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PREDICTING THE BALLISTIC STRENGTH OF ARAMID FIBER COMPOSITES BY IMPLEMENTING FULL FACTORIAL EXPERIMENTAL DESIGN

ORIGINAL SCIENTIFIC PAPER

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ABSTRACT

The purpose of the study is to predict the ballistic strength of hard aramid fiber/phenolic ballistic composites by implementing the full factorial experimental design. 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 protection. The hard ballistic aramid/phenolic composites were made by open mold high pressure, high-temperature compression of prepreg made of plain woven aramid fibre fabric and polyvinyl butyral modified phenolic resin. The preparation of the composites was done by applying the 2^2 full factorial experimental design. The areal weight of the composites was taken to be the first factor and the second – fibre/resin ratio. The first factor low and high levels were 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 on the response function was established, as well as the interaction of the two factors. It was found out 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 fibre, ballistic composites, factorial design, regression equation, V5

INTRODUCTION

Since the beginning of armed conflict, armour has played a significant role in the protection of warriors. In present-day conflicts, armour has unarguably 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 armour have led to better protection and a reduction in the weight of armour. Body armour, 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 fibres to protect a person against direct strikes from armour-piercing projectiles and fragments of explosive devices. The advances in vehicle armour capabilities have similarly been driven by new materials.

The ever increasing needs for safety and security are driving the demand for armour 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 an aramid fibre.

The aramid fibre is a crystalline molecule that consists of long molecular chains that are highly oriented and show strong intermolecular chain bonding in the para position, as shown in Figure 1.

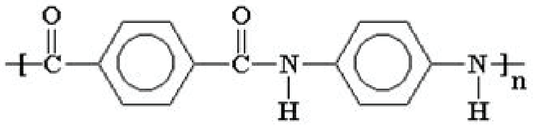

Figure 1. Chemical structure of para-aramid

It is made from the reaction of para-phenylenediamine (PPD) and molten terephthaloyl chloride.

The resounding characteristic of the aramid fibre is its remarkable strength. This very strong fibre has made its biggest impact in the ballistics defence where it is used in bulletproof vests and helmets. It is stronger than fibreglass and five times stronger than steel on a kilogram-for-kilogram comparison. Aramid fibre molecules are ordered in long parallel chains, and the key structural feat is the benzene aromatic ring[1,2] 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. This creates an extremely strong structure with little weak points and flaws. It is one of the strongest man-made fibres. 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 fibres is an essential factor in the energy absorbing mechanism needed to defeat dynamic ballistic impact or to mitigate blast. This makes aramid fibres 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 fibres are widely used for personal ballistic vests or as reinforcements for composites for personal protection[5, 6, 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 fibre fabric with thermosetting phenolic resin modified with polyvinyl butyral. Intrinsically brittle phenolic resin is modified for flexibility which better contributes to the kinetic energy absorption of the high-speed bullet and fragment impact and its dispersion in adjacent layers. As reinforcement plain woven aramid fibre fabric was used with the areal weight of 435 g/m^2, finished with a phenolic resin compatible coupling agent. The composites i.e. laminates were produced by open-mold compression at high pressure and a temperature of 155 ^{o}C within 150 minutes for fully curing i.e. cross-linking of the resin. No post-curing treatment was done.

During the impregnation several factors were observed (speed of impregnation, resin viscosity, metering rolls gap in the impregnating machine) so that the required resin pick-up and its content in the prepreg were 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 the 2^2 full factorial experimental design (FFED) the areal weight of the composite was taken to be the first factor and the second factor was taken to be the fibre/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 for personal ballistic protection, linear dependence of ballistic strength vs. areal weight was assumed. That is why the first-degree model with interactions was used to predict the response i.e. the ballistic strength of the composites within the study domain (2 – 9) kg/m^2 x (80/20 – 50/50) fibre/resin ratio.

The full factorial experimental design allows making a mathematical modelling of the investigated process in the study domain in the vicinity of a chosen experimental point[8,9,10]. To cover the whole study domain, for the areal weight of the composites the experimental point 5,5 ± 3,5 kg/m^2 was chosen, and for the resin content , the experimental point 35 ± 15 % (which corresponds to previously defined levels for fibre/resin ratios).

All tests were done 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. The ballistic limit velocities, V50, were calculated in accordance to the STANAG 2920 calculation method. V50 value presents 50% probability of penetration i.e. of non-penetration and is a 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.

Table 1. 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

The coding of the variables was done in accordance to Table I.

RESULTS AND DISCUSSION

The test results are presented in Table II together with the experimental matrix

Table 2. Experimental matrix with results

Trials	x_1	x_2	x_1x_2	Aramid composite V_{50}, (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 out that response function with coded variables, y_k, was:

$$\boldsymbol{y_k} = 379,43 + 151,26\boldsymbol{x}_1 - 18,53\boldsymbol{x}_2 - \\ -7,78\boldsymbol{x}_1\boldsymbol{x}_2 \quad (1)$$

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 can be found out 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 an inversely proportional effect on ballistic strength which means, the higher the resin content, the lower the ballistic strength. The interaction of the two factors, with a coefficient of -0.15, has a slightly negative effect on the ballistic strength which is of secondary order compared to the influence of areal weight and resin content.

To validate the equation, theoretically calculated results are compared with experimental values for composites with areal weight of 2, 3, 4, 5, 6, 7, 8 and 9 kg/m^2 and constant resin content of 35%.

The results are presented in Figure 2.

This comparison can be done with any other value for the resin content as long as it is within the study domain.

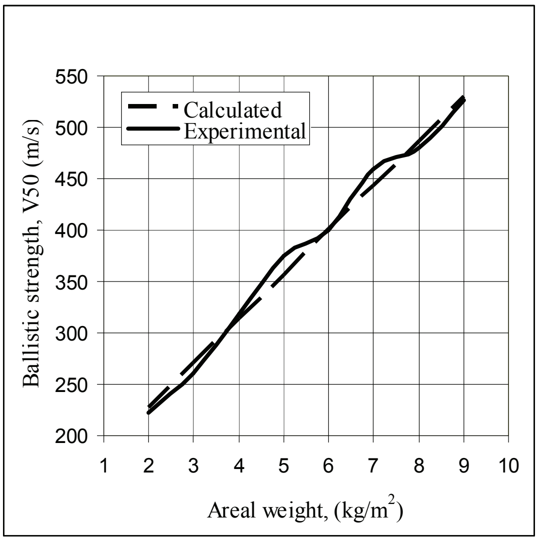

Figure 2. Ballistic strength vs. areal weight of composites

As it can be seen from Figure 2 there is a very good match between calculated and the experimental values. 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 can the regression equation (2) be used?

a) For a given request for the ballistic strength, by substitution of y_n the areal weight of the composites can be calculated.
b) For a given weight limit (x_1 factor) y_n can be calculated.
In both above cases the resin content (x_2 factor) has to be 20% for the most favourable outcome.

CONCLUSION

Although, for the wide range, the ballistic strength is not a linear function of the areal weight of the composites[11,12,13], if the study domain is precisely established (narrow enough), the 2^2 full factorial experimental design can be applied, to give a good approximation of the experimental data.

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