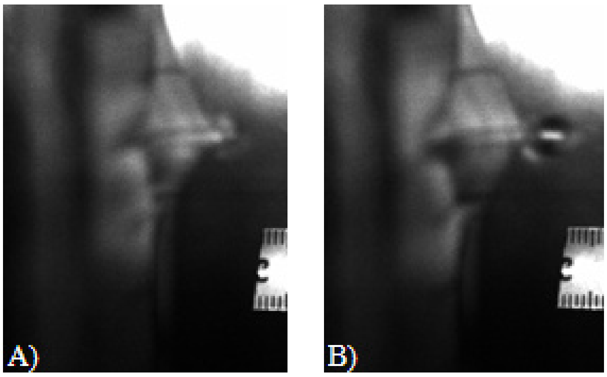

Fig. 2. Snap-shots showing the transverse deflections of Kevlar KM2 dry fabric impacted at 310m/s for a) t = 50µs and b) 100µs

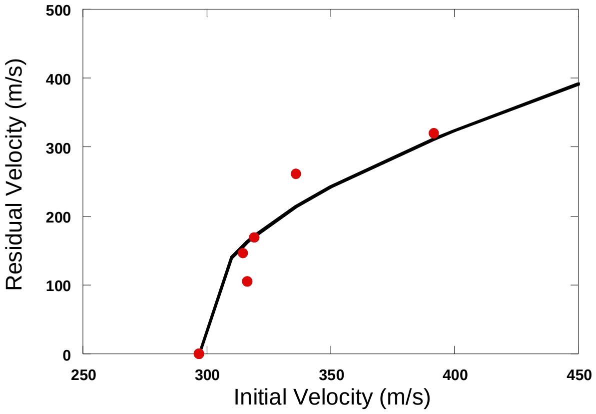

Fig. 3. Ballistic limit curve for 4 layers of Kevlar KM2

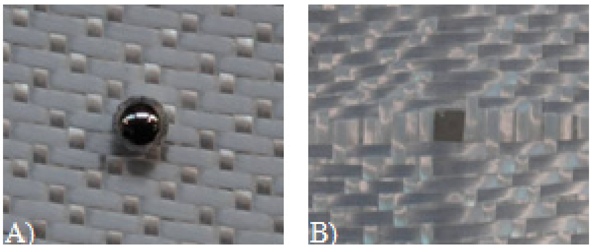

Fig. 4. Dyneema SK65 fabric characteristics, a) comparison between yarns width and projectile diameter and b) yarn sliding after impact

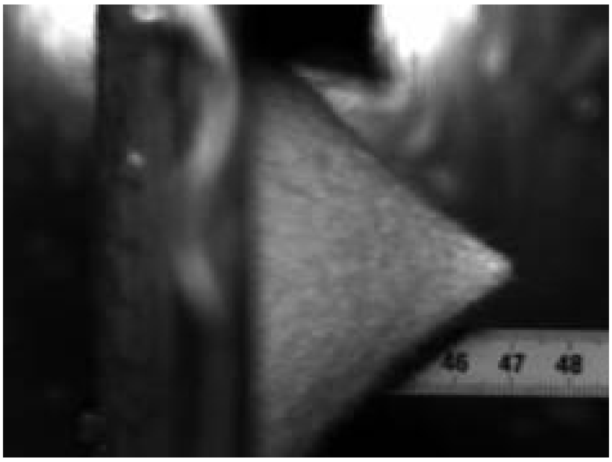

Fig. 5. Transverse deflection of 1 layer of Dyneema Fraglight Felt impacted at 320m/s

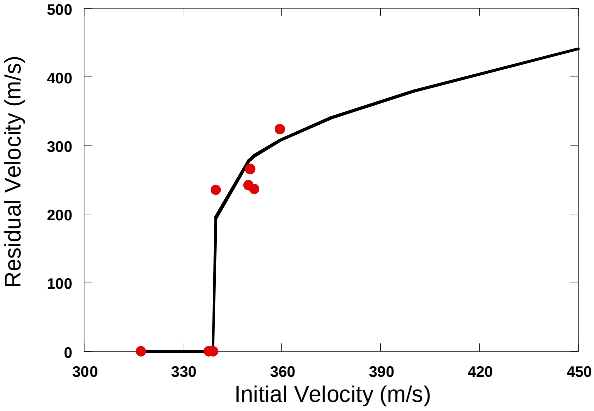

Fig. 6. Ballistic limit curve for 1 layers of Fraglight Felt

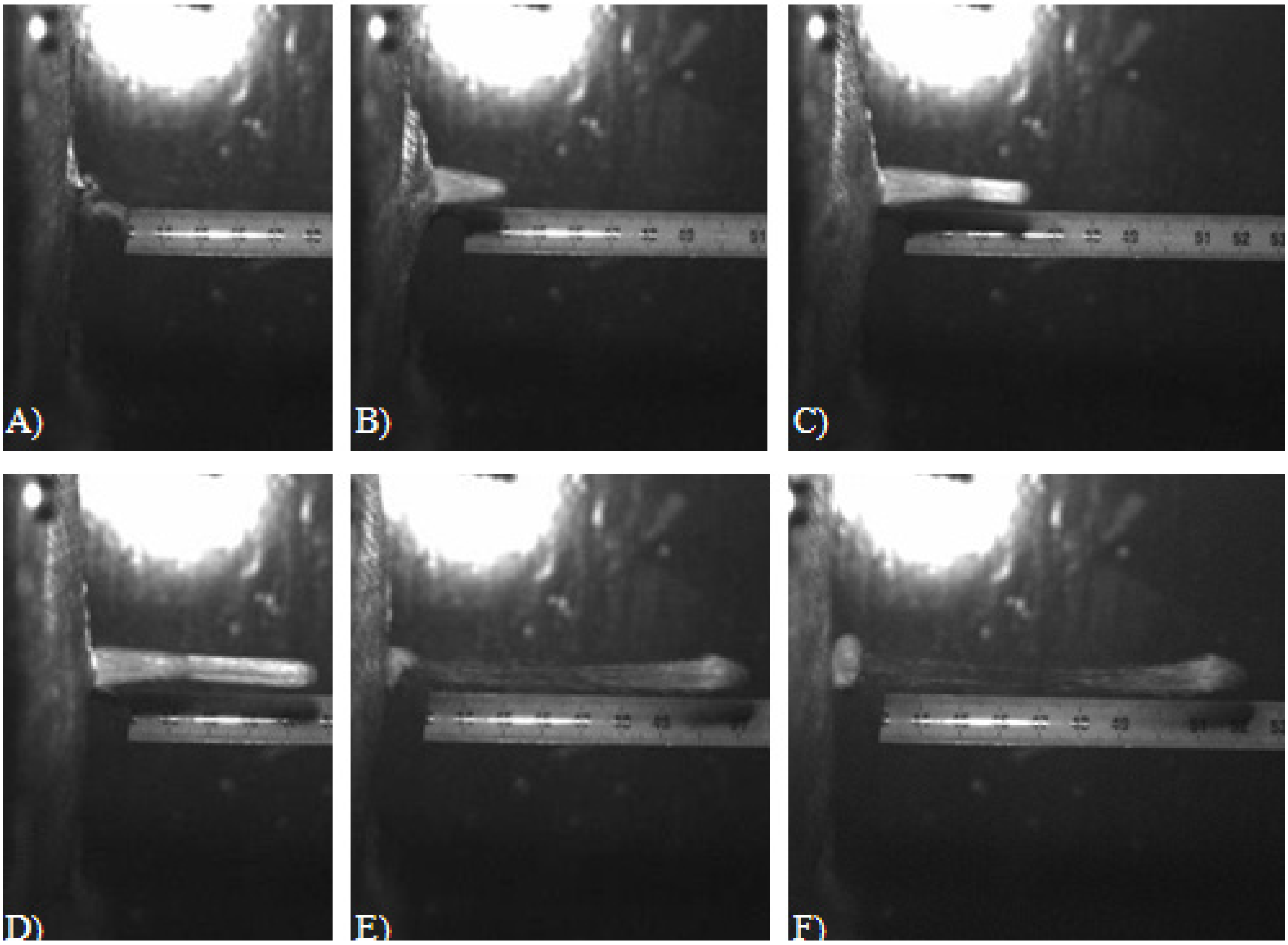

Fig. 7. Snap-shots showing the transverse deflections of the laminate compose by 1 layer of Fraglight Felt and 4 layer of Dyneema SK65 impacted at 370m/s for a) t = 50μs, b) t = 150μs, c) t = 350μs, d) t = 600μs , e) t =1350μs and f) t = 1650μs

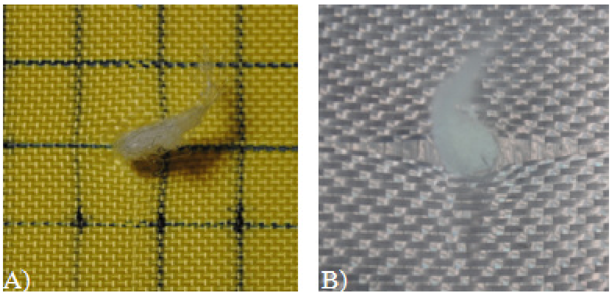

Fig. 8. Penetration of the felt into the dry woven fabric. a) 1 layer of Fraglight Felt and 1 layer of Kevlar KM2, b) 1 layer of Fraglight Felt and 4 layers of Woven Dyneema SK65

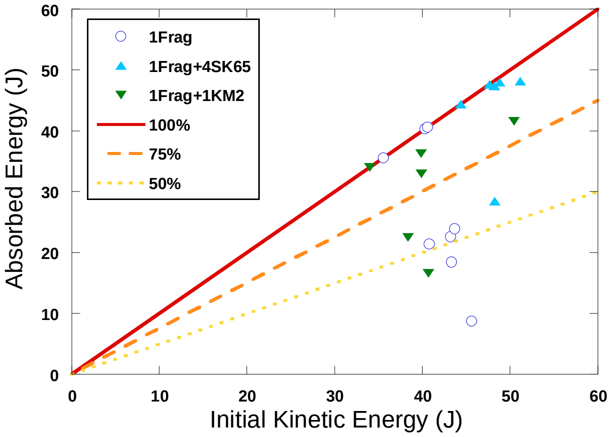

Fig. 9. Absorbed energy vs initial kinetic energy for three different targets based on Fraglight

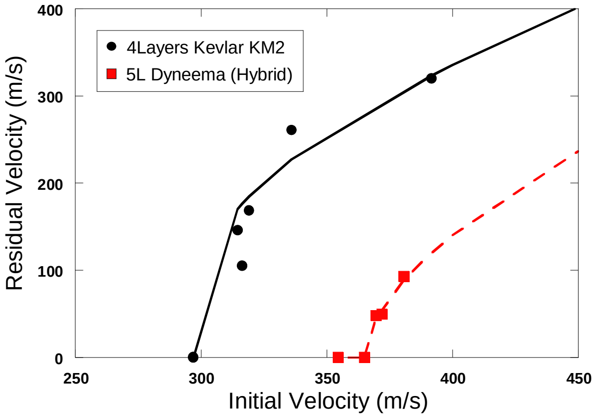

Fig. 10. Ballistic limit curve for 4 layers of Kevlar KM2 and a hybrid configuration composed by 1 layer of Fraglight and 4 layers of Woven Dyneema

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