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Blast actions in aircrafts: An integrated methodology for designing protection devices

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ABSTRACT

We introduce a numerical approach for evaluating the behaviour of aircraft fuselages subjected to internal explosions. At variance with available approaches, we consider fluid-structure interactions through a novel integrated methodology able to take into account both stress at cruise altitude and blast fast-dynamics in interaction with pressurization not considered as a static load. The precision of the proposed numerical procedure allows us to foresee a nonstandard composite protective device.

1. Introduction

We record non-accidental airplane internal explosions since 1933, in the cargo hold of a Boeing 247D; the explosive was nitroglycerin. Table 1 shows a list of similar subsequent events. Until the explosion induced in the Boeing 707-124 in 1962, explosive devices placed in the baggage compartment plaid role. Then, in-cabin explosions became dominant. First, in 1987 liquid explosives were used and rapidly replaced by plastic explosives placed inside shoes, laptops, and other devices. Prevention based on a screening before boarding contrasted so far these actions. Gillen and Morrison [1] report a comparative study of European total expenditures on aviation security: 5.7 billion euros in 2011.

In this context, the idea of the so-called *unit load devices* (ULD) emerged. It is a design of luggage containers with the aim of absorbing energy from an in-cargo explosion. Examples are ULDs made of fiber-reinforced composites [2] and bilayer hardened luggage containers. In the latter case, the inner layer of lightweight foam captures debris, the outer layer mitigates pressure [3]. Usual protections (see e.g. [4,5]) consist of blowout panels designed to be weaker than the surrounding airframe. During an in-cabin explosion, blowout panels fail with consequent pressure decrement and possibly controlled fuselage failure. At a cruise altitude, pressurization and gravity play a non-negligible role together with the inertia of the rigid-body component of the airplane motion.

Standard experiments on the overall mechanical behaviour of fuselages usually deal with a fatigue design. Those involving explosions commonly exploit an aircraft at ground, loaded just by gravity (see [6]). The experiment described in reference [7] considers a partial pressurization in a Boeing 727, while those reported in reference [8] refer just to a plane panel with a preceding pressurization. Large-scale effects afflict fuselage dynamics.

We record [10] attempts of designing reinforced plates made of Aluminum-based alloys or glass-reinforced Aluminum (GLARE) by taking into account blast actions. A question not yet largely investigated is, however, the behaviour of the aircraft in its whole.

There are computational analyses of blast actions on fuselages, based on a Coupled-Eulerian-Lagrangian (CEL) approach. In particular Dacks and Toczyski [11] consider an explosion in the luggage compartment of an Aluminum-based fuselage, represented as a cantilever beam; their analysis neglects possible rigid-body motion of the whole structure. Kotzakolios and Vlachos [12] refer to Airbus A380 and introduce pressurization just as a static load on the skin.

In this paper, we propose a numerical procedure for evaluating the response of a fuselage subjected to an in-cabin explosion, with the aim of indicating a possible passive cabin protection.

At variance of other approaches, our analysis includes gravity and pressurization loads at cruising altitude. We consider different volumes of air inside and outside cabin, different velocities of traveling shock waves, and changes in pressurization.

In Section 2 we describe fuselage's geometry and schemes for the pertinent design. Sections 3 and 4 deal with the representation of blast actions and the constitutive behaviour of Aluminum-based alloys, respectively. Section 5 describes possible passive protections based on

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Table 1
Non-accidental explosions in airplanes, from [9].

Date	Flight	Description	Casualties
1933	Boeing 247D, United Air Lines	Bomb made of nytroglicerin Placed in the baggage compartment	7
1949	Douglas C-47-DL, Canadian Pacific Airlines	Bomb made of dynamite Placed in the baggage compartment	23
1955	Douglas DC-6B, United Air Lines	Bomb made of dynamite	44
1962	Boeing 707-124, Continental Air Lines	Explosive device inside passenger cabin	45
1966	Douglas RD4-1, Aden Airlines	Explosive device inside passenger cabin	30
1967	DH-106 Comet 4, British European Airways	High explosive device Within the cabin under seats	66
1970	Convair CV-990-30A-6 Conorado, Swissair	Bomb in the baggage compartment	47
1976	Douglas DC-8-43, Cubana de Aviación	Explosive device at the rear of the cabin	73
1976	Boeing 720-023B, Middle East Airlines	Bomb in the baggage compartment	81
1982	Boeing 747-121, Pan Am	Bomb placed under a seat cushion	1
1985	Boeing 747-237B, Air India	High explosive device inside The cargo compartment	329
1986	Boeing 727-231, Trans World Airlines	Explosive device in the cabin	4
1986	Boeing 737-270C, Iraqi Airways	Two hand grenades in the cabin	63
1987	Boeing 707-3B5C, Korean Air	Liquid explosives concealed As liquor bottles	115
1988	Boeing 747-121, Pan Am	High-explosive device in the cabin	270
1989	McDonnel Douglas DC-10-30, Union de Transport Aériens	High explosive device In the cargo hold	170
1989	Boeing 727-21, Avianca Airlines	Explosive near the fuel tank	110
2001	Boeing 767, American Airlines	Plastic explosive concealed Within shoes	0
2004	Tupolev Tu-134-3, Volga-Avia Express Tupolev Tu-154B-2, Siberia Airlines	High explosive Devices	90
2015	Airbus A32-231, Metrojet	1 kg of TNT	224
2016	Airbus A321-111, Daallo Airlines	Explosive device concealed within A laptop computer	1

Kevlar and polyurethane foams. We describe our numerical strategy in Section 6. Finally, in Section 7 we report simulations of in-cabin explosions and analyze the reliability of the proposed passive protection.

2. Fuselage geometry and design schemes

The design of fuselages refers commonly to three different schemes: truss, monocoque, and semimonocoque.

- The truss design, commonly belonging to the first generation of aircrafts, consists of steel tubes, welded together in a framework.
- The monocoque scheme refers to formers, frame assemblies, and bulkheads.
- The semimonocoque is a modification of the latter design consisting of frame assemblies, bulkheads, and formers, supplemented by additional reinforcements, called longerons, which make the structure lightweighted and stiffer. Semimonocoque fuselages are usually made of aluminium alloys, although steel and titanium are used in high temperature regions (Fig. 1).

In the simulations presented here, we adopt the simplified semimonocoque design, shown in Fig. 2. The fuselage is 4 m long and has a diameter of 3 m. Longerons and bulkheads appear in Fig. 2, together with their sections.

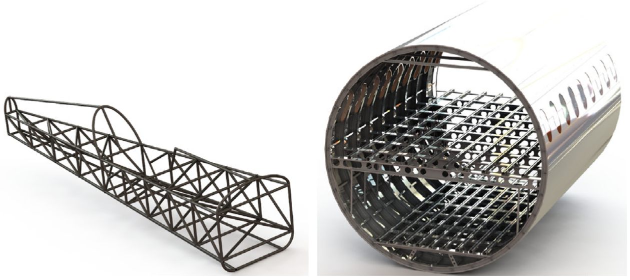

Fig. 1. Truss design (left) and semimonocoque design (right).

The floor consists of plates with 8 mm thickness, while the skin has 2 mm thickness. Tied contact pairs assure continuity between different parts.

Al2024-T3 constitutes frames along the floor, longerons, and bulkheads.

3. Blast actions

Explosion produces a blast wave with high-pressure accompanying high-temperature expansion of gases. First, detonation induces a supersonic shock front.

With reference to a free-field explosion, Fig. 3 shows a schematic representation of the hydrostatic overpressure $P_s = P - P_o$, i.e., the difference between the hydrostatic pressure P determined by the explosion and the ambient one, P_o, as a function of the stand-off distance from the explosive.

The shock front is a discontinuity surface for the velocity field. Behind the wave front, a rarefaction wave propagates. Hydrostatic pressure and density decrease to values lesser than those in the ambient before the explosion. The hydrostatic overpressure, P_s, at a point located at a distance R from the explosive decreases with both time $t > t_A$ (t_A is the shock time arrival) and R. Generally, the time rate reduction is much greater than the spatial one. Fig. 4 shows the schematic time variation of P_s at a point. After a delay t_A from detonation, the overpressure jumps suddenly from zero to P_{so}. For $t > t_A$, the overpressure decreases extremely fast until the instant $t_A + t_o$, the end of the so-called *positive phase*. At the instant $t_A + t_o$, the so-called *negative phase* starts. It pertains to the rarefaction wave, triggered by the expansion of the detonation products: P_s decreases to negative values and asymptotically approaches zero after $t_A + t_o + t_{o-}$. Positive and negative impulses can be defined as the integrals of the hydrostatic overpressure along