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COMPUTING THE LOADS AFFECTING A STRUCTURE SUBJECTED TO A HIGH-VELOCITY PROJECTILE IMPACT USING THE RIERA APPROACH

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This is why this paper considers an approach to computing the loads affecting a structure subjected to a high-velocity projectile impact (the projectile being an aerial vehicle, AV) introduced by J. Riera [1, 2]. This approach is widely used for computing loads affecting protective structures of nuclear power stations. This issue is of great practical importance, since nuclear power station buildings and structures, according to Russian civil engineering regulations [3] should be designed taking the effects of possible aircraft crash into account. The approach proposed by J. Riera makes it possible to determine the load as a function of time for a “soft” (subject to failure) penetrator, such as an airplane moving at its landing speed, interacting with a rigid target. We will replicate the derivation of the Riera equation according to [2].

The ratio of force to impulse for a system is the same as for a single particle:

$$F_x = \frac{dQ_x}{dt}, \tag{1}$$

where F_x is the projection of the resultant force onto the *x* axis;

Q_x is the projection of the total impulse onto the *x* axis.

Let *m* be the mass found within a fixed control volume *S* at an arbitrary moment t_a. When the period $dt = t_b - t_a$ is over, the boundaries of the system are generally already different from *S*. Moreover, let Q_{xa} and Q_{xb} denote the impulse along the *x* axis of all the medium contained within *S* at t_a and t_b respectively, while $dQ_{x\,in}$ and $dQ_{x\,out}$ represent the impulse in- and outflow along the *x* axis over dt.

The resulting force acting in the control volume *S* may be expressed as follows:

$$F_x = \frac{Q_{xa} - Q_{xb}}{dt} + \frac{dQ_{x\,out} - dQ_{x\,in}}{dt}. \tag{2}$$

A simplified "soft" penetrator model [5, 6] implies the existence of two zones: a negligibly thin "deformation" zone adhering to the target surface within the control volume S_d and a rigid zone within the control volume S_r (fig. 1 [6]). Additionally, let $S = S_d \cup S_r$. If t_a now denotes the moment of contact, and the equation (2) is applied to *S*, then

$$Q_{xa} = mV, \tag{3}$$

$$Q_{xb} = (m - dm)(V - dV) + dQ_{x,dm}, \tag{4}$$

where V is the velocity of the mass m at the moment t_d;
dm is the portion of the mass entering the deformation zone S_d over the time dt;
$dQ_{x,dm}$ is the "residual" impulse along the x axis of the mass dm.

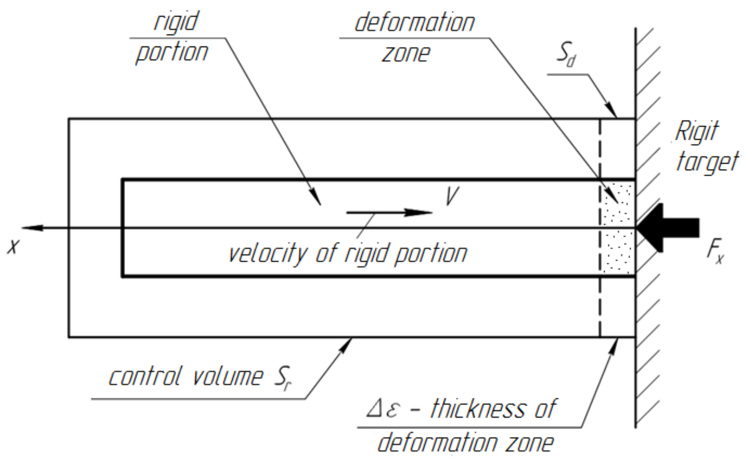


Figure 1. "Soft" penetrator model [6]

Let us introduce the designations $dQ_{x,dm} = V_r dm$. Since the in- and outflow of mass through S are equal to zero, we obtain:

$$F_x = m\frac{dV}{dt} + (V - V_r)\frac{dm}{dt}. \tag{5}$$

Riera's [1, 2] primary assumption is that the "residual" velocity V_r is zero. Then applying the second Newtonian law to the rigid portion of the penetrator allows us to equate mdV/dt to the loading P_s required for the penetrator to fail or deform (crush). Let us also write down the following expression:

$$\frac{dm}{dt} = \mu\frac{dx_c}{dt} = \mu V, \tag{6}$$

where μ is airplane mass per unit length.
Then we can use the equation (5) to derive the following expression [1, 2]:

$$F_x(t) = P_c[x_c(t)] + \mu[x_c(t)] \cdot V^2(t), \tag{7}$$

where $x_c(t) = \int_0^t V(\xi)d\xi$ is the distance to the penetrator tip.

In the international design practice the loading as a function of time is computed using (7) directly, obtaining the $x_c(t)$ and $V(t) = \dot{x}_c(t)$ functions numerically. In Russian practice the A.N. Birbraer solution by quadrature became popular [4, 5]. It involves [4, 5] considering the airplane fuselage, which may be divided in two zones at an arbitrary moment (fig. 2): the crushed portion adjoining the target *1* and the intact portion *2* moving at the speed $V(t) = \dot{x}_c(t)$

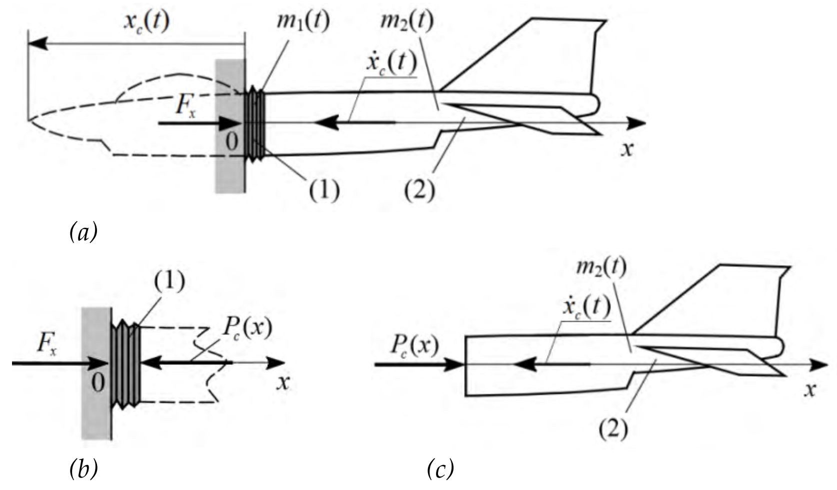


Figure 2. Airplane fuselage model [4, 5]:
a – "soft" penetrator; *b* – crushed fuselage portion ("deformation" zone);
c – intact fuselage portion

The mass of the crushed portion *1*:

$$m_1(t) = \int_0^{x_c} \mu(x_c)dx_c = \int_0^{t} \mu[x_c(t)] \cdot \dot{x}_c(t)dt \tag{8}$$

The mass of the intact portion *2*:

$$m_2(t) = m_c - m_1(t), \tag{9}$$

where m_c is the total airplane mass.

The equation of momentum [5]:

$$\frac{d\vec{Q}_i}{dt} = \vec{F}_i^e + \vec{u}\frac{dm_i}{dt}, \tag{10}$$

where $\vec{Q}_i$ is the momentum of the *i*-th zone (*i* = 1, 2); $\vec{F}_i^e$ is the net vector of the external forces applied; dm_i is the mass of the zone; $\vec{u}$ is the absolute velocity of attaching (separating) particles.

The expression (10) makes it possible to derive the differential equation of motion for the intact portion of the penetrator [4, 5];

$$\ddot{x} = -\frac{P_c[x_c(t)]}{m_c - m_1[x_c(t)]}. \tag{11}$$

The initial conditions are: $x(0) = 0$, $\dot{x}(0) = v_0$.

Let us reduce the order of the equation (11);

$$\ddot{x} = \frac{d\dot{x}}{dt} = \frac{d\dot{x}}{dx}\frac{dx}{dt} = \dot{x}\frac{d\dot{x}}{dx} = \frac{1}{2}\frac{d\dot{x}^2}{dx}. \tag{12}$$

Let $z = \dot{x}^2$, then we obtain the equation $\frac{dz}{dx} = -\frac{2P_c(x)}{m_c - m_1(x)}$ with the initial condition $z(0) = v_0^2$.

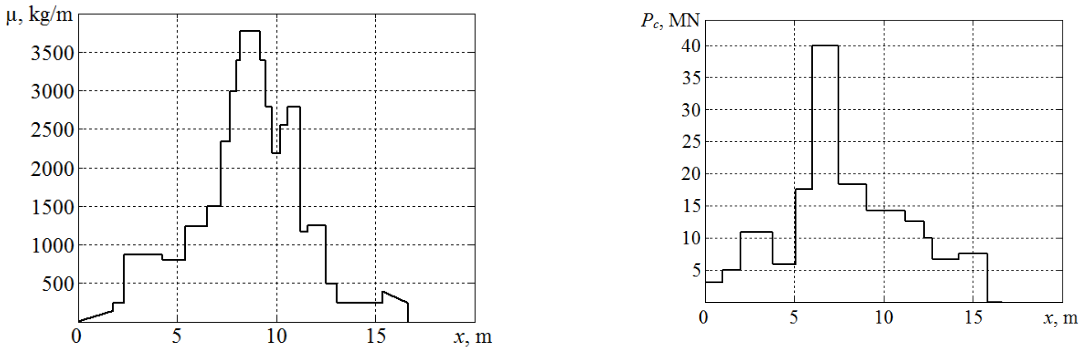
The integral of this differential equation:

$$z = -2\int_0^{x} \frac{P_c(\xi)d\xi}{m_c - m_1(\xi)} + v_0^2 \tag{13}$$

Let $\Phi(x_c) = \int_0^{x_c} \frac{P_c(\xi)d\xi}{m_c - m_1(\xi)}$ then $z = -2\Phi(x_c) + v_0^2$, $\frac{dx_c}{dt} = \sqrt{v_0^2 - 2\Phi(x_c)}$,

$$t(x_c) = \int_0^{x_c} \frac{d\xi}{\sqrt{v_0^2 - 2\Phi(x_c)}} \tag{14}$$

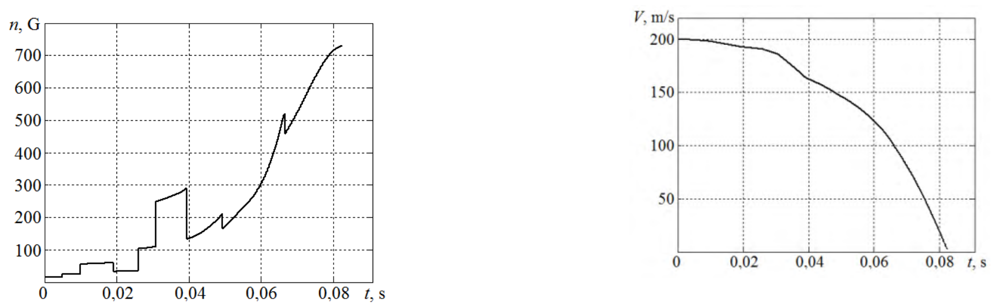
Inverting $t(x_c)$, we derive the desired function for varying crushed portion length $x_c(t)$. Then we can determine $P_c[x_c(t)]$, $\mu[x_c(t)]$ and $F_x(t)$.



(a) *(b)*

Figure 3. Input data from [4, 5]:
a – mass per unit length; *b* – failure or deformation force for the fuselage

Let us consider an example computation of loading caused by a Phantom RF-4E impact; the plane has a mass of 20 t and comes at a speed of 200 m/s. According to Russian regulations [3], the most critical buildings and structures of a nuclear power station should be able to withstand this impact. The input data and the results of this computation are shown in figures 3-5.



(a) *(b)*

Figure 4. Computation results: *a* – deceleration G-force; *b* – slowdown dynamics at impact

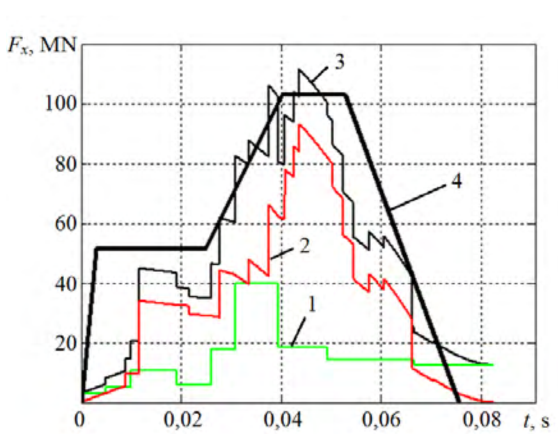


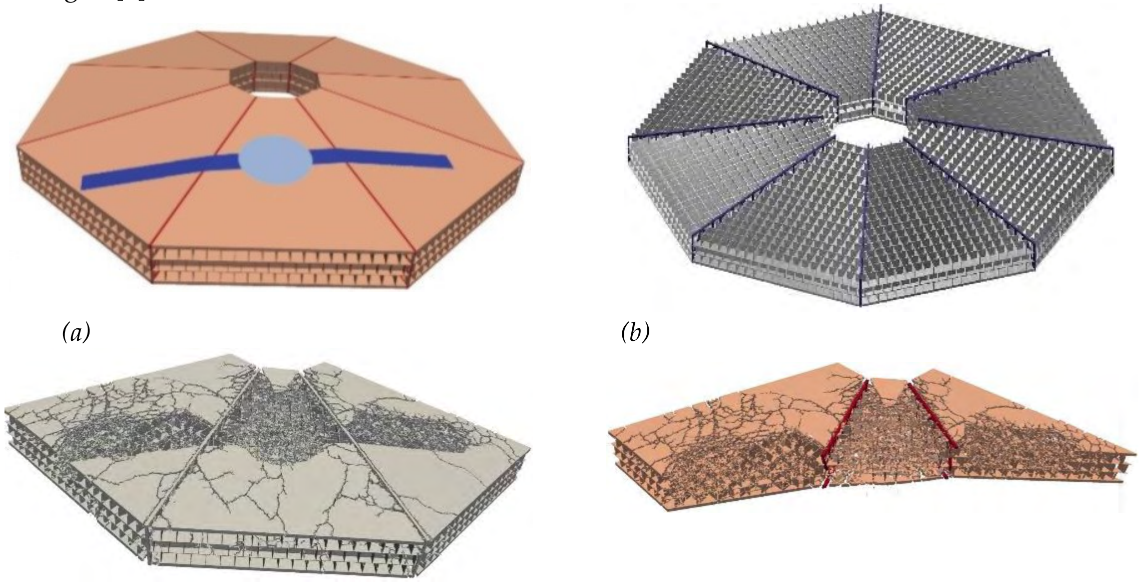
Figure 5. Rigid wall loading: 1 – strength component; 2 – inertial component;
3 – computed rigid wall loading; 4 – loading according to regulations [3]

Therefore, the loading specified in Russian regulations is close to that computed using the Riera approach. The primary assumption in [1, 2] is that the structure (target) is poorly flexible and can be idealised as a rigid target. Obviously in the case of non-rigid structures (targets) the loading computed using the equation (7) should be considered to represent the top boundary of the "accurate" plot [2]. According to [2], other works used the same model to investigate how the target deformation may affect the outcome in the case of the target moving along the x axis at a velocity of $V_a(t)$:

$$F_x(t) = P_c[x_c - x_a] + \mu[x_c - x_a](V - V_a) - M_a \frac{dV_a}{dt}, \quad x_a(t) = \int_0^t V_a(\xi)d\xi, \tag{15}$$

where M_a is the mass of the deformed portion (the one undergone failure) on the airplane-target interface.

However, loadings computed according to the Riera approach concerning airplane impact against a rigid wall are often used [6] for numerical finite-element computations of buildings and structures without taking the flexibility of structures into account or adjusting the loads. Figure 6 [6] shows the results of such a computation. The work [6] deals with a Boing-747-400 airplane interacting with the protective shell of a nuclear power station. The authors replaced the contact interaction with the shell by the impulse according to [5].



(a) *(b)*

(c) *(d)*

Figure 6. Schematic of an airplane interacting with the nuclear power station shell [6]:
a – zones where loads are applied; b – internal honeycomb structure of the shell;
c – outside surface of the shell at t = 300 ms; d – shell failure over its thickness at t = 300 ms

It should be noted that the minimum displacement of the loaded zone is 2-3 m along the impact direction. Therefore, the loading applied should be adjusted, taking the pliability of the target into account. This loading adjustment process is of an iterative nature and requires recomputing when the external loading is adjusted.

Our paper analysed the system of assumptions found in J. Riera's approach. We determined that the primary assumption of this model is the rigidity of the structure, that is, the target, during impact. Interaction with a flexible structure requires adjusting the load applied as a function of time, which leads to a decrease in loading. This refinement process may be iterative. However, considering the loading and the response of the structure separately is only possible for small displacements of the target. This makes using the method of successive approximations possible, since then the response is barely sensitive to the motion of the target.

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СЕГМЕНТИРОВАНИЕ ЗАРЯДА ВВ КАК СПОСОБ ПОВЫШЕНИЯ ПАРАМЕТРОВ ВОЗДУШНОГО ВЗРЫВА

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Как известно [1], сегментированием называется процесс деления целого на составляющие части (сегменты). Применительно к воздушному взрыву заряда ВВ под сегментированием нужно понимать деление единого заряда на одинаковые сегменты, разнесение их в пространстве, инициирование каждого сегмента одновременно или со смещением во времени, чтобы за счет взаимодействия воздушных ударных волн (УВ) между отдельными сегментами, получить повышенные значения параметров взрыва в отдельных областях пространства и суммарно для всего заряда в целом.

В работе проведено численное моделирование взрыва в воздухе монолитного цилиндрического заряда ТНТ массой 100 кг и относительным удлинением ~ 10 (первый вариант). Заряд располагался над жесткой поверхностью, моделирующей поверхность земли, перпендикулярно ей, при этом нижний торец заряда находился на высоте 1 м.

При сегментировании заряд делился в поперечном направлении первоначально на два равных сегмента (второй вариант), а потом на три сегмента (третий вариант), которые раздвигались по оси симметрии заряда вверх на расстояния, равные диаметру заряда Ø 200 мм (рисунок 1).

Инициирование монолитного заряда осуществлялось одноточечно в центральной точке на поверхности нижнего торца, а сегментированных зарядов – двухточечное в центральных точках торцов нижнего сегмента и одноточечное на верхнем торце остальных сегментов одновременно в начальный момент времени $t = 0$. Такое инициирование проводилось для того, чтобы условия задачи соответствовали [2].

В расчетах оценивалось влияние характеристик сегментированных зарядов ВВ на параметры воздушного взрыва, фиксируемых в маркерах, расположенных на жесткой поверхности.