Blast response of a thin-walled aircraft structure

Adam Dacko and Jacek Toczyski

Faculty of Power and Aeronautical Engineering, Warsaw University of Technology
Nowowiejska 24 Street, 00-665 Warsaw, Poland
e-mail: adam.dacko@meil.pw.edu.pl
e-mail: jtoczyski@meil.pw.edu.pl

Abstract

The most important task in tests of resistance of aircraft structures to the terrorist threats is to determine the sensitivity of thin-walled structures to the blast wave load. For obvious reasons, full-scale experimental investigations are carried out exceptionally. In such cases numerical analyses are very important. They allow to tune model parameters for proper correlation with experimental data. Based on preliminary analysis experiment can be planned properly. The paper presents a summary of the results of dynamic analysis of FE model of a medium size aircraft fuselage. Characteristics of the materials used in FE simulations were obtained experimentally. Modeling of C4 detonation was also discussed. Studies have shown very strong sensitivity of the results to chosen numerical models of materials, formulations of elements, assumed parameters etc. Studies confirm also very strong necessity of the correlation of analysis results with experimental data. Without such a correlation it is difficult to talk about the validation of the results obtained from the "explicit" codes.

Keywords: thin-walled structures, blast wave load, fluid-structure interaction, ALE, LS-Dyna

1. Introduction

Due to the growing threat of terrorist attacks some experimental work has been performed to study the dynamic behavior of a fuselage subjected to blast pressure loads [4]. Unfortunately the most of experimental data are not accessible to the open research community, therefore numerical modeling of aircraft explosions plays so important role. For obvious reasons, full-scale experimental investigations are carried out exceptionally. In such cases numerical analysis are very useful. They allow to tune model parameters for proper correlation with experimental data.

In the paper a numerical analysis of the explosion of C4 in a medium passenger airplane is discussed. These studies are a continuation of the research presented in the Journal of KONES [1]. In order to investigate the dynamic behavior of a fuselage, numerical simulations with the commercial explicit FE code LS-Dyna V971 were used.

2. FE modeling

2.1. Geometry

The FE model represents a simplified section of a medium airplane fuselage (Fig. 1., [2]). The airplane structure is meshed with ca. 160000 QUAD elements using the *Belytschko-Leviathan shell* formulation.

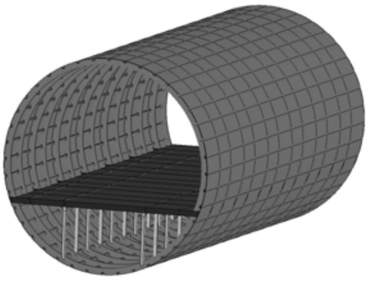

Figure 1: Geometry of the FE model

2.2. Material properties

The airplane structure (excluding floor and bolts) is made of aluminium alloy (2024-T3). The required material constants of AL2024-T3 are as follows:

- mass density (kg/m^3): $\rho = 2923$,
- Young's modulus (GPa): E = 68.7,
- Poisson's ratio: $\upsilon = 0.35$,
- plastic strain to failure: 20%,

Fig. 2. describes behavior of the material (in plastic range).

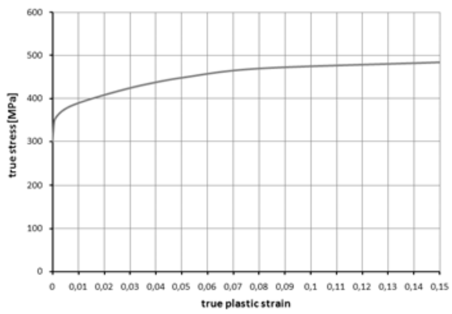

Figure 2: AL2024-T3 stress-strain characteristic [1]

The floor is a sandwich structure. It is composed of four 0.25mm thick GFRP layers and the Nomex honeycomb core with the thickness of 9mm.

Riveted connections between parts were modeled using two different techniques. The skin-stiffener connections were modeled using beam elements, the skin-frame connections utilizing spot welds with failure criteria for shear and normal strength.

2.3. Loads

The structure is loaded by the pressure generated by the explosion of C4 explosive charge of mass m_0. Two locations of the charge relative to the fuselage structural members were chosen: "between two frames" (the blast wave will focus on the skin area between two frame beams) and "opposite to a frame" (the blast wave will focus directly on a frame beam).

Simulation of the blast was performed using the Arbitrary Lagrangian-Eulerian (ALE) formulation. Fluid-structure interaction was performed using a dedicated coupling algorithm with an option that allows for erosion of Lagrangian elements.

Optionally pre-stress (e.g. operation loads, gravity) can be applied to the structure. There are three methods of applying static preloads in LS-Dyna [3]:

- an explicit analysis is used, in which nodal velocities are artificially dumped each time step, until the convergence tolerance is reached,
- the preloaded state is reached by linearly ramping nodal displacements and rotations to prescribed values over 100 time steps (an ASCII file which describes the initialized state is required),
- an implicit analysis is used.

After the preloaded state is achieved, the time is set to zero and the normal phase of dynamic solution automatically begins from the preloaded state.

2.4. The Euler domain

The Euler domain (C4 and air) is modeled by ca. 860000 HEXA elements with the *1 point ALE multi-material element* formulation.

At the free surfaces of the Euler mesh the pressure of 1 bar is applied in order to ensure that the analyzed thermodynamic system will, after the explosion, return to an equilibrium state.

The numerical model used also:

- the linear polynomial equation of state (1) as an EOS describing the behavior of air:

$$p = C_0 + C_1\mu + C_2\mu^2 + C_3\mu^3 + (C_4 + C_5\mu + C_6\mu^2)E \qquad (1)$$

$$\mu = \rho/\rho_0 - 1$$

p – pressure [Pa], C_i – polynomial equation coefficients, E – internal energy per unit reference specific volume [J/m^3], ρ – mass density [kg/m^3], ρ_0 – initial mass density [kg/m^3]

- the JWL equation of state (2) as an EOS describing the burning process of C4:

$$p = A\left(1-\frac{\omega}{R_1V}\right)\exp\left(-R_1V\right)+B\left(1-\frac{\omega}{R_2V}\right)\exp\left(-R_2V\right)+\frac{\omega E}{V} \qquad (2)$$

A, B, R_1, R_2, ω – constants, p – pressure [Pa], E – internal energy per unit reference specific volume [J/m^3], V – relative volume [-]

Typical values of constants in the equations of state and the properties of the explosive charge were accepted from the literature [5].

3. Discussion of results

The deformation of the fuselage subjected to explosion of relatively small charge shows no perforation of the skin, however, a severe damage of structural members of the reinforcing system occur. In the "between frames" case the blast wave reaches the skin first. The skin deflects what causes failure of skin-stiffener and skin-frame connectors. Next, unattached parts of stringers and frame beams start deforming. Plastic strain in these parts reach a critical value of 20%. Two frame beams, between which the explosive charge was placed, break in their weakest point – the mousehole area (Fig. 3.). Nearby stringers are also destroyed.

In the case "charge opposite to a frame" the blast wave focuses directly on the frame beam. As a result of exceeding the critical value of plastic strain the loaded beam is destroyed at the level of C4 charge (see Fig. 4.).

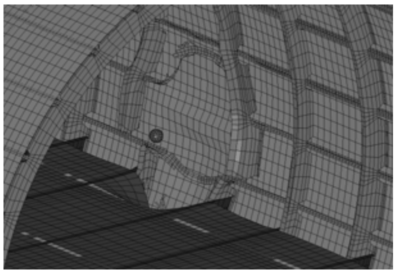

Figure 3: Fuselage deformation (between frames; t = 10ms)

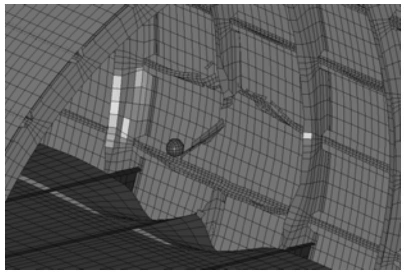

Figure 4: Fuselage deformation (opposite to a frame; t = 10ms)

In both considered cases the floor below the explosive charge was also destroyed.

4. Conclusions

Studies, not discussed here in detail, have shown very strong sensitivity of the results to the numerical models of materials, formulations of elements etc. Studies confirm also very strong necessity of the correlation of analysis results with experimental data, if available. Without such a correlation it is difficult to talk about the validation of results obtained from the "explicit" codes.

Commercial FE packages now offer broad spectrum of material models. The same concerns very "rich" formulation of element models, which results in number of parameters to set (or to choose from). The variation of these parameters results in wide-spread scatter of obtained results, all of them correct from formal point of view.

References

[1] Dacko, A. and Toczyski, J., Structural Response of a Blast Loaded Fuselage, *Journal of KONES*, Vol 17, 2010, No.1, pp. 101-109

[2] Habas, D. et al., *Selection and Design of Scaled Simplified Sub-Aerostructures*, EU Project VULCAN: AST5-CT-2006-031011, VULCAN Deliverable D1.4, Tanagra, 2008.

[3] LS-Dyna V971, Livermore Software Technology Corporation, Livermore, 2006.

[4] Wentzel, C. M., van de Kasteele, R. M. and Soetens, F., *Investigation of Vulnerability of Aircraft Structure and Materials Towards Cabin Explosions*, First International Conference on Damage Tolerance of Aircraft Structures, Delft, 2007.

[5] Włodarczyk, E., *Wstęp do mechaniki wybuchu* [*Introduction to Physics of Explosion*], PWN, Warsaw, 1994.