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A RELIABILITY ANALYSIS PROCEDURE FOR THE DESIGN OF A HELICOPTER COMPOSITE ARMOR WITH CORRELATED DESIGN VARIABLES

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Abstract— **A procedure for reliability analysis of a two layer - ceramic and composite - aeronautical armor is presented, where the reliability is assessed for various projectile and armor performance criteria. The armor is designed to comply with several constraints and uncertainties in the design parameters, such as projectile mass and velocity, and armor material and geometry. Numerical results were obtained to evaluate the reliability of an optimal armor, using a stochastic optimization procedure and a partial least squares approach to consider the correlation of the random design variables. The reliability analysis considers three performance criteria: residual projectile velocity, maximum armor displacement, and number of remaining layers of the armor. Analytical models for these performance criteria were fitted to finite-element simulation data, adjusted as meta-models using regression and design of experiments techniques. The performance criteria were obtained both for the average and optimal values of the design variables. The optimal armor presented a slightly improved reliability, for all performance criteria. Monte Carlo simulations were used to assess the armor reliability, considering the performance criteria separately, and also the system reliability. The system reliability results were slightly worse than the expected results considering independent performance criteria, showing some correlation between these criteria.**

Keywords— **Reliability Analysis, Ballistic Impact, Composite Materials, Optimization**

I. INTRODUCTION

In this work a reliability analysis for helicopter armor is performed based on a stochastic optimization technique and on Monte Carlo simulation. The armor, designed for the helicopter floor, is modeled as a bi-material plate, consisting of a single ceramic layer and several composite ones. The reliability analysis is an important feature for the design of armors. Studies on the use of a combination of ceramic and composite layers for armors and its corresponding reliability are scarce in the literature.

The operational use of military and police aircraft requires their exposure to high risk situations, where the aircraft could be hit by projectiles. In such situations, armors can be used to protect the lives of the crew and to avoid loss of the aircraft. Several types of materials could be used in the manufacturing of armors, such as steel, aluminum, ceramic and composite materials. The use of composite layers and ceramic materials is common in armors, where the thickness of each layer must be in accordance with the required level of protection.

Composite materials consist of a matrix and fiber reinforcement combination. A common type of matrix is the epoxy resin, and common types of reinforcement fibers include graphite, glass or polymer fibers. The material properties of a composite can be tailored by using different types of matrix and fiber arrangements. For example, fibers can be placed in only one direction or randomly distributed into a matrix. In most cases, the composite will have stronger mechanical properties in the direction of the fibers [1]. The many advantages of composite laminates including their light weight, robust specific stiffness and strength, and superior vibration, noise, and electromagnetic wave damping capacities, the application of such composite laminates to industrial structures has been rapidly increasing during the last few decades [2].

Several researches can be found in the literature regarding the design and performance of bi-material armors, but usually not include a reliability analysis. The first work using a two-layer armor was using aluminum and ceramic materials [3]. Composite materials have been used in primary structures of aircraft, particularly in helicopters. The main advantages of their usage are the low weight and the ability to produce complex shell structures, widely used in armors [4]. A two-layer armor was also investigated, wherein the layers were made of boron carbide (ceramic) and Kevlar 49 (composite) materials, with specified thickness for each layer [5]. Other research also discusses the usage of composite materials in

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armor design, highlighting the importance of the use of different layers in a composite armor [6].

In the work by [7], the impact of a low-speed projectile with semi-spherical tip into glass fiber/epoxy laminate plates with layer orientations of 0º/90º/0º/90º was assessed, focusing on the observed cracks and delamination. Other research was developed a structural ballistic armor system for the floor of the RAF C-130 aircraft. Three different types of plates and five different types of materials were assessed, wherein each layer had a specified thickness [8]. The work developed by [9] investigates the performance of an armor using ceramic/composite layers, subjected to both normal and oblique impacts with a 7.62 AP projectile. Another researcher investigated the use of honeycomb-based structures as armor for low-speed projectile impacts [10]. The ballistic compaction and penetration of ceramic powder targets also has been studied experimentally and computationally using powder compacts of different initial densities and thickness [11].

Several researches involving impact problems use numerical simulations, usually with a finite-element numerical code. For instance, in [12] an explicit finite element method, the r-adaptive, also called Single-Material Arbitrary Lagrangian Eulerian (SALE) was used in the numerical simulations.

This work investigates the reliability of a two-layer - ceramic and composite - optimal armor. The first step was the use of a finite element code to simulate the dynamics of the projectile penetration in the armor. Numerical results are obtained by using this code during the projectile penetration for: i) the velocity of the projectile, ii) the distribution of stresses in the armor, iii) the displacement of the different regions of the armor; and iv) the remaining layers of the armor which are still resisting further penetration. The second step was the building of meta-models as response surfaces for these parameters by using a regression technique. The third step consists of an optimization procedure using these reduced-order models to obtain an optimal armor. This optimization minimizes the kinetic energy of the projectile after a given penetration, taking into account several constraint equations, such as the minimum number of remaining layers after penetration, the maximum displacement allowed after penetration, armor weight limitations, and limitations in the helicopter center of gravity. The fourth step consists of setting performance criteria for the projectile residual velocity, maximum displacement of the armor, and number of remaining layers of the armor. By using these performance criteria, the armor reliability for both the original and the optimal armor is investigated. Each criterion is considered individually as well as and the armor as a system, for the failure due to these combined criteria. A comparison between the individual and system probabilities of failure was made to investigate for the possible independence or correlation among these performance criteria. Monte Carlo simulations were also performed for the system reliability, considering these performance criteria altogether. The approaches to obtain the meta-models, the optimization techniques, and the performance criteria adopted are also discussed. Numerical results for the simulations are presented. The armor reliability is discussed for the various performance criteria, highlighting the effectiveness of the optimal armor.

II. ASPECTS OF THE SIMULATION TECHNIQUES

A. Material properties

The composite armor plate consists of two layers with different material properties; one of ceramic material and another of a composite material. These materials act in a complementary way during the projectile penetration process. The material properties for the ceramic (Alumina) and composite layer (Kevlar 49) and for the projectile are adapted from [13].

Some good results can be obtained when the first layer, supporting the initial impact, is made of a fragile material as Alumina. The main purpose of this material is to destroy the projectile head and also to dissipate most part of its energy. The next layer is made of a ductile material which must absorb the residual energy from the projectile fragments and armor material by changing the kinetic energy into plastic deformation energy [9].

B. Computational ***simulation***

A 3D finite element (FEM) analysis model is created using ANSYS/LS-DYNA® to simulate the transverse impact of a projectile into a patch of ceramic/composite material. Impact analysis involves the hit of a 7.62 mm diameter projectile into an armor plate. For this simulation, the following parameters were made to vary: i) the number of layers for the composite plate; ii) the angle of incidence of the projectile; iii) the mechanical properties of the composite plate (E - Young modulus) and σ_x - mechanical strength); and iv) the projectile initial velocity.

Some comparisons were made before setting the modeling as: comparison between elements solid and shell, comparison between layers of guidance, boundary condition, the tip of the projectile and quantity elements.

Following the ballistic protection [14], a 25 cm × 25 cm armor plate was idealized. The ceramic thickness is assumed as 6 mm while the composite thickness varies according to the number of layers. The simulations with elements of solid / shell and shell / shell for the two layers did not respond well to the impact. The junction of these elements suffered much bending and shear stresses which are not well represented by the shell element. Comparing the results the best representations of reality were the two materials (ceramic and composite) were used *SOLID* element 164. The mass of projectile is assumed as 9.7 g following [14].

The projectile geometry is very close to reality except for a flattened tip with the goal of reducing the singularity of the mesh. The projectile mesh was designed with sweep tool, using

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solid elements hexahedrons. Fig. 1 shows a typical arrangement with a ceramic layer and 12 composite layers (1mm each). The mesh of the plate was divided into four parts with the objective of reducing the number of elements. The region closest to the projectile has 2 x 1 cm and the elements are smaller. The plate mesh is mapped displaying elements that grow from the center to the borders.

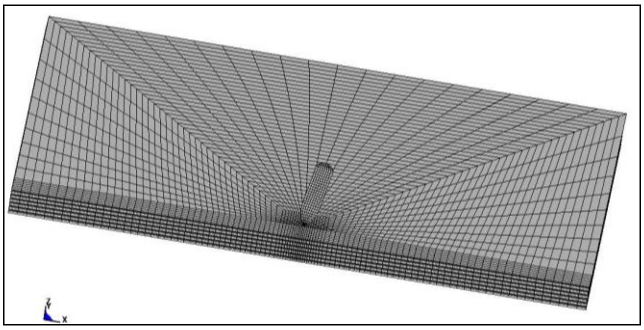

Fig. 1. Model simulation for the armor: typical 3D mesh arrangement.

To reduce the computational cost, symmetry conditions were used, and only half of the plate was simulated. Further reduction of the model to one-fourth of a plate was not possible, due to non-symmetry of one of the design variables (the incidence angle of the projectile), which may vary around its central value of 90 degrees with respect to the plate. The only symmetric condition for this angle of incidence is at its central value.
In order to analyze the effect caused in the materials due to the impact of the projectile into the armor plate, a plastic kinematic model for the projectile and for the ceramic plate, and a damage composite material model for the composite plate [15] were used in the simulation.

C. Meta-models: obtaining the response surfaces

To create a meta-model for the responses of interest as a function of the basic variables of the problem, two steps are needed. In the first step, a design of experiments (DOE) approach is needed to decide upon which design points to use in the numerical simulations. The second step consists in fitting the various response results into response surfaces by using a multiple regression technique.
A central composite design (CCD) for the DOE was used. According to [16], this method contains an embedded factorial or fractional factorial design with center points which are augmented with a group of star points that allow estimation of curvatures. The CCD has 3 types of designs, which depend on where the star points are placed. The CCD type used in this work was the CCF (Face Centered). In this design, the star points are in the center of each face of the factorial space. This design requires 3 levels for each factor (minimum, center and maximum values for each variable). The total number of tests of a CCD experiment is based on a full or fractional factorial experiment with a total of experiments n = 2k +2k + m, where:

- 2k - number of factorial points;
- 2k - number of axial points;
- M - number of replications of the central point.

Thus, the CCD generated 32 experiments with 16 points in the cube, 10 axial points, and 6 central points with a replica using a fractional factorial design.
The data was generated by using a finite element code, and for this reason there was no need for replication of each design point, as the responses would be the same for such points. The CCD used in this work generated more points than the corresponding 2K factorial and fewer points than the corresponding 3K factorial, which was considered satisfactory for this project. Where K is the number of factors and in this case we have 5 design variables. These 5 design variables are: Nlayer (number the layers for the composite plate), Aproj (angle of incidence of the projectile), the mechanical properties E and σ (Young's modulus and mechanical strength, respectively), and V (initial velocity of the projectile).
The normal distribution model N (μ, σ^2), wherein μ is the mean and σ^2 is the variance, was assumed in this work for the following random variables: *Nlayer*, *Aproj*, the mechanical properties E and σ, and V.
The parameters for the random variable related to the composite plate number (*Nlayer*) were assumed as μ = 12 and σ = 1. For this variable, upper and lower design limits were established as mean plus or minus three standard deviations.
The angle of projectile incidence (*Aproj*) was made to vary between ± 10º, with a mean of μ = 0º. An angle of 0^o corresponds to a direct impact, in which a deeper penetration is expected. In impact problems, there is a need to assess the behavior of the armor in relation to the incidence angle. Other research assessed the performance of the residual velocity with projectile obliquity (0^0, 15^0, 30^0, 45^0, 60^0, 90^0) [17]. This researcher stated that the residual velocity increases as the projectile obliquity increases.
Several parameters are important to define the failure modes of the composite material. The load applied on the plate, the sequence of piling up of the layers, the plate geometry, and the mechanical and chemical properties of the layers (fiber, matrix and interface) are parameters which usually define a failure mode. Some parameters can be more important than others, and different parameter combinations can generate a variety of failure modes.
In this work, the two-layer armor consists of a first layer of ceramic material and a second layer of a composite material. In this case, when the ceramic material is placed above the composite material, the pressure distribution along the projectile is less than in the case where the projectile is impacting directly on the composite material. In this sense, the

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plate made of composite material receives less pressure from the projectile [3]. In order to analyze the effect caused in the material and the fracture models on the penetration of the projectile into the armor plate, for the given impact velocity, FE simulations are conducted using a plastic kinematic model for the projectile and for ceramic plate, and a damage composite material model for the composite plate [15]. Plastic kinematic hardening material model is a strain rate dependent elastic–plastic model. Composite Damage Model was developed by Chang and Chang [15], for failures in the composite material. The Chang/Chang criteria is given as follows: for the tensile fiber mode, for the compressive fiber mode, for the tensile matrix mode, for the compressive matrix mode. The material parameters, such as, longitudinal tensile strength, transverse tensile strength, shear strength, transverse compressive strength, and nonlinear shear stress parameter, are used in the failure criteria. These five material parameters are obtained from strength measurement of the material. Also, elastic modulus, material density e Poisson ratios are used at the model.

The following two variables (E and σ) correspond to material properties used in the computational simulation.

For design purposes, material properties are often taken from standard properties tables obtained from engineering books. These tables usually do not consider the inherent randomness of these variables. The randomness and correlation of the design variables in the impact process plays an important role and needs to be investigated and included in the analysis. This investigation refers to material properties when high strain rates are present. When the material is under these conditions, as in the case of impacts, the material properties may vary.

This feature makes it impossible to use the stress-strain relationships of the materials, available for the static case. When considering the effects of the strain rate on the composite behavior, [18] found that the tensile mechanical properties of Kevlar 49 fiber bundles depend both upon the strain rate and the temperature. The strain rate for a temperature of 15 ºC was used, and the corresponding mechanical properties for the composite material, σ (mechanical strength), and E (Young's modulus) are shown in Table 1.

Table 1. Mechanical Properties of Kevlar 49 fiber bundles versus strain rate at 15 ºC (adapted from [5]).

Mechanical properties	**Strain rate**		
	140	**440**	**1350**
***σ* (GPa)**	2.94	3.02	3.08
***E* (GPa)**	112	119	125

The velocity of the projectile (*V*) used in the simulation model complied with the parameters of the norm for Ballistic Resistant Protective Materials [14]. According to this norm, the projectile was assumed, for these simulations, to be a 7.62-caliber of 4.7x10-3 kg mass, with speed of 838m/s ± 15 m/s. The design variables and their respective μ and σ are summarized in Table 2

Table 2. Design variables.

Design Variables	**μ**	**σ**
N_{layer}	12	1
A_{proj}	0º	10º
V	838m/s	15 m/s

The variables Aproj and V are design variables however, uncontrolled. In this paper, analyses were made for the worst conditions of each variable. For the projectile incidence angle (Aproj) the worst situation occurs when the angle is 0° and with a standard deviation 10. In this case, if the plate can absorb the worst condition, it can absorb the others situations. For the variable velocity (V) we adopted an initial velocity of 838 m/s, according to [14]. For this variable, we used a variance of ±15 m/s. Here, when the variance reaches +15 m/s it presents the worst situation and if the plate can absorb this worst situation, it can absorb the others conditions.

Meta-models were obtained as response surfaces for the various response variables of interest, as a function of the basic independent variables (predictors) through regression techniques, with data obtained from the computational simulations at the design points.

In the present work, a partial least squares (PLS) technique was used. PLS is a regression technique that generalizes and combines features from principal component analysis (PCA) and multiple regressions. The reason for using PLS is to predict a set of dependent variables (responses) from a set of independent variables (predictors) [19]. According to [20], this prediction is achieved by extracting from the predictors a set of orthogonal factors called latent variables which have the best predictive power. The regression parameters are estimated so as to give a "best fit" of the data. This technique is a frequently applied technique for multivariate regression in the case when the explaining variables or predictor variables are highly correlated [21]

Obtaining relationships between response variables of interest and the given variables represents considerable computational effort. Several experiments need to be performed to measure the effects of one or more variables in the final response of a particular problem. The decision of which factors would influence in a particular process or product is often faced. To perform an experiment, some factors are selected and a multiple-variable regression technique can be used. In this work, three regressions were performed; one for the decrease in the projectile velocity, another for the maximum displacement of the armor plate and finally the number of perforated layers of composite material. The three performance criteria namely residual projectile velocity, maximum armor displacement, and number of remaining layers of the armor as well as the design variables (*Nlayer*, *Aproj*, *E*, σ, and *V*) are random variables.

The variables Nlayer, Aproj, the mechanical properties E and

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σ, and *V* were normalized with respect to their mean values in order to obtain coefficients of the same order of magnitude [22]. The three performance criteria were obtained from ANSYS/LS-DYNA®. The study of the relationships between the variables is done through a statistical regression technique. A correlation coefficient was considered (R^2), which measures the linear relation between two variables [23]. This coefficient shows that a given variance in a variable is explained through another variable under study, indicating how the model fits the data.

III. Response Optimization and Reliability Analysis

A. Sequential quadratic programming (SQP)

Three response surfaces were generated as functions of the basic independent variables (*Nlayer, Aproj, E,* σ, *V*), through PLS techniques. The equations generated were: the final velocities of the projectile, the maximum displacement of an element in the last composite layer, and the number of remaining layers (not perforated) in the composite plate. These response equations can be used as objective functions or constraint equations in the optimization procedure. The resulting problem is a nonlinear decrease in the projectile velocity, to be minimized, subject to nonlinear constraint equations for the displacement, for the number of remaining layers, and other constraint equations already available for the plate weight and helicopter center of gravity. These equations can be set in the general framework of a nonlinear programming problem. The sequential quadratic programming (SQP) technique was used to obtain a local minimizer, i.e. a local solution for the optimization problem. SQP is a method that consists in solving a general problem in the form of Eq. (1):

$$\begin{aligned} &\min_{x \in R^n} \quad f(x) \\ &\text{Subject to} \quad g(x) \le 0 \\ &h(x) = 0 \end{aligned} \tag{1}$$

where

$f(x): R^n \to R \quad g(x): R^n \to R^{md}, \; h(x): R^n \to R^{mi}$

n – Number of variables;
md – Number of inequality constraints;
mi – Number of equality constraints.

This optimization problem was used to find a local optimal point. Contrary to other methods which try to convert the problem into a sequence of subproblems of optimization with no constraints, SQP tries to solve the optimization problem iteratively. The solution in each step is obtained by the solution of an approximation of the non-linear problem, where the objective (f(x)) is substituted by a quadratic approximation and the non-linear constraints (h(x) and g(x)) are substituted by linear approximation.

B. Risk-based design and Monte Carlo simulation

The first reliability method used in this work is the risk-based design methodology presented in [24]. Once obtained the optimal points through the SQP procedure, the armor reliability was evaluated for both the optimal and the original armor design, the latter being considered as the mean values of the design variables. For the reliability analysis, a structure with a resistance R subject to a single load S is considered. If both R and S are normal variables, that is, $N(\mu_R,\sigma_R)$ and $N(\mu_S,\sigma_S)$ then a new random variable z can be introduced as
Z = R – S.
Variable S is related to some design variables as the number of layer and composites materials properties, velocity and projectile incidence angle and variable R is related to the capacity of the armor to support a load from projectile.
Assuming R and S are statistically independent, z is also a normal random variable, with mean and variance given by $N(\mu_R-\mu_S,\sqrt{\sigma_R^2+\sigma_S^2})$ [24]. With this assumption, the probability of failure can be defined as:

$$P_f = 1-\Phi\left[\frac{\mu_R-\mu_S}{\sqrt{\sigma_R^2+\sigma_S^2}}\right] \tag{2}$$

where Φ is the cumulative distribution function (CDF) of the standard normal variable, and P_f is the probability of failure. The event of failure is given by R < S or z < 0 and the probability of failure depends on the average and standard deviation of z. The reliability probability can thus be calculated as 1 - P_f .
In this work, Monte Carlo simulation is also used as an alternative method for reliability evaluation in order to compare the armor reliabilities with the reliability results from the corresponding Monte Carlo simulations.
Monte Carlo simulation is able to simulate processes which depend on random factors [22]. In this paper, N successive samples are randomly generated for the input variables, then the performance functions are evaluated for each random set of input variables, and finally the armor reliability is obtained as the proportion of the successful cases among all simulations, for the various performance criteria.

IV. Numerical Results

Numerical results were obtained for several finite element simulations in the impact process. The data from these simulations were retained for the responses as a function of the independent variables, and DOE and regression techniques were used to create meta-models for these responses. These meta-models were subsequently used in an optimization procedure. The randomness in the responses was used to evaluate the reliability of the armor original and the optimal designs, for various performance criteria.

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Several energies are involved in the impact process, and need to be considered when obtaining the response surfaces. The first energy to be considered is the projectile kinetic energy due to its velocity, which starts from its initial value, decreasing to its final value, after penetrating the armor and exiting on the other side of the armor plate, or decreasing to zero, if the projectile is stopped by the armor plate. Other types of energy are related to the energy absorbed by the projectile in its plastic deformation (mostly due to the ceramic part of the armor plate), or the energies absorbed by the armor plate in its own deformation, either in the form of elastic potential energy of deformation. The energy can also be related to the energies absorbed by the armor plate in the form of plastic energy of deformation, including here the destruction of the ceramic layer, or the rupture of the fibers, or the breach of the resin in the composite layer. Also, some amount of the projectile initial energy could be transferred to the armor in the form of kinetic energy, but at its final position the armor kinetic energy goes back to zero. The amount of kinetic energy lost by the projectile must be absorbed by its deformation, or by the armor deformation, or by the deformation of the aircraft structure to which the armor is attached [25]. In this study, only the total loss of the projectile kinetic energy or velocity is considered, and the fractions of energy that go to each of these processes are not investigated.

The model used for the numerical simulations assumes a rectangular plate with fixed boundaries. A finer mesh is introduced near the location of the projectile impact. For the remaining parts of the armor plate, a coarse mesh is used, as the influence of the impact is small and becomes negligible in regions far away from the impact location. Also, the model considers that, for an effective armor, the plate should absorb the entire kinetic energy due to the projectile velocity. To obtain the response surface for the velocity equation (to be used later as an objective function in the optimization procedure), data from the numerical simulation were tabulated as function of the basic variables (N_{layer}, A_{proj}, E, σ, V), and the obtained regression equation is shown in complete optimization model is represented by Eq. (7).

A performance criterion for the velocity was assumed so that the remaining velocity is equal or less than 3% of the projectile initial velocity of 25.14 m/s. This residual velocity criterion was used both as a constraining equation in the optimization procedure and also as a performance criterion for the armor reliability evaluation.

Three parameters were generated from the regression equation for the velocity. The first parameter obtained was the coefficient of determination R^2 which evaluates the fit of the regression model to the numerical data and indicates the amount of data variability explained by the regression curve. A value for the R^2 coefficient close to one indicates a good correlation. The second parameter obtained was the significance level, p-value, of the various coefficients of the regression equation, each coefficient being assigned its own p-value. A small p-value of a particular coefficient in the equation should be expected, indicating the significance of this particular coefficient. When considering only these two parameters, the results for this regression were considered poor, as the R^2 was very small (around 0.6) and the p-values were considered too high (bigger than 0.05).

The third parameter analyzed in this problem was the variance inflation factor (VIF) which is associated with each basic independent variable (predictor) [26]. This factor detects multicollinearity or correlation among predictors. The VIF measures the correlations among the predictors. A VIF = 1 indicates no relation among predictors; a VIF > 1 indicates that the predictors are correlated; and a VIF > 10 indicates that the regression coefficients are poorly estimated. The results obtained in this work showed a VIF > 10 for most of the coefficients in the regression equation, hence confirming that the regression equation was not acceptable, due to the presence of high multicollinearity. Some possible solutions to this problem can be adopted, such as: i) eliminate predictors from the model, especially if deleting them has little effect on R^2; ii) change predictors by taking linear combinations of them using partial least squares regression (PLS) or principal components analysis (PCA); and iii) in the case of fitting polynomials, subtract a value near the mean of a predictor before squaring it. The solution adopted here for the problem of multicollinearity of the design variables was to use a PLS model. The results obtained from the PLS regression model adopted indicate an adequate fit, with a $R^2 = 0.9196$ and a p-value of 0.002 for the equation (in this case, no p-value is assigned for the individual coefficients).

The optimization model includes the above-obtained response surface for the velocity as the objective function, and a number of constraint equations. Some of these constraint equations are not available as closed-form equations, and also need to be obtained as response surfaces by using regression techniques similar to the one used for the objective function. The first constraint equation in the model was related to the weight of an armor plate of mass m, $P = m.g$. Assuming the acceleration of gravity g as constant, a function for the mass of the armor plate can be set as indicated in Eq. (3):

$$w = \left(T_{cer} \times \rho_{cer} + N_{layer} \times T_{comp} \times \rho_{comp} \right) A \leq 40kg \tag{3}$$

where:

$T_{\text{cer}} = 0.006$ is the ceramic plate thickness (in m);

$\rho_{\text{cer}} = 3720$ is the ceramic material density (in kg/m^3);

N_{layer} = is the number of layers of composite;

T_{comp} = each layer with thickness of 0.001 m;

$\rho_{\text{comp}} = 1460$ is the composite material density (in kg/m^3);

A is the armor plate area (width times length in this case of a rectangular plate).

For this weight equation, the maximum value allowed for the armor weight was assumed as 40 kg. In this optimization model, the armor plate was idealized as a (1 x 1.5) m rectangular plate in the aircraft cockpit. This armor plate is made of small square plates of (25 x 25) cm each, and for our purposes, only one of these small plates was simulated. In order to guarantee some degree of effectiveness in the protection of the aircraft crew, the armor plate was assumed to be on the helicopter floor. This armor plate was assumed to be installed in a HELIBRAS-EUROCOPTER Squirrel helicopter model AS350 B2, which is a model currently in use by several military and police operators.

The aircraft center of gravity (CG) must remain within operational limits, usually established by means of an analysis of stability and control of the aircraft. The aircraft mass M changes while the fuel is burned and the ammunition is used. A critical situation for the variation of the aircraft center of gravity due to the presence of the armor plate occurs when the aircraft is light, with a minimum of fuel and ammunition. Here, this situation is assumed to occur when the aircraft mass is 2000 kg. With respect to the total mass of the aircraft, another constraining equation could have been established, with the critical situation occurring when the aircraft is heavy, with maximum fuel and ammunition. This constraining equation was not considered in this work, as the armor masses involved in this problem were small with respect to the total aircraft mass.

For every aircraft type, an envelope establishing operational limits for the aircraft CG and mass is the documentation available for the user, usually in the pilot manual. When the armor is placed below the pilot's seat, the aircraft CG must remain within the limits specified in this envelope. From the mass-CG envelope in the Squirrel pilot manual [27], the longitudinal CG of the aircraft is seen to vary between the forward limit of 3.17 m and the aft limit of 3.46 m, for a 2000 kg aircraft mass. In this pilot manual, the origin (or reference) for the CG location is a point located 3.40 m in front of the center line of the main rotor head. In this work, the origin of coordinates is assumed to be exactly below the head of the main rotor, corresponding to the position of the aircraft CG without the armor plate. From this origin, two distances can be measured: X, the aircraft CG position without the armor plate (therefore zero), and X_{CG}, the position of the armor plate center inserted in the aircraft (assumed to be constant). The equation for X_{CG} leads to two constraint equations, one for each operational limit of the longitudinal CG, the forward and the rear limits, which now complies with the following operational interval: ($-0.23 \leq X_{CG} \leq 0.06$) m. The position of the aircraft CG is written in Eq. (4) as

$$X_{CG} = \left(X.M + X_{CG'}.w \right) / \left(M + w \right) \tag{4}$$

where:

X_{CG} – center position of the armor plate (assumed constant);

X – CG origin (assumed zero);

M – aircraft mass without the armor plate (assumed in its critical case);

$X_{CG'}$ – armor center position with respect to X_{CG};

w – armor plate mass (varying with thickness and material density).

Substituting (3) into (4), X_{CG} is obtained as in Eq. (5):

$$X_{CG} = \left(X_{CG'}.w \right) / \left(M + w \right) \tag{5}$$

The forward and aft operational limits for the aircraft CG, as discussed above, lead to two constraining equations shown in Eq. (7):

$$\begin{aligned} X_{CG} &= \left(X_{CG'}.w \right) / \left(M + w \right) \leq CG_{aft} = 0.06 \\ X_{CG} &= \left(X_{CG'}.w \right) / \left(M + w \right) \geq CG_{forward} = -0.23 \end{aligned} \tag{6}$$

The fourth constraint equation (*Disp*) is related to the critical displacement of an element belonging to a layer of composite material below the region where the impact has occurred. The equation (*Disp*) was obtained through the regression of the finite element results for the displacement of this element (Eq. (7)).

The maximum displacement for this element was limited to 2 mm. The values obtained using the PLS approach were R^2 = 0.7443 for the coefficient of determination, and p = 0.215 for the equation p-value.

The last constraint equation in the optimization procedure is related to the number of remaining layers of the composite material, and its corresponding fit obtained from the regression technique is shown in Eq. (7):

The criterion assumed for the number of remaining composite layers was that at least two layers must not be perforated for a successful armor. In case this criterion is not achieved, the armor plate is considered not effective. For this equation, the values obtained from the PLS model were R^2 = 0.9336 for the coefficient of determination and p = 0.001 for the equation p-value. The PLS models for the objective function (V_f) and for the response surface corresponding to the number of layers (*Layers*) provided good fits, while the fit of the PLS model for the displacement (*Disp*) was slightly poorer, but considered acceptable for this work.

The above-described equations were used in the optimization problem, consisting in one function to be minimized, and a set of five constraint equations. These constraint equations were related to the aircraft CG, the plate weight, the displacement of the element opposite to the projectile in the composite plate, and the number of remaining layers, while the function to be minimized was the projectile velocity. This optimization problem was solved by using a Sequential Quadratic Programming (SQP) procedure to find a local optimal. The complete optimization model is represented by Eq. (7):

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$$
\begin{aligned}
&V_f = 33343.8 - 146.0N_{layer} + 130.6A_{proj} + 8803.9E - 20433.3\sigma - 54721.7V - 115.6N_{layer}^2 - 8.3A_{proj}^2 \\
&-3625.0E^2 + 10610.1\sigma^2 + 28474.6V^2 + 0.3N_{layer}A_{proj} + 0.9N_{layer}E + 176.7N_{layer}\sigma + 175.7N_{layer}V \\
&-32A_{proj}E + 154A_{proj}\sigma - 252.7A_{proj}V - 82.3E\sigma - 1434.8EV - 1006.0\sigma V \le 25.14m/s \\
&w = \left(T_{cer} \times \rho_{cer} + N_{layer} \times T_{comp} \times \rho_{comp}\right) A \le 40kg \\
&X_{CG} = \left(X_{CG'}.w\right) / \left(M + w\right) \le CG_{aft} = 0.06 \\
&X_{CG} = \left(X_{CG'}.w\right) / \left(M + w\right) \ge CG_{forward} = -0.23 \\
&Displ = 1.9 + 0.02N_{layer} - 0.001A_{proj} + 0.13E + 1.01908\sigma - 4.9754V + 0.00052N_{layer}^2 - 0.00042A_{proj}^2 \\
&-0.0889E^2 - 0.40221\sigma^2 + 2.5982V^2 - 0.0001N_{layer}A_{proj} - 0.01N_{layer}E - 0.004N_{layer}\sigma - 0.006N_{layer}V \\
&+0.00023A_{proj}E + 0.00107A_{proj}\sigma + 0{,}000A_{proj}V + 0.02940E\sigma + 0.03819EV - 0.24023\sigma V \le 2mm \\
&layers = -2636.53 - 68.57N_{layer} - 64.11A_{proj} - 1572.46E + 1011.50\sigma + 5888.54V - 1.18N_{layer}^2 + 2.43A_{proj}^2 \\
&+307.86E^2 - 1060.78\sigma^2 - 3351.12V^2 + 1.75N_{layer}A_{proj} + 4.56N_{layer}E + 32.25N_{layer}\sigma + 41.9N_{layer}V \\
&+5.7A_{proj}E + 18.81A_{proj}\sigma + 38.41A_{proj}V + 636.94E\sigma + 318.28EV + 450.43\sigma V \le -2
\end{aligned} \tag{7}
$$

After using an SQP solver available in MATLAB®, a minimum value for the projectile velocity was obtained for the minimizer point where the values of the basic variables were obtained as: (i) number of composite layers $N_{\text{layer}} = 12$; (ii) angle of projectile incidence $A_{\text{proj}} = 0$; (iii) Young's modulus $E = 119$ GPa, (iv) mechanical strength $\sigma = 3.02$ *GPa*, and (*v*) velocity for the projectile $V = 838$ m/s. The optimization procedure was written in terms of response surfaces, which are meta-models of the original FEM model. The variables N_{cam}, A_{proj}, E and V were normalized with respect to its mean values in order to obtain coefficients of the same magnitude. Following, the response surface equations [22] were generated. Here, we used as initial values for the variables, in the optimization procedure, the lower value of each variable, considered as the worst situation. Then, the optimal value of each design variable was found in the optimization procedure. To investigate the quality of the obtained optimal point, another FEM analysis was performed with the values of the design variables at this optimal point. The following results were obtained from this FEM simulation: V_f= 22.65m/s; *Displ* = 1.7 mm, and *layers* = 3, showing that the optimal armor does satisfy all constraint equations as desired. The numerical results for the optimal point, obtained by using the SQP procedure, are expected to depend on the initial guess adopted in this optimization procedure, especially if the constraint equations are highly non-linear or lead to a con-convex feasible region. In this work, starting from different initial guesses had only a minor influence in the optimal results. Thus, for this optimization procedure, the initial guess for all design variables was assumed at their mean values, as a first approximation.

After the optimal armor was obtained, the armor reliability was then evaluated, both for the optimal armor (with the design variables at the optimal point) and for the original armor (with the design variables at their mean values). The reliability analysis was performed using a simplified technique in which a performance function $z_1 = R\text{-}S$ was defined, following [24]. This performance criterion was defined as the difference between the load-carrying capacity of the armor (R) and the external loading (S) due to the impact of the projectile. The variable S is related to the demand on the system, and the variable R is related to the system capacity.

Both S and R are random in nature; their randomness is characterized by their mean values μ_S and μ_R, standard deviations σ_S and σ_R, and corresponding probability density functions $f_S(S)$ and $f_R(R)$. From the uncertainties in the S and R variables, expressed in the form of their probability density functions, one can express the risk measure in terms of the probability of the failure event $P(R < S)$ as: $p_f = P(failure) = P(R < S)$. If both R and S are assumed as normal variables, then the performance function z_1 also behaves as a normal random variable. With this assumption, the reliability could be easily evaluated as the probability $P(success) = P(z_1 > 0)$, while the probability of failure of the armor plate is obtained as $P(failure) = P(z_1 < 0) = 1\text{-}P(success)$.

In this work, three performance criteria were investigated. The first performance criterion is related to the remaining velocity of the projectile after some simulation time (the same simulation time of 80 μs, as used to obtain the numerical results in the optimization procedure). In this case, an acceptable velocity after this simulation time should not exceed 3 % of the initial velocity of the projectile. The second performance criterion is related to the maximum displacement of a layer below the projectile, which was assumed not to exceed 2 mm. Finally, the third performance criterion is related to the number or remaining layers in the composite plate, after the projectile has crossed over the initial layers of the armor, during the simulation time allowed. For our purposes, an acceptable number of two remaining layers were assumed. For all three criteria, the corresponding reliability of the optimal armor was evaluated and compared to the reliability of the original armor.

The following discussion details the procedures for the first performance criterion concerning the original armor (with the design variables at their mean values). For an armor plate to provide protection, the projectile must not penetrate, and the initial kinetic energy of the projectile must be completely absorbed by the armor or by a combination of the armor plate and the aircraft structure in the impact process. The numerical simulations are computationally very extensive, and the time interval for the projectile velocity to become zero can be very large, leading to great computing times for the simulation until a complete stop of the projectile. A stop criterion was adopted in the simulations to account for the amount of kinetic energy lost by the projectile during the impact. A set of data for the projectile velocity while it penetrates the armor plate was obtained from the numerical simulations as a function of time, and of the basic variables N_{layer} (composite plate thickness), A_{proj} (angle of projectile incidence), E and σ (material properties), and V (initial velocity for the projectile). The projectile velocity at the time of 80 μs was then noted. A multiple regression of the velocity data, as a function of, N_{layer}, A_{proj}, E, σ, and V was then performed, and a response surface was obtained as an equation. Then, to ensure non-penetration of the armor plate, the performance criterion assumed that the remaining velocity must be equal or less than 3 % of the initial

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velocity of the projectile. Eq. (8) was obtained as

$$z_1 = 3\% V_{initial} - V_f \tag{8}$$

where $V_{initial}$ = 25.14 m/s and V_f was previously obtained in Eq. (5). By replacing the variables N_{layer}, A_{proj}, E, σ, and V with their respective mean values $\mu(N_{\mathrm{layer}})$, $\mu(A_{\mathrm{proj}})$, $\mu(E)$, $\mu(\sigma)$ and $\mu(V)$, the mean value of z_1 was = 4.14. Also, the derivatives of z_1 with respect to N_{layer}, A_{proj}, E, σ, and V were obtained in Eq. (9) as, respectively:

$$\begin{aligned}
\left(\frac{\partial z_1}{\partial N_{layer}}\right) &= -146 - 231.2N_{layer} + 0.3A_{proj} + 0.9E + 176.7\sigma + 175.7V \\
\left(\frac{\partial z_1}{\partial A_{proj}}\right) &= 130.6 - 16.6A_{proj} + 0.3N_{layer} - 32.0E + 154.0\sigma - 252.7V \\
\left(\frac{\partial z_1}{\partial E}\right) &= 8803.9 - 7250E + 0.9N_{layer} - 32.0A_{proj} - 82.3\sigma - 1434.8V \\
\left(\frac{\partial z_1}{\partial \sigma}\right) &= -20433.3 + 21220\sigma + 176.7N_{layer} + 154.0A_{proj} - 82.3E - 1006.0V \\
\left(\frac{\partial z_1}{\partial V}\right) &= -54721.7 + 56949.2V + 175.7N_{layer} - 252.7A_{proj} - 1434.8E - 1006.0\sigma
\end{aligned} \tag{9}$$

With data from Eq. (9), the mean and variance of the response for the performance criterion concerning velocity were obtained in Eq. (10) as:

$$\begin{aligned}
\mu_{z1} &= \mu(25.14 - V_f) = 25.14 - \mu_{Vf} = 4.14 \\
\sigma_{z1}^2 = \sigma_{vf}^2 &= \left(\frac{\partial z_1}{\partial N_{layer}}\right)^2 \sigma_{N_{layer}}^2 + \left(\frac{\partial z_1}{\partial A_{proj}}\right)^2 \sigma_{A_{proj}}^2 + \left(\frac{\partial z_1}{\partial E}\right)^2 \sigma_E^2 + \left(\frac{\partial z_1}{\partial \sigma}\right)^2 \sigma_\sigma^2 + \left(\frac{\partial z_1}{\partial V}\right)^2 \sigma_V^2 = 2.2889
\end{aligned} \tag{10}$$

To validate the use of the sensitivities from Eq. (9) into Eq. (10), the design variables were made to vary in a range of ±10 % as shown in Table 3:

Table 3. Variability of the design variables.

% Variability	N_{layer}	A_{proj}	E	σ	V
+10%	$1.8422e^{-10}$	$4.1068e^{-6}$	$8.9179e^{-5}$	$7.1884e^{-14}$	0.9999
Mean	$1.8421e^{-10}$	$4.1063e^{-6}$	$8.9241e^{-5}$	$7.1456e^{-14}$	0.9999
- 10%	$1.8421e^{-10}$	$4.1059e^{-6}$	$8.9291e^{-5}$	$7.1107e^{-14}$	0.9999

The results from Table 3 show that there was no significant change when the design variables values were imposed changes in ±10 % range.

The sensitivity of the variance of the response z_1 with respect to separate variations of the design variables was also evaluated. For that, the design variables were made to vary +20 % from each mean value, changing the corresponding derivative in Eq. (10). The remaining derivatives were kept at their mean values. The values of the variance of z_1, obtained for all cases, are presented in Table 4.

Table 4. Sensitivity of the variance of z1 with respect to separate variations of the design variables.

Variables at their mean values	1.1411e+020
Nlayer - at +20% level	1.1411e+020
Aproj - at +20% level	1.1409e+020
E - at +20% level	1.1395e+020
σ - at +20% level	1.1411e+020
V - at +20% level	1.6460e+020

A comparison of the variance values from Table 6 indicates that σ^2_{z1} is more sensitive to variations of the projectile velocity, and is reasonably robust with respect to changes in the other design variables.

Considering the small sensitivity both in the mean value and in the variance of z_1, as presented in Tables 3 and 4, respectively, the evaluation of the sensitivities in Eq. (9) can be made for the design variables evaluated at their mean values, with no significant loss in accuracy for the mean and variance of the response, as evaluated in Eq. (10).

The obtained performance criterion z_1 is a normal random variable, with mean μ_{z1} and standard deviation σ_{z1}. To obtain the corresponding reliability, the probability of failure is evaluated after a transformation of z_1 into a corresponding standard normal variable z, as shown in Fig. 2. The critical value of z is obtained in Eq. (11), as the value corresponding to $z_1 = 0$.

$$z_c = \frac{z_1 - \mu_{z_1}}{\sigma_{z_1}} = \frac{0 - 4.14}{\sqrt{2.2889}} = -2.73 \tag{11}$$

Thus, from a standard normal probability table, one can see that the probability of failure is given as $\Phi(-z_c)$ = 0.32 %, and the corresponding reliability of the armor, for this performance criterion, is 99.68 %.

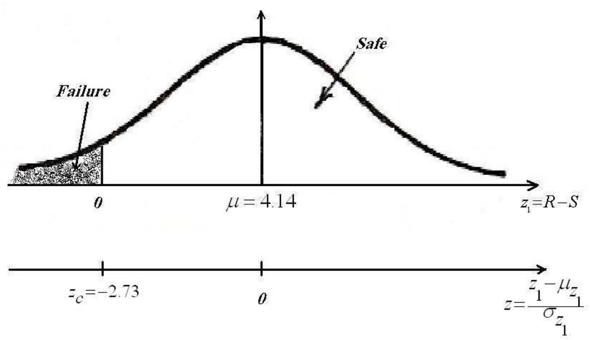

Fig. 2. Probability of failure for performance criterion z1, assumed as normal random variable.

The reliability of the original armor (with the design variables at their mean values) was evaluated with this technique, for the first performance criterion, as a simplification for the case

where *R* and *S* could be assumed as independent normal random variables. Thus, the performance function z_1 was also normal, and the reliability of the armor plate, given as the probability of $z_1 > 0$, was obtained using simple standard normal tables.
The reliability of the original armor was also obtained for the other two performance criteria. The details of the calculations were not included in this text, as the reasoning is the same and only function z_1 and its derivatives were different, for each case. The reliability of the optimal armor was obtained in a similar way, for all three performance criteria, by replacing the values of the design variables at the optimal point in Eq. (8) to (10), instead of their mean values. From these three performance criteria, the reliability results are shown in Table 5, for the original and optimal armors.

Table 5: Comparison of the values of reliability for the original and optimal armors.

Performance criteria	Reliability (original armors)	Reliability (optimal armors)
Projectile velocity	99.68 %	99.81 %
Maximum displacement	91.65 %	95.82 %
Number of remaining composite layers	99.99 %	99.99 %

From the above results, it can be seen that the second performance criterion, the maximum displacement, was much more stringent than the other two criteria adopted, and a failure of the armor is expected to happen according to this criterion. Thus, the second criterion was considered as the critical one, in this case. The reliability results obtained using these three performance criteria were not of the same order of magnitude. One must note that this displacement criterion uses the regression equation (*Displ*) with the worst fit (the obtained R^2 is not close to 1 and the *p*-value is too big). This possible correlation between the poor results for the displacement criterion and the poor fit of the displacement equation obtained from regression suggests that the regression equation could be further enriched with higher order terms. These terms may be missing in the current regression, which was limited to second-order terms.

Monte Carlo (MC) simulation was also used to compare with the reliability results presented in Table 4. Each MC simulation was performed by randomly generating values for the design variables and by replacing these values in the performance equations for the three criteria (for example in Eq. (10), for the velocity criterion). The values of reliability found using this method are shown in Table 6, for the three performance criteria. When comparing Tables 4 and 5, one can see that the MC results correlate well with the performance criteria results that used the approximations of quadratic response surfaces and normal distribution for the probability of failure. It must be noted that again the maximum displacement was the critical criterion. This could be related to the fact that the MC simulation was performed based on the regression equation with a poor fit, as the computational cost of performing a MC simulation using directly the finite element model would have been too high.

Table 6: Reliability values using Monte Carlo simulation.

Performance criteria	Monte Carlo
Projectile velocity	98.28 %
Maximum displacement	93.23 %
Number of remaining composite layers	98.85 %
System failure probability	87.38 %

Results were also included in Table 6 for the evaluation of the system reliability using MC simulation. The system reliability was evaluated considering the total cases of failures, regardless of the failure criterion, where concurrent failures counted as one failure only. The obtained system reliability (87.38 %) can be compared to the system reliability that would have been obtained assuming that the three performance criteria were independent. In that case, the system reliability would have been obtained directly as the product of the three individual reliabilities, which leads to 90.57 %. The system reliability led to slightly different (smaller) results, when comparing to the case of independent criteria, indicating a slight correlation between these criteria.

V. CONCLUSION

In this work, a procedure was presented to optimize an armor plate for a helicopter, and to obtain its corresponding reliability. The armor was assumed as a two-layer plate, in which the first layer was made of a brittle material (in this work, alumina) to smash the projectile head, and the second layer was made of a composite material (in this work, aramida fibers in a resin matrix), to absorb the projectile energy, to avoid perforation.
Numerical data was obtained from finite element simulations performed at a number of design points, adopted from a Design of Experiments (DOE) approach. From this numerical data, meta-models were obtained, using a regression technique, as response surface equations to be used in the optimization procedure. The design points were generated from a Central Composite Design (CCD) procedure, which has generated a number of design points considered satisfactory for this project.
The high correlation between the basic variables caused a problem of multicollinearity. To account for this problem, a partial least squares regression (PLS) model was adopted. The PLS regression model adopted, including quadratic terms, has presented better results, both considering the R^2 and p-value regression parameters, when compared with a simple quadratic regression.
The optimal armor was obtained from an optimization procedure for the objective and constraint equations obtained through this meta-modeling. The objective equation selected was related to the velocity of the projectile after a given simulation time. The constraint equations included were related to the weight of the armor plate, the aircraft stability

(written in terms of the path of the aircraft center of gravity), the displacement of a layer of composite below the projectile, material properties and the number of remaining layers of composite material after the projectile penetration. A Sequential Quadratic Programming (SQP) procedure was adopted, in which a local optimal was searched in the vicinity of the mean values of the basic design variables.

For the reliability analysis, three performance criteria were used, for the residual velocity of the projectile, maximum displacement of the armor, and number of remaining layers of the armor after projectile penetration. Analytical models for these performance criteria were fitted from simulation data obtained from several runs of a finite element code, adjusted as meta-models using regression and design of experiments techniques.

The sensitivities in the equations for the performance criteria were evaluated at the mean values of the design variables, as no significant loss in accuracy for the mean and variance of the response was obtained, with changes in the design variables.

The performance criteria were obtained both for the average values and the optimal values of the design variable. The numerical results obtained showed slightly improved reliability for the optimal armor design, for all three performance criteria considered. For comparison, Monte Carlo simulations were performed for the armor reliability using the three performance criteria adopted, with comparable results. Monte Carlo simulations were also performed for the system reliability, considering the three performance criteria altogether. The system reliability results were slightly worse than the expected results considering independent performance criteria, showing some correlation among these criteria.

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