

Optimization Study of Ballistic Impact Tests on Carbon-Carbon Composites

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Abstract

In this study it is intended to optimize a high velocity impact case of a composite plate. The case is selected from the literature based on its dataset properties (e.g. amount of inputs and outputs, number of tests, physical relations with real life situations and relations between the properties studied on). The base study focused on failure response of advanced carbon-carbon composites under high velocity impacts. In the present study, two unique models are introduced within the scope of the present study as dimensionless damage areas of front and back sides of the composite plate. Multiple nonlinear regression method is used for objective functions of the optimization problem. The prediction models found in the present study are in first order trigonometric multiple nonlinear regression form; thus, these models can be considered as the basic prediction functions of high velocity impact response of carbon-carbon composites under high temperatures, in processing power terms. Since the determination coefficient values have been found quite similar with the ones in the base study, the presented models in this study can be considered successful to predict the results.

Introduction

Carbon-carbon composites are known about their unique behaviors. These relatively new developed engineering materials show ceramic behavior in nature but behave in a range from brittle to pseudoplastic. These materials have a wide range of real-life applications depending on their thermo-structural properties. These application areas include rocket nozzles, re-entry nose tips, aircraft brake discs etc. Working on these types of materials will enhance the performance of aerospace vehicles against basic natural drawbacks of the application area.

One of the experimental ballistic studies from literature is chosen as the base study and it is intended to develop a model to predict results of different experimental parameters by using optimization methods.

Xue et al. [1] worked on effects of hypervelocity impact on SiC coated carbon-carbon composites. In their study, ablation response of SiC coated carbon-carbon composites is investigated, and they concluded that impact velocity affects ablation rates. Also, they concluded that coating carbon-carbon composites with SiC improves ablation response of the plates.

Grujicic et al. [2] conducted a transient non-linear-dynamics-based analysis to investigate damage and failure response of carbon-carbon/carbon-foam composites under hypervelocity impact. These types of panels are used in common aero vehicles and they concluded that the damage is depending on normal component of the momentum of the projectile just before the impact. Additionally, it was observed that carbon-foam increases the hypervelocity impact resistance of common aero vehicles.

The study of Park and Fahrenthold [3] is shaped on the concern of orbital debris impact hazard on spacecrafts. They simulated the impact experiments of hypervelocity impacts on space shuttle wing leading edge made of carbon-carbon composite. They concluded that momentum scaling method can predict perforations accurately and validated simulations can bring results of beyond experiment conditions.

Curry et al. [4] discussed the arcjet test results of reinforced carbon-carbon composites impacted by hypervelocity debris. These tests are conducted at the NASA Johnson Space Center and test specimens were exemplar of the ones used in Space Shuttle Orbiter. They presented the correlation functions for front and back face mass loss and oxidation characteristics of reinforced carbon-carbon composites discussed in consideration of the results.

Xie et al. [5] investigated the structural integrity of advanced carbon-carbon composites under high temperature environments. In their study, heated carbon-carbon composites are exposed to high velocity projectile impacts to observe their mechanical responses and obtain the effects of different impact

parameters. They conducted tensile tests on the carbon-carbon samples to measure residual stresses after the high velocity impact tests. This study is selected as the base study and the dataset of their experiments are taken as the examples to the present study. Their impact test results are shown in Table 1.

Table 1. Impact test results [5] (“1” represents perforation while “0” represents no perforation)

T (°C)	v ₀ (km/s)	Test result	t _w /d _p	A _{front} /d _p ²	A _{back} /d _p ²	Impact energy (J)
1205	1.690	1	1.667	3.537	4.207	69.449
1206	1.680	1	1.667	1.781	2.498	68.629
1225	1.710	1	2.5	1.268	2.198	21.067
1230	1.700	0	5	2.95	0	2.603
25	1.690	1	1.667	3.501	5.519	69.449
1212	1.980	1	1	3.100	3.225	441.334
1218	1.676	0	3	3.42	0	2.530
1270	2.000	0	5	3.82	0	3.602
1230	1.704	1	1	3.376	3.999	326.871
1193	1.760	1	1.667	2.928	3.799	131.374
1205	1.700	1	1	2.640	3.303	70.273
900	1.700	1	3.333	2.090	3.591	70.273
819	1.886	1	1.667	8.998	10.956	86.492
1429	1.608	1	1.667	4.143	10.754	62.873
1220	4.600	1	1.667	21.32	25.169	514.525
1205	3.090	1	1.667	11.133	11.364	232.171
1234	3.900	1	5	12.554	14.52	13.698

The base study presented an experimental and analytical investigation on the effects of high velocity impact (1608 m.s⁻¹ – 4600 m.s⁻¹) and related damage on carbon-carbon composites at high temperatures (between 25 °C and 1429 °C) using a fast-electric heating system and two-stage light gas gun.

Two equations were presented as prediction of the effect of high velocity impact on the structural integrity of advanced carbon-carbon composites for high temperature applications in the base study. They concluded that the residual strength of the carbon-carbon composite samples improved by 47% by heating the samples.

Method

To obtain accurate models of objective functions, regression analysis method is used. Regression analysis method can accurately determine which variables have how much impact on the interested phenomena. Operating this method gives crucial information about the process of phenomena. First order trigonometric multiple nonlinear regression analysis method is used for the optimization process of this study. Standard form of first order trigonometric multiple nonlinear regression is:

$$Y = a_0 + a_1 \sin x_1 + a_2 \sin x_2 + a_3 \sin x_3 + a_4 \cos x_1 + a_5 \cos x_2 + a_6 \cos x_3 \quad (1)$$

Multiple form of nonlinear regression defines that there are more than one independent variables (for the present case, input types) in the objective function. The design variables are temperature of the composite sample during the impact test (°C), impact velocity of the projectile (km/s), and the fraction between the laminate thickness and diameter of the projectile (t_w/d_p). The system outputs are dimensionless frontal damage area (A_{front}/d_p²) and dimensionless back damage area (A_{back}/d_p²) for the present case. Optimization process has been done by using Wolfram Mathematica 11.0 software.

Results

In the base study, the models are presented with the additional variables of T_0 as room temperature and c_t as speed of sound in carbon-carbon composites, beside design variables. The presented models for dimensionless front and back damage areas in the base study are [5]:

$$\frac{A_{front}}{d_p^2} = 11.090 \left(\frac{T}{T_0}\right)^{-0.027} \left(\frac{v_0}{c_t}\right)^{1.175} \left(\frac{t_w}{d_p}\right)^{-0.150} - 4.925 \quad (2)$$

$$\frac{A_{back}}{d_p^2} = 11.219 \left(\frac{T}{T_0}\right)^{-0.117} \left(\frac{v_0}{c_t}\right)^{1.655} \left(\frac{t_w}{d_p}\right)^{-0.223} - 2.068 \quad (3)$$

The new first order trigonometric multiple nonlinear regression models presented in this study are:

$$\begin{aligned} \frac{A_{front}}{d_p^2} = & 10.487 - 0.677 \cos x_1 + 0.259 \cos x_2 + 0.314 \cos x_3 + 0.881 \sin x_1 \\ & - 7.406 \sin x_2 + 1.370 \sin x_3 \end{aligned} \quad (4)$$

$$\begin{aligned} \frac{A_{back}}{d_p^2} = & 12.102 - 2.510 \cos x_1 + 2.345 \cos x_2 + 0.503 \cos x_3 + 2.059 \sin x_1 \\ & - 8.389 \sin x_2 + 3.653 \sin x_3 \end{aligned} \quad (5)$$

where x_1 , x_2 and x_3 represent temperature of the composite plate ($^{\circ}\text{C}$), impact velocity of the projectile (km/s), and the ratio between the laminate thickness and diameter of the projectile (t_w/d_p), respectively.

After obtaining the models of the system, the determination coefficients (R^2) values are calculated for each of the output functions. Global minimum values of the system are determined for each of the two objective functions of damage areas. To consider the models as successful, determination coefficients should be over 0.9 (≤ 1), and this is the defined criteria of the success of the present study.

Comparison of the determination coefficient results found in the present study with the results given in the base study are shown in Table 2.

Table 2. Comparison of the determination coefficients

	Present study	Base study [5]
A_{front}/d_p^2	0.910	0.998
A_{back}/d_p^2	0.978	0.944

The new models presented in this study shows different determination coefficient agreements with the ones in the base study and it shows that, for one of the objective functions, optimization process of the present study has higher success rate than the one in the base study. Finally, global minimum optima outputs are found with applied constraints.

To obtain the effect of the ratio between the plate thickness and the diameter of the projectile, other input types are kept equal and the results are shown in Table 3. Similarly, same study is done for the effect of impact velocity and the results are shown in Table 4.

Table 3. Optimized input results and the effect of t_w/d_p value

Outputs	Minimized values	x_1 ($^{\circ}\text{C}$)	x_2 (km/s)	x_3 (t_w/d_p)
A_{front}/d_p^2	0.883	25	1.608	4.487
A_{back}/d_p^2	7.1×10^{-9}	25	1.608	3.294

Table 4. Optimized input results and the effect of impact velocity

Outputs	Minimized values	x_1 (°C)	x_2 (km/s)	x_3 (t_w/d_p)
A_{front}/d_p^2	0.883	25	1.608	4.487
A_{back}/d_p^2	6.3×10^{-8}	25	2.275	4.489

Conclusion

To determine the dimensionless damage areas, two novel equations are presented. The new models presented in this study show good determination coefficient agreements with the ones in the base study. The new presented model of dimensionless front damage area is better than the base model to predict the phenomena. According to the global optima results, it is seen that the effect of the impact velocity on the impact resistance of carbon-carbon composites appears to be more important than the dimensions of the projectile diameter, the testing temperature and the thickness of the samples. Dimensionless damage area can be minimized by decreasing the ratio between the laminate thickness and diameter of the projectile.

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