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Original scientific paper

PREDICTING BALLISTIC STRENGTH OF LIFE-SAVING ARAMID FIBER COMPOSITES FOR PERSONAL PROTECTION

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Abstract: The purpose of the study is to access the applicability of full factorial experimental design in predicting ballistic strength of aramid fiber/phenolic ballistic composites for personal protection. When designing ballistic composites, two major factors are the most important: the ballistic strength and the weight of the protection. The ultimate target is to achieve the required ballistic strength with the lowest possible weight of the protection. The hard ballistic aramid/phenolic composites were made by the open mold high pressure, high-temperature compression of prepreg made of plain woven aramid fiber fabric and polyvinyl butyral modified phenolic resin. The preparation of the composites was conducted by applying 2^2 full factorial experimental design. The areal weight of composites was taken to be the first factor and the second – fiber/resin ratio. For the first factor, low and high levels are chosen to be 2 kg/m^2 and 9 kg/m^2, respectively and for the second factor – 80/20 and 50/50, respectively. The first-order linear model to approximate the response, i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m^2 x (80/20 – 50/50) ratio was used. The influence of each individual factor to the response function is established, as well as the interaction of both factors. It was found that the estimated first-degree regression equation with interaction gives a very good approximation of the experimental results of the ballistic strength of composites within the study domain.

Key words: aramid fiber, ballistic composites, factorial design, regression equation, V50

Introduction

Since the beginning of armed conflict, armor has played a significant role in the life protection of warriors. In present-day conflicts, armor has inarguably saved countless lives. Over the course of history—and especially in modern times—the introduction of new materials and improvements in the materials already used to construct armor have led to better protection and a reduction in the weight of the armor. Body armor, for example, has progressed from the leather skins of antiquity, through the flak jackets of World War II to today's highly sophisticated designs that exploit ceramic plates and polymeric fibers to protect a person against direct strikes from armor-piercing projectiles and fragments of explosive devices. The advances in vehicle armor capabilities have similarly been driven by new materials.

The ever increasing needs of modern times for safety and security are steadily driving the demand for armor solutions capable of countering present and future threats. But optimal protection needs to be achieved without compromising practical constraints such as weight and cost reductions. One of the "new" materials which is widely used in the last three decades is aramid fiber.

Aramid fiber is a crystalline molecule that consists of long molecular chains that are highly oriented and show strong intermolecular chain bonding in the para position. It is made from the reaction of para-phenylenediamine (PPD) and molten terephthaloyl chloride.

The resounding characteristic of aramid fiber is its remarkable strength. This very strong fiber has made its biggest impact in the ballistics defense where it is used in bulletproof vests and helmets. It is stronger than fiberglass and five times stronger than steel on a kilogram-for-kilogram comparison. Aramid fiber molecules are ordered in long parallel chains, and the key structural feat is the benzene aromatic ring that has a radial orientation which gives the molecule a symmetric and highly ordered structure that forms rod-like structures with a simple repeating backbone [1, 2]. This creates an extremely strong structure with little weak points and flaws. It is the one of the strongest man-made fiber. Its high elongation at break, high modulus and high strength make it the ideal reinforcement solution for reducing weight and for combating increasing threats [3, 4].

Very high strength of aramid fibers is essential factor in the energy absorbing mechanism needed to defeat dynamic ballistic impact or to mitigate blast. This makes aramid fibers the material of choice for:

- Ballistic vests and helmets
- Blast panels that protect against land mines
- Engineered ballistics panels (either stand-alone or as part of a combined solution)
- Spall liners

Because of their high strength/weight ratio, aramid fibers are widely used for personal ballistic vests or as reinforcements for composites for personal protection used in helmets [5-7].

By combining fibres with an appropriate resin matrix system – typically phenolic – essential mechanical and physical properties can be engineered into the composite.

Experimental procedure

Experimental composite plates were made by impregnation of aramid fiber fabric with thermosetting phenolic resin of resole type modified with polyvinyl butyral. Intrinsically brittle phenolic resin is modified for flexibility which better contributes to kinetic energy absorption of the high-speed bullet and fragment impact and its dispersion in the adjacent layers. As reinforcement plain woven, aramid fiber fabric with areal weight of 280±7 g/m^2 was used, finished with phenolic resin compatible coupling agent. The main features of the fabric are given in Table 1.

Table 1. Main properties of aramid fiber fabric

Property	Unit	Value
Type of aramid	/	para
Weave		plain (1x1)
Thread count (warp x weft)	/	11 x 11
Areal density	g/m^2	280±7
Yarn linear density	tex	126
Thickness	mm	0.43
Fabric tensile strength (warp x weft)	N/5cm	9500 x 10000

The composites, i.e. laminates were produced by open-mold compression at high pressure and temperature of 155 ^{o}C within 150 minutes for fully curing, i.e. cross-linking of the resin. No post-curing treatment was conducted.

During the impregnation, several factors were observed (speed of impregnation, resin viscosity, metering rolls gap on the impregnating machine), so that the required resin pick-up and its content in the prepreg was achieved.

The areal weight of the composites was adjusted simply by adding more prepreg layers in the press packet from the lowest to the highest area weight in accordance to the experimental design.

In 2^2 full factorial experimental design (FFED) that was used, the areal weight of the composite is taken to be the first factor, and the second factor - fiber/resin ratio. For the first factor the low and the high levels are 2 kg/m^2 and 9 kg/m^2, respectively, and for the second factor – 80/20 and 50/50, respectively. Within this relatively narrow areal weight region, which is of importance only for panels intended for personal ballistic protection, linear dependence of ballistic strength vs. areal weight was assumed. With that assumption, we have taken the first-order linear model with interactions to predict the response function, i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m^2 x (80/20 – 50/50) fiber/resin ratio.

The full factorial experimental design allows making of mathematical modeling of the investigated process in a study domain in the vicinity of a chosen experimental point [8-10]. In order to include the whole study domain, we have chosen the central points of both ranges to be experimental points. For the areal weight of the composites we have chosen the experimental point to be 5,5 kg/m^2, and for the resin content the experimental point - 35 % (which corresponds to previously defined levels for fiber/resin ratios).

All ballistic tests are conducted with a standard 1.1g chisel-nosed fragment simulating projectile which is non-deformable; made of quenched and tempered steel with a flat rectangular tip. Figure 1 depicts the ballistic test setup.

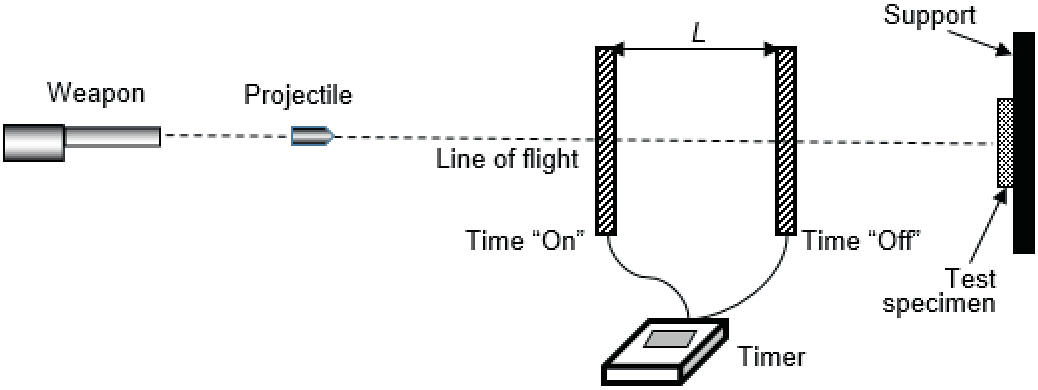

Figure 1. Ballistic test setup

The ballistic limit velocities, V50 (which we used as criteria for accessing ballistic strength) are calculated in accordance with STANAG 2920 calculation method. V50 value presents 50% probability of penetration, i.e. of non-penetration and is statistical method developed by US military. In accordance to the FFED procedure 4 (2^2) trails are needed, i.e. all possible combinations of the variables are tested. The coding of the variables is conducted in accordance with Table 2.

Table 2. Coding convention of the variables

	Areal weight, kg/m^2	Resin content, %
Zero level, $x_i=0$	5.5	35
Interval of variation	3.5	15
High level, $x_i=+1$	9	50
Low level, $x_i=-1$	2	20
Code	x_1	x_2

Results and discussion

The test results are presented in Table 3, together with the experimental matrix.

Table 3. Experimental matrix with results

Trials	x_1	x_2	x_1x_2	Aramid composite
				V50, (m/s)
1	-1	-1	+1	238,9
2	1	-1	-1	557,0
3	-1	1	-1	217,4
4	1	1	+1	504,4
-1 Level	2 kg/m^2	20%	-	-
+1 Level	9 kg/m^2	50%	-	-

By implementing the 2^2 full factorial experimental design, it was found that response function with coded variables, y_k, is:

$$y_k = 379{,}43+151{,}26x_1 - 18{,}53x_2 - 7{,}78x_1x_2 \quad (1)$$

and in engineering variables, y_n:

$$y_n = 156{,}42+48{,}40x_1 - 0{,}42x_2 - 0{,}15x_1x_2 \quad (2)$$

In the FFED, the term x_1x_2 is the interaction between factors which also might have influence on the response, in our case V50 value.

Analyzing the regression equation, it should be noted that the main positive contribution to the V50 is given by the areal weight of the composites, i.e. V50 is directly proportional to the areal weight of the composites. On the other hand, the resin content of the composite has inversely proportional effect on ballistic strength, which means, the higher the resin content, the lower the ballistic strength. The influence of areal weight is two order of magnitude larger than the influence of resin content. The interaction of the two factors, with coefficient of -0.15, has slightly negative effect on the ballistic strength which is of one order of magnitude smaller than the influence of the resin content.

To validate the implementation of the FFED in the study and the assumed model, theoretically calculated results (Eq. 2) are compared with experimental values for the composites with areal weight of 2, 3, 4, 5, 6, 7, 8 and 9 kg/m^2 and fixed resin content of 35%.

This comparison can be conducted with any other value for the resin content as long as it is within the study domain. The results are presented in Figure 2.

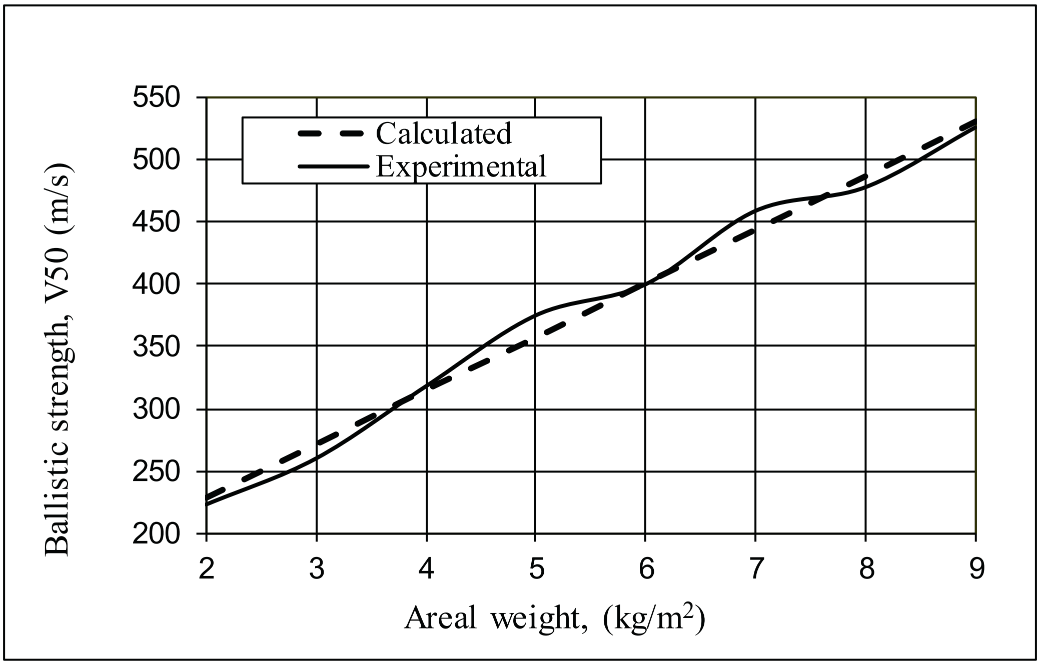

Figure 2. Ballistic strength vs. areal weight of composites

As it can be seen from Fig.2, there is a good agreement between calculated and the experimental values of V50. All calculated values are placed in a straight line which is in accordance with the assumed model of the experiment and are in close proximity of the experimental data.

How do we design composites using the regression equation?

a) For a given request for the ballistic strength V50 of composites, by substitution of y_n in the equation (2) the areal weight of the composites can be calculated and then the appropriate number of prepreg sheets used in fabrication of the composites.

b) For a given weight limit (x_1 factor) by substitution for x_1 in equation (2), $y_{n,}$ i.e. the value of V50 can be calculated.

In both above cases, the resin content (x_2 factor) has to be fixed at 20% for the most favorable outcome.

Conclusion

- Ballistic strength V50 is directly proportional to the areal weight of the composites and inversely proportional to the resin content. Areal weight is a more dominant factor than resin content.
- Experimental measurements of ballistic strength of composite laminates for a range of areal weight and for a range of resin content have been carried out implementing 2^2 full factorial experimental design. A correlation equation was established for V50 as a function of the areal weight and the resin content of the composites. Very good agreement has been found between experimental and calculated values. It was observed that if the study domain is precisely established (narrow enough), the full factorial experimental design can be employed to give good approximation of the response, i.e. V50 value.

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