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Weight And Reliability Optimization Of A Helicopter Composite Armor Using Dynamic Programming

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Summary

This work presents an approach for weight and reliability optimization of aeronautical armors. Military and police helicopters are usually exposed to highly risky situations, with a high probability for these aircrafts to be hit by projectiles. In this context, floor aircraft armor can be used to protect the crews' lives. However, the armoring of an aircraft causes an increase in weight. If this extra weight is poorly arranged, the changes in aircraft centroid position may even destabilize the aircraft. Thus, it is essential to design an armor not only to protect the aircraft, but also not to conflict with aircraft design restrictions, such as the maximum allowed weight and the aircraft centroid position. To reach these design objectives, it is necessary to use analytical and numerical tools. In this work, the weight and reliability optimization is made for a helicopter composite armor by means of dynamic programming. An ANSYS/LS-DYNA® model is used for the numerical simulation, using the built-in code for non-linear transient dynamic events, such as the ballistic impacts in study. To simplify the aircraft armor analysis, the protected area is divided into a mesh, consisting of a set of rectangular plates, and only the impact in one plate is considered. In this work, the armor is a thin two-layer plate, wherein the first layer reached by the projectile is made of a ceramic material and the second one is made of a composite material. The impact is assumed to occur in the center of the plate. For each failure mode assumed for the armor, a failure criterion was established. For example, a possible breach is analyzed considering the kinetic energy absorbed by the armor, the permissible displacement for the armor is evaluated considering the displacement of a certain representative point, and limits in weight exist due to limitations in the aircraft centroid path. Optimum values for the weight or the reliability are obtained, complying with the imposed restrictions.

keywords: ballistic impact; composite materials; optimization; reliability

Introduction

Weight and reliability are important parameters in the design of an aeronautical armor. Armors are expected to be reliable when offering protection against projectiles and munitions fragments, and at the same time, to have low weight and to be easy to manufacture. In general, composite materials are lighter than metallic materials of same strength, and add flexibility in the design, as they can be easily

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manufactured into very complex forms. A composite armor represents an additional weight to be minimized, constrained to satisfy certain mechanical characteristics of interest (resistance to the rupture, resistance to aggressive environments, etc. [1]).

In this work, the weight and reliability of an helicopter armor are optimized using a numerical model for the dynamics of the system projectile-plate, and dynamic programming for the optimization procedure. This armor, intended for the helicopter floor, has two layers, the first one made of a ceramic material, and the second one made of a composite material. Armors like this have been used for ballistic protection by many military operators, employing composite materials such as Kevlar® or Dyneema®. The combination of ceramic and composite materials for the armor is still an on-going research, with few available published results.

The weight and reliability optimization are performed using a dynamic programming approach, running several finite element models for different values of the thicknesses of the two layers. In this work, about 1400 numerical simulations were run. As a comparison, in the work of Liu and Mahadevan [2], five thousand cases were performed for the Monte Carlo simulations, under four different applied stress levels, to compute the fatigue life. The minimum thickness for non-penetration of the projectile is observed for each material combination, using numerical data obtained from several values of the total plate thickness. The reliability analysis considers constraint equations for the position of the helicopter center of gravity, or centroid (CG), for the maximum armor thickness allowed, for the energy absorbed by the armor as a function of the kinetic energy of the projectile, and for the displacement of a point in the composite layer of the armor plate.

Material Properties and Computational Simulation

The composite armor is formed by a combination of two materials with different properties. These materials act in a complementary way during the projectile penetration process. Best protection results are obtained when the first layer, the one that receives the initial impact, is made of a fragile material, such as Alumina. The objective of this layer is to destroy the projectile top and also to dissipate most part of the projectile energy. The next layer is made of a ductile material that has the purpose of absorbing the residual energy of the fragments from the projectile and also from the armor material itself, by changing the kinetic energy into plastic deformation energy [3].

A computational simulation is carried out using ANSYS/LS-DYNA®. A 3D finite element (FE) analysis model is created, to simulate the transverse impact of a projectile into a patch of Alumina/Kevlar® or Alumina/Dyneema® fabric. The impact analysis involves the hit of a 7.62mm-diameter projectile with a semi-spherical nose shape into an armor of varying thickness. The investigation of the resulting penetration is done in order to evaluate the effect of the material and 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 material model for the projectile and the Alumina coating, and a damage composite material model for the composite plate [4]. In the modeling of the latter, not all of the possible parameters for the FE model were used, due to the lack of material data.

Following the norm for Ballistic Resistant Protective Materials (NIJ STANDARD 0108,01) [5], the armor plate was idealized as a 25cm × 25cm square plate, surrounded by a plate region not deformed by the impact. Thus, in order to comply with this norm, the projectile was assumed, in the simulations, to be a 762-caliber of with a speed of 838 m/s. The mass of the projectile (1.94e3 kg) is obtained from the density of the material, which is considered to be 4340 steel. The norm allows for an interval of ±15 m/s in the projectile speed, not considered in this work. Also, the initial projectile speed detailed in the norm is higher than the speed at the moment of the impact, as the projectile slows down during its trajectory, thus the value stated in the norm relates to the worst-case scenario. Also, in this work the projectile is assumed to reach the armor plate perpendicularly, which was also considered to be a worst-case scenario.

Weight and Reliability Analysis

The model used in this work for the numerical simulations assumes a rectangle plate with fixed boundaries. To reduce the computational costs only half of the plate was simulated. Also, the model considers that, for an effective armor, the plate absorbs the entire kinetic energy of the projectile. In future works, new considerations could be included in the model, such as changes in projectile mass and speed, different angles of projectile incidence, the effect of high rates of deformation in the material properties, the maximum tension permissible for the materials, aircraft stability, and different boundary conditions, in order to consider more realistic parameters. The armor plate reliability analysis was performed for the two material combinations (Kevlar/Alumina and Dyneema/Alumina). After defining the possible failure modes, the failure probability p_f is defined simply as$p_f = N_f/N$, where N_f is the number of simulations in which occur failures occur (for example, the number of plates which perforate), and N is total number of simulations.

The analysis for the armor weight can be performed using the same dynamic model as for the reliability case. In this work, the uncertainty in the armor weight is not considered. Assuming the acceleration of gravity g as constant, the weight function has the following form:

$$f_1 = (3720X_1 + X_2X_3)A \tag{1}$$

with: X_1– first plate thickness (ceramic material); X_2 – second plate thickness (composite material); A – armor plate area (for a rectangular plate, width multiplied by length); X_3 – composite material density ρ (ρ_1 = Kevlar or ρ_2 = Dyneema).

In this work, an average density is considered for the composite materials, and only two cases are considered: a density ρ_1 for Kevlar, and a density ρ_2 for Dyneema. For the reliability analysis, the armor was idealized as a 1.00 m × 1.65 m rectangular plate. In order to guarantee some degree of effectiveness in the protection of the aircraft crew, the armor plate was assumed to be located at the helicopter main cabin floor. This armor plate was assumed to be installed in a HELIBRAS-EUROCOPTER helicopter model AS350 B2 SQUIRREL, which is a helicopter model currently in use by several military and police operators.

The aircraft 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 burnt and the ammunition is used. In terms of the variation of the position of the aircraft CG due to the presence of the armor, the critical situation occurs when the aircraft is light, with a minimum of fuel and ammunition. In this work, 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 a maximum of 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, operational limits for the aircraft's CG and mass are presented in the aircraft documentation available for the user, usually in the pilot manual. When the armor is placed below the pilots' seat, the aircraft CG must remain within the specified limits. For the mass-CG plot in the SQUIRREL pilot manual [6], the position of the longitudinal CG of the aircraft can vary between the forward limit of 3.17 m and the rear limit of 3.46 m, for the case of 2000 kg aircraft total 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 passing through 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. From this origin, two distances can be measured: X_{CG}, the aircraft CG position without the armor (hence zero), and $X_{CG'}$, the position of the center of the armor plate that is being inserted in the aircraft (assumed to be constant). The equation for X_{CG}, the centroid of the aircraft with the armor, leads to two constraint equations, one for each operational limit of the longitudinal CG, the forward and the rear limits, now complying with the following operational interval: $-0.23\ m \quad \leq X_{CG} \quad \leq 0.06\ m$.

Another constraint is related to the energies involved in the process. For an armor plate to provide protection, the projectile must not penetrate. Thus, the initial kinetic energy of the projectile must be completely absorbed by the armor, or by a combination of armor plate and aircraft structure, during the impact process. The numerical simulations are computationally very extensive and the time interval for the projectile kinetic energy to become zero can be very large, leading to great computing times for the simulation of a complete stop of the projectile. In this work, a stop criterion was adopted in the simulations to account for the amount of kinetic energy lost by the projectile during the impact. This criterion was such that if the projectile had lost 98% or more of its initial kinetic energy at a time 50 μs after initial contact, the armor was considered effective.

Another constraint equation comes from the armor maximum displacement. In the simulations performed in this work, the displacement of the element opposite to the projectile in the 2nd plate (composite material) was considered as the critical case. The maximum displacement is assumed to be reached after a 50 μs time, and the maximum allowable displacement is limited to 18 mm. The last constraint equation relates to the maximum admissible weight for this armor, which was assumed not to exceed 40kg.

Numerical Results

For the simulations, the thicknesses of the two armor layers were divided into intervals, with two intervals for X_1 (2.0 to 2.5 and 2.6 to 3.0) and thirteen intervals for X_2 (2.1 to 3.0 up to 14.1 to 15.0). The reliability (that is, the complement of the failure probability) was found, having, as constraining equations, the kinetic energy (leading to an assessment if the armor breaches or not) and the displacement of a node in the last element of the armor plate (as seen from the line that contains the projectile trajectory). A count was performed for the number of cases in which the armor failed, considering the kinetic energy constraint. Next, for the cases in which a success was counted with respect to this energy constraint, the displacement constraint was then assessed, and a new count was performed for the number of failure occurrences with respect to this second constraint. For each interval for X_1 e X_2, the value for the armor reliability was noted, so that a plot for the reliability as a function of these thicknesses was generated. In this work, another constraint was also considered, in terms of the armor weight. For each interval, the armor weight was evaluated, such that the maximum allowable value for the aircraft CG displacement was not exceeded. A comparison between the results found for the two types of composite materials evaluated didn't show a significant difference. Thus, in this work, only the results for one of the ma-

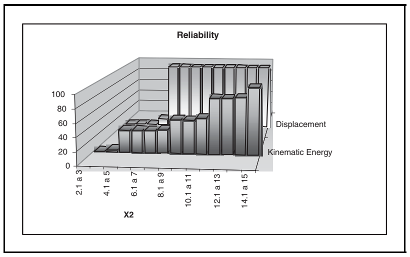

Figure 1: Reliability of the armor plate with varying layer thickness X_2, for X_1 between 2.0 and 2.5.

terials are presented. The reliability results are shown in Fig. 1, for each thickness interval for the two layers of the plate (X_1 e X_2). As can be seen in Fig. 1, reliability values above 95% can be attained, if the thickness X_2 exceeds 14mm, while X_1 is kept between 2 e 2.5mm. It must be noted that if the armor is breached (kinetic energy constraint is not satisfied), the constraint for the displacement does not work, as the point where the displacement is evaluated was destroyed in the perforation. The case for X_1 between 2.6 mm and 3.0 mm (with reliability at 100%) was not presented in Fig. 1. Analyzing the maximum admissible displacement plot in Fig. 1, one can see that there was a significant change in the armor structure rigidity with the increase in thickness. The armor weight also increases with the thickness in a similar pattern, and the plot is not included here. The assumed limitation in maximum weight is not surpassed for X_1 between 2.6 mm and 3.0 mm, and X_2 between 2.1 mm and 8.0 mm.

Conclusions

This work presented a weight and reliability optimization analysis of a helicopter armor plate made of a two-layer material, using dynamic programming. The equations used in the optimization model were obtained by regression of data acquired from finite element simulations. The armor weight and reliability were obtained as functions of the layer thicknesses X_1 and X_2, and a reliability maximum was attained, complying with all the constraints, including the maximum allowable weight. For both composite materials considered, the analysis did not show a significant difference. For future works, other constraint equations can be included in the analysis, in order to consider more realistic models and thus to improve the quality of the results.

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