A Semi-Empirical Airborne Particle Erosion Model for Polyesteric Matrix Fiberglass Composites

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Abstract: *The paper deals with the mathematical modeling of the airborne solid particle erosion rate of composite materials, in particular non-oriented fiberglass reinforced polyesteric matrices. Using the mathematical tool of non-linear regression, based on experimental data available in the state of the art, an algebraic equation has been determined to estimate the relative erosion rate of such composites. The formulation is tailored so that it relates to classical erosion models such as Finnie's, Bitter's or Tulsa angle dependent model which can be implemented into commercial computational fluid dynamics software. Although the implementation - per se - is not described herein, the model proposed can be useful in estimating the global effect of solid particle erosion on composite materials in this class. Further theoretical developments may add to the model the capacity to evaluate the erosion rate for a wider class of matrices as well as more types of weavings.*

Key Words: *fiberglass, polyester reinforced composites, erosion rate, Gaussian distribution, non-linear regression*

1. INTRODUCTION

Composite materials have been used in the aeronautical applications since the early days of the industry, in most cases due to their high tensile strength and low specific weight Ref [1]. Areas such as helicopter blades Ref [2] and turbofan blades Refs [3, 4] have been designed to incorporate composite material shells with metallic leading edges that protect the blade against FOD impacts.

Apart from the impact with large objects or debris, helicopter or fan blades are also subject to erosion due to the impact with small particles that contaminate the air. Advanced physical-mathematical models describing the erosion rate of metallic materials exist in the specialized literature Refs [5-7] however they cannot be applied to composite materials because of two main reasons: the nature of the matrix is fundamentally different than that of metals and the interaction between the two phases (matrix and fibers) leads to a more complex behavior than with metals. In fact, even metal matrix composites behave differently to erosion than their base alloy (that makes up the matrix) Refs [8, 9].

Some analytical effort has been put into the in modeling the erosion rate of composite materials subject to contact erosion Ref [10], although the solid particle erosion has only been approached – in most cases – through experimental research Refs [11,12]. This is because of the semi-ductile behavior of composites. Due to its two phases, the composite displays both ductile and brittle behaviors in accordance with the two materials – carbon or glass fibers and phenolic or esteric matrix.

Moreover, as Barkoula and Kocsis Ref [13] and Roy et al. [14] point out, the polymer matrix composites erodes in a brittle manner whereas the thermoplastic matrix presents a ductile erosion pattern.

In order to study the complex physical phenomena occurring in the process of composite material erosion with solid particles entrained in fluids, numerical simulations have been developed Ref [15].

However, as is the case with most engineering applications, the main interest is focused on the global effects rather than the explanation of the process, therefore, CFD software have implemented erosion models Ref[16] for this particular task Ref [17]. It is one of the purposes of this paper to provide a simple mathematical relation that can be used for estimating the erosion rate in a similar way.

Because a pure theoretical deduction could only rely on the complete understanding of the processes that take place in the interaction of the entrained particles and the material, a semi-empirical approach was preferred instead.

Based on substantial experimental data provided in the literature Refs [18- 20], and knowing the generic dependencies of erosion to the angles of impact, velocity and material physical properties, an algebraic equation was determined. This equation, although lengthy, fits well with the dataset that was used to generate it and also has a formulation that allows it to be implemented in some commercial CFD software.

2. THE INTERPRETATION OF THE EXPERIMENTAL DATA

For the purposes of this paper, the data from Ref [18] were considered due to the more extended depiction of the experimental setup.

The experimental results provided by Patnaik (2008) Ref [18] are obtained through the implementation of the Toguchi algorithm Ref [21] for 300μm spherical erodent at an impact velocity of 32m/sec and a stand-off distance of 120mm.

Various methods were considered and tried for describing the dataset, including polynomial regression. However, as is the case with all polynomial curve fitting techniques, this method was prone to the Runge phenomenon as seen in Fig. 1.

The classic case where the oscillation around the correct values near the end of the dataset can be observed.

If this behavior were located at the left-hand side of the chart, where the low impact angles are plotted, the mean error might not have influenced too much the global result (since the erosion rate is in direct relation with the impact angle).

However, at the right-hand side of the chart, where the high angles of impact are located, the Runge phenomenon cannot be ignored. This approach was abandoned in favor of a more accurate curve fit.

As such, an initial processing of the raw data was deemed necessary. The first step was to change the variables as follows:

For the Ox axis:

$$\frac{1}{\sin(\alpha)} - 1 \tag{1}$$

for the Oy axis:

$$\frac{E_r}{E_{r(15^\circ)}} - 1 \tag{2}$$

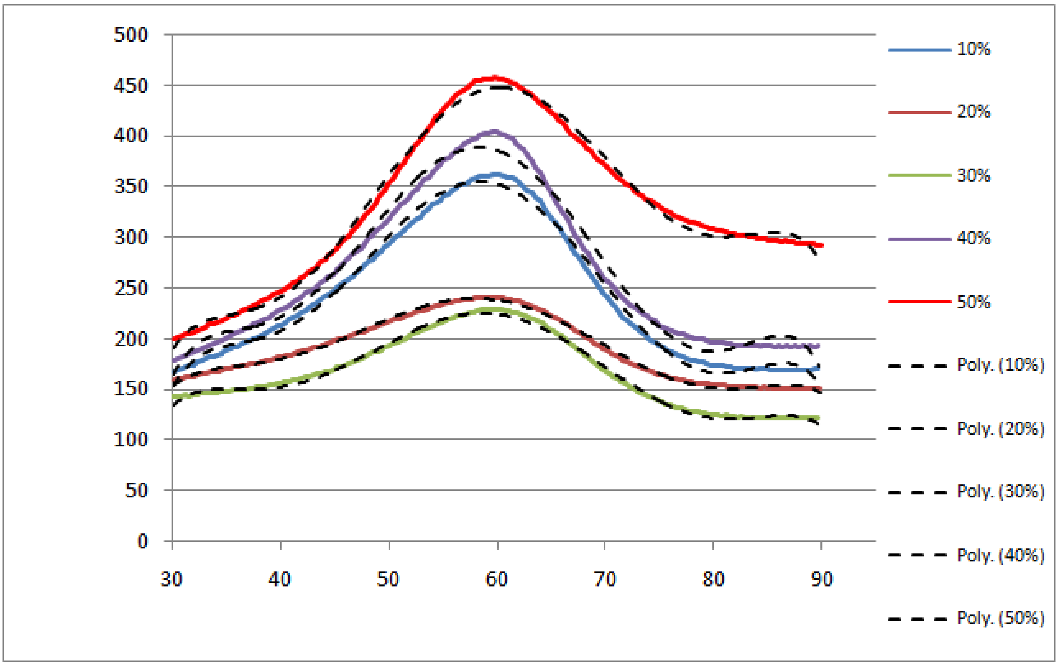
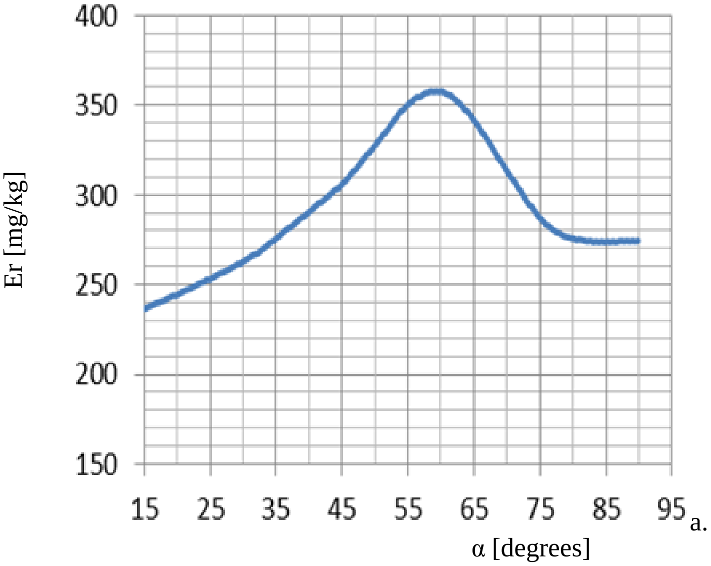


Fig. 1 – The Runge phenomenon observable for the polynomial curve fitting of the raw experimental data presented in Ref [20]

Note that the variable change for Oy, was constructed specifically to scale the top value to 1 and also to relate the entire dataset to the reference value of 15º angle of impact, the lowest angle tested.

A comparison of the two plots, initial and modified, is depicted below:



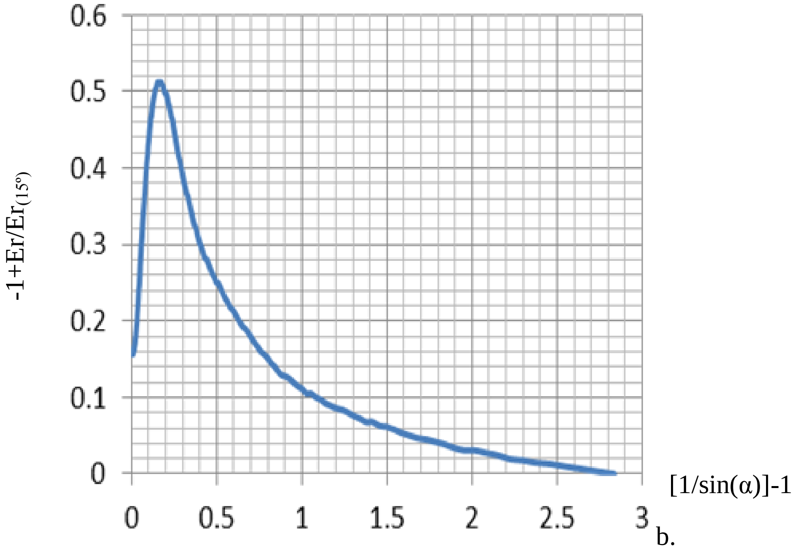


Fig. – 2 a. The initial dataset and b. the re-scaled chart
(the example isa re-interpretation for the 50% wt fiber content from the dataset given in [18])

The Ox change of variable was constructed in such a manner that the 90º angle of impact is represented in the origin of the axis. Therefore, although similar in shape, the second chart should not be mistaken with an erosion chart for a ductile material.

After a careful consideration of the new chart it can be observed that a good fit would be that of a logarithmic Gaussian function with the general expression below

$$f(x) = A \cdot Exp\left\{\frac{[ln(x/c)/l]^2}{-2}\right\} \tag{3}$$

where

A is the amplitude parameter
c is the center value
l is the width of the interval

In this case, non-linear regression Ref [22-24] was used in order to describe the experimental data.

Curve fits were thus calculated for each weight loading (fiber mass/total composite mass) and the results synthesized in the table below.

Table 1 – The individual values for the parameters of the log Gaussian fit function considered versus the fiber mass loading of the composite

Weight loading	Scaled percentage (x%/50%)	Amplitude	Center	Width
50%	1	0.4745	0.142	1.172
40%	0.8	0.4585	0.1481	1.093
30%	0.6	0.4649	0.1463	1.098

Since each of the three variables of the general equation considered depends on the fiber mass loading, each of them may be expressed as an equation depending only on the fiber weight percentage.

It should be stated that a re-scaling was preferred. Therefore the parameters for Amplitude, Center and Width were not directly expressed as a function of percentage but rather as a function of a scaled percentage which had the reference value to 50%.

The final equation, below, incorporates all the dependencies known from the experimental dataset:

$$f\,\frac{E_r}{E_{r(15°)}} = 1 + \left[0.28\,\left(\frac{p_m}{50}\right)^2 - 0.424\,\left(\frac{p_m}{50}\right) + 0.618\right] \cdot Exp\left\{-0.5 \cdot \left[\frac{ln\left(\dfrac{\frac{1}{\sin(\alpha_{imp})}-1}{-0.098\left(\frac{p_m}{50}\right)^2 + 0.147\left(\frac{p_m}{50}\right) + 0.093}\right)}{1.05\left(\frac{p_m}{50}\right)^2 - 1.495\left(\frac{p_m}{50}\right) + 1.617}\right]^2\right\} \quad (4)$$

Note that the input parameter is pm which is expressed in percent, although in all instances it appears in its rescaled form (divided by 50%).

3. CONCLUSION

Current aeronautical technologies rely increasingly on composite materials, even for some highly exposed parts such as the airframe, engine cowlings or even rotor blades. Exposure to FODs is one of the obvious reasons for designer concerns.

However, solid particle erosion can prove just as dangerous since, due to its nature, a composite rotor blade may lead to de-lamination or even detachment of the composite skin. It is therefore useful to have a mathematical model based on which to estimate, through simulations and calculations, the effects of exposure to particle-laden flows over the composite materials that make up certain aircraft components.

Since a complete and accurate theoretical analysis of the composite material erosion mechanism is not available in the literature, a semi-empirical approach was taken in order to estimate the global effects rather than the detailed processes at work in this particular type of erosion.

The paper discusses the possibility of incorporating the experimental data from solid particle erosion of composite materials into an algebraic equation in order to estimate the erosion rate as a function of the angle of impact and the weight content of fibers. A relative erosion rate equation was preferred for several reasons:

1. The impact velocity parameter can be more easily implemented based on a single experimental point known. In this case, the starting point is the erosion rate at 15° for the impact velocity of 32 m/sec with a spherical shape erodent of 300μm diameter.

2. For the mathematical processing of the raw data it was seen that, for the classical fitting equations, the graph shape was only suited for polynomial regression – which induced large errors particularly because of the Runge phenomenon. Therefore, a change of variable was used for both axes in order to use a different equation for fitting.

After this pre-processing of the experimental data, a non-linear regressing method was used for the curve fitting using a logarithmic Gaussian function dependent on three variables. In turn, each variable was found to depend on the fiber mass loading percentage. Using further fitting, by quadratic polynomials, the final equation was determined.

The envisioned application for this equation is the implementation into computational fluid dynamics (CFD) software, however the algorithm for this will be highly dependent on the CFD code itself rather than the physical phenomena.

Other implications of the proposed equation refer mainly to its form, meaning that similar equations may be determined for other composite materials, leading to further dependencies added. Such dependencies may be the addition of the physical properties of the matrix, fibers, the weave patterns as well as technological processes employed while creating the material.

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