THE IMPLEMENTATION OF FULL FACTORIAL EXPERIMENTAL DESIGN IN PREDICTING THE BALLISTIC STRENGTH OF GLASS FIBER/PHENOLIC COMPOSITES

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Abstract

The purpose of the study is to predict the ballistic strength of rigid glass fiber/phenolic resin composites by using the full factorial experimental design. Ballistic glass/phenolic composites were made by the open mold high pressure, high-temperature compression of prepreg made of plain woven glass fiber fabric and polyvinylbutyrale modified phenolic resin.

The preparation of the composites was done by applying the 2^2 full factorial experimental design. The areal weight of composites is taken to be the first factor and the second – fiber/resin ratio. The first factor low and high levels are 2 kg/m^2 and 9 kg/m^2, respectfully and for the second factor – 20/80 and 60/40, respectfully. We used the first-order linear model to approximate the response i.e. the ballistic strength of the composites within the study domain (9 – 2) kg/m^2 x (20/80 – 60/40) ratio. The influence of each individual factor to the response function is established, as well as the interaction of the two factors. We 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 word: glass fiber, ballistic, factorial design, regression equation

1. Introduction

The ever increasing needs for safety and security are 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. Glass-fiber's high elongation at break, high modulus and high strength make it the ideal reinforcement solution for reducing weight and for combating increasing threats. Specialty glass-fibres meet the Class B strength requirement of military specification MIL-DTL-64154B with a fibre strength of no less than 2758 MPa. The ever increasing needs for safety and security are 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. Ballistic glass-fiber's high elongation at break, high modulus and high strength make it the ideal reinforcement solution for reducing weight and for combating increasing threats. Very high strength of glass fibers (no less than 2758 MPa) is essential factor in the energy absorbing mechanism needed to defeat dynamic ballistic impact or to mitigate blast. This makes ballistic glass fibers the material of choice for:

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

Because of the higher weight, compared to other ballistic fibers (nylon, aramid, PE) glass fibers are not used for ballistic items or composites for personal protection.
By combining fibres with an appropriate resin matrix system – typically phenolic – essential mechanical and physical properties can be engineered into the composite.

2. Experimental procedure

In the 2^2 full factorial experimental design (FFED) the areal weight of the composite is taken to be the first factor, and the second factor is taken to be te fiber/resin ratio. For the first factor the low and the high levels are 2 kg/m^2 and 9 kg/m^2, respectfully, and for the second factor – 20/80 and 60/40, respectfully. We used the first-order linear model to approximate the response i.e. the ballistic strength of the composites within the study domain (9 – 2) kg/m^2 x (20/80 – 60/40) fiber/resin ratio.
Glass/phenolic composites are taken in this study because of the price favorability compared to polymeric fiber composites.
The full factorial experimental design allows to make mathematical modeling of the investigated process in a study domain within the experimental in the vicinity of a chosen experimental point. To cover all the study domain, for the areal weight of the composites we have chosen the experimental point 5,5 $\pm$ 3,5 kg/m^2, and for the resin

content , the experimental point 35 ± 15 % (which corresponds to previously defined levels for fiber/resin ratios)

All test are done with fragment simulating projectiles in accordance to STANAG 2920 standard. Ballistic strength of the laminates is measured through V50 value (50 % probability of penetration). In accordance to the FFED procedure 2^2 = 4 trails are needed, i.e. all possible combinations of the variables are tested.

The coding of the variables is done in accordance to table 1.

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

3. Results and discussion

The results of the test are presented in table 2 together with the experimental matrix

Table 2. Experimental matrix with results

Trials	x_1	x_2	x_1x_2	Glass composite V_{50}, (m/s)
1	-1	-1	+1	188.4
2	1	-1	-1	395.6
3	-1	1	-1	169.4
4	1	1	+1	336.2

By implementing the full factorial experimental design we have found out that response function with coded variables is:

$$y_k = 272.4 + 93.5x_1 - 19.5x_2 - 10.1x_1x_2$$

and in engineering variables:

$$y_n = 134{,}1714 + 33{,}4476x_1 - 0{,}2486x_2 - 0.1924x_1x_2$$

The term x_1x_2 is the interaction between factors which also contributes to the response, in our case V50 value.

To validate the equation we have compared the calculated results with the

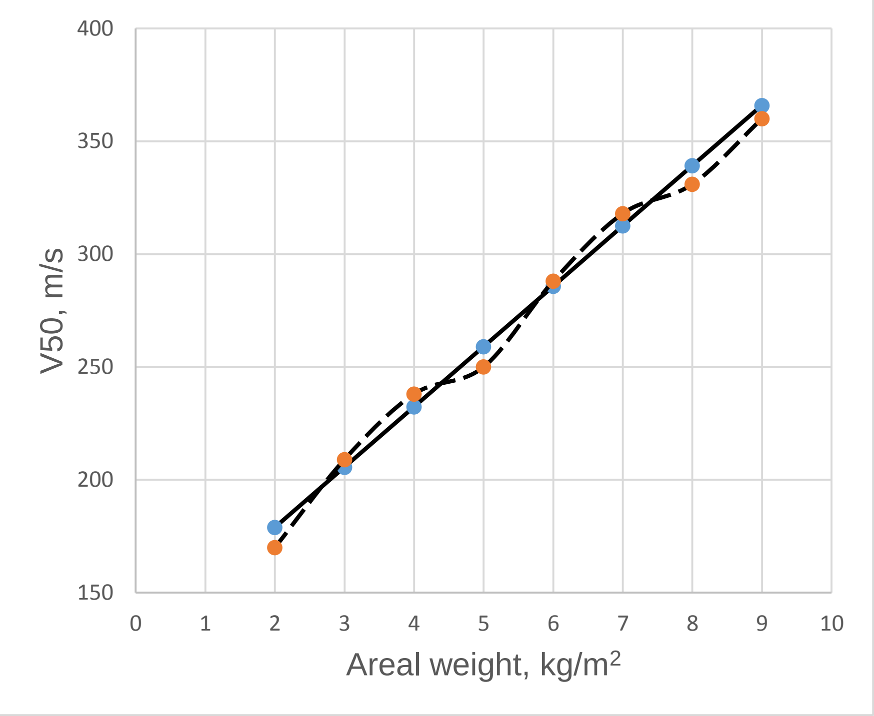

Figure 1. Theoretical vs. experimental (dashed line) values

experimental values obtained for composites with areal weight of 2, 3, 4, 5, 6, 7 ,8 and 9 kg/m^3 and resin content of 35 %, the results are presented in figure 1.

As we can see from figure 1 there is a good match between calculated and experimental data which means that we can rely on the regression equation for the chosen study domain.

Conclusion

Although the ballistic strength is not a linear function of the areal weight within a narrow study domain it can be used to predict the ballistic strength of composite material with a good degree of validity.

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