The load exerted on a rigid wall by a highly porous cylinder during impact

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Abstract. The paper shows the directions to improve the assessment of the external load on a rigid structure during the crash of an aircraft. Our estimates describe the modeling of initial stage of impact (deformation of the nose compartment). The main goal is to evaluate the correctness and applicability of the Riera approach to mechanical equivalent of onboard equipment. Volume-perforated samples of the aluminum alloy D16T were used as mechanical equivalents in numerical and experimental studies. Both our model which uses constitutive equations of high-porous elastoplastic medium (Carroll-Holt model) and direct 3D modeling of the structure of volume-perforated samples by finite element method in the LS-DYNA allows us to obtain the history of load on a rigid wall. We demonstrate the features and differences between this approaches and the Riera approach.

1. Introduction
Currently nuclear power station buildings and structures should be designed taking the effects of possible aircraft crash into account, according to Russian civil engineering regulations [1] and international regulations reflected in the International Atomic Energy Agency (IAEA) guidelines [2, 3]. According to the Russian regulations [1], the calculation and design of structures takes impact of a 20-ton aircraft at a speed of 200 m/s into account. This situation can correspond to an aircraft crash such as F-4 Phantom II fighter [4].

In modern design practice it is customary to perform decomposition of the aircraft impact problem. Under such extreme impact we first determine the external impact load, and then investigate the dynamic response of the structure under predefined load. The external impact load of the aircraft is considered separately from the rest of the elements and is usually determined by the Riera approach [5, 6], which considered the impact of one-dimensional rigid-plastic rod (equivalent of an aircraft) against a rigid (non-deformable) wall.

The Riera approach is based on momentum conservation and allows to calculate the loads \( F_x(t) \) on the rigid wall at the rod impact as

\[
F_x(t) = P_c[x_c(t)] + \mu[x_c(t)] \cdot V^2(t),
\]

where \( x_c(t) = \int_0^t V(\xi)d\xi \).

Rod’s mass \( \mu(x) \) and critical fuselage failure strength \( P_c(x) \) is distributed along its length. J. Riera notes in [6] that differences in results from various researchers are due to the use of different functions \( P_c(x) \), but in [5, 6] he didn’t offer any recommendations.
It was previously shown in [7, 8] that the load declared by Russian regulations [1] is the envelope to the ones calculated by the Riera approach (with some exceptions Figure 1).

![Figure 1. Rigid wall loading: strength component (1); inertial component (2); computed rigid wall loading (3); loading according to regulations (4) [1].](image)

In the studies known to the authors, when considering mass and critical failure strength distributed along aircraft length, the researchers don’t mention or take into account the mechanical properties of onboard equipment located in the nose of an aircraft.

In modern military aircrafts, the mass both of onboard equipment and its share in aircraft’s total mass continue to increase [9]. This is due to increase in requirements for equipment reliability.

Onboard equipment blocks take up 70÷75 % of nose compartment’s internal equipment mass and fill 90÷95 % of the compartment’s cross-sectional area. Mechanical properties of nose compartment’s onboard equipment are determined mainly by the properties of its blocks [10].

2. Computational and experimental studies
The onboard equipment blocks are high-porous composite structures that in terms of layout characteristics, material content and mechanical properties are very close to a highly porous aluminum alloy or a honeycomb structures made of aluminum alloys and can be applied as a medium model for aircraft nose compartment’s internal equipment, both in calculations and experiments [10].

In this paper, computational and experimental studies of high-velocity impact of onboard equipment’s mechanical equivalents (rods of highly porous aluminum alloy [11]) were performed.

Volume-perforated cylinders made of D16T aluminum alloy were used as experimental samples. Sample sizes (the symbols correspond to Figure 2 [11]) were $D = 24$ mm; $H_0 = 60$ mm; $d = 2.0$ mm; $z = 5.2$ mm ($\alpha_0 = 2.16$); $z = 4.8$ mm ($\alpha_0 = 2.59$); $z = 4.3$ mm ($\alpha_0 = 3.77$); $z = 4.1$ mm ($\alpha_0 = 4.83$), where $\alpha_0$ is initial porosity (ratio of matrix material density to average density). Obtained results were verified with experiments by the residual length of the projectile [11].
Effective yield stress obtained from 3D numerical simulation with a direct porosity assignment (Figure 3) was used to determine crash load limit in the cross section of a projectile. Four different samples were tested this way.

The Carroll-Holt model is one of simple models, but it allows for relatively accurate description of the behavior of a highly porous medium based on the properties of the matrix material and initial porosity. M. Carroll and A. Holt considered the collapse of an isolated spherical pore in one-dimensional approximation. The behavior of the highly porous medium includes elastic, elastoplastic and plastic stages. This model allows to obtain the first approximation for deformation diagrams without experiments or direct finite element modeling.

The rigid wall load histories obtained as results of numerical modeling in LS-DYNA were compared with the results of the Riera approach calculation and the numerical result in our model (Figure 4). The solution of finite-difference equations of continuum mechanics was performed in a one-dimensional setting in the author’s program. The Carroll-Holt model [12] was used to describe the
behavior of a high-porous medium. The dotted line (⋯⋯) shows the load for the author’s program. The
dashed line (–––) shows the load for the Riera approach. The solid line (──) shows the load calculat-
ed in LS-DYNA for 3D setting.

Figure 4. History of load on the rigid wall at the impact velocity of 100 m/s (a), 150 m/s (b),
200 m/s (c), 250 m/s (d).

3. Conclusions
The Carroll-Holt model gives an upper estimate for pressure in highly porous medium. The history of
load obtained this way is envelope to the true one.

1. The Riera model is quite close to the result of the numerical solution with direct porosity modeling
at the impact velocity of 100 m/s, especially for less dense samples. It’s important to note that effec-
tive yield stress from direct modeling was used to estimate the strength component of the load. This
model also shows a good correspondence with the results obtained via 3D model with the exception
of the initial and final load stages, when load/unload is determined by wave effects.

2. Hardening begins to appear in denser samples when the impact velocity is increased to 150 m/s,
which isn’t taken into account in the Riera approach. Load fluctuations appear at the impact velocity
of 200 m/s for less dense samples. This is due to the collapse of the pores. These effects are amplified
when the velocity is increased to 250 m/s and lead to loads exceeding those calculated by the Riera
approach.

3. Studies of high-speed deformation of onboard equipment mechanical equivalents showed a sig-
nificant peak load at the initial stage. The peak load is associated with its shock nature. The load drop
on the rigid wall is smooth. There is a hardening of the material, but the load on the Riera approach
took into account only the value of the effective yield stress.
4. One-dimensional approximation and application of the Carroll-Holt model [12] to describe the behavior of the medium allows us to calculate the load, which is the envelope in amplitude to the one obtained via 3D model, but this approach does not allow us to model the initial peak of the load due to the use of averaged characteristics of the medium.

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