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Simulating the SMART1 Orbiter Impact on the Moon's Surface

V. A. Bratov[a,*], Academician N. F. Morozov[a, b], and Corresponding Member of the RAS Yu. V. Petrov[a, b]

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INCUBATION-TIME CRITERION

Previously, we formulated [1–3] a fracture criterion on the basis of the incubation time concept for material separation. In recent investigations [4–7], the approach based on the incubation time was successfully applied for describing the initiation, propagation, and cessation of dynamically loaded cracks. For estimating the fracture possibility at a given point x and time t, the proposed criterion can be written as

$$\frac{1}{\tau}\frac{1}{d}\int_{x-d}^{x}\int_{t-\tau}^{t}\sigma(x^*, t^*)dx^*dt^* \geq \sigma_c, \quad (1)$$

where τ is the fracture incubation time, which is the parameter describing the response of a material to applied dynamic loads (this value is constant for a given material, which is independent of the sample configuration, the load application mode, and the action pulse duration shape and amplitude); d has a characteristic fracture size that depends on the given material and the scale level on which the experiment is carried out; σ is the time-dependent stress at a given point; σ_c is the critical stress value under static conditions (also characteristic of the given material and the scale level on which the experiment is carried out); and x^* and t^* are the local coordinate and time, respectively.

In the quasi-static case ($t \to \infty$), criterion (1) coincides with the known Novozhilov–Neuber fracture criterion. The applicability condition of criterion (1) for the description of slow processes is its conformity to the classical static fracture criteria (the critical stress for defect-free media and the critical stress coefficient for solids with cracks). Obviously, in the case of a defect-free medium under the action of quasi-static loads, Eq. (1) is equivalent to the condition of attaining the critical stress level ($\sigma \geq \sigma_c$). In the case of slowly loaded solids with cracks (under conditions of applicability of the asymptotic representation of the stress field in the neighborhood of the crack tip with a root-type singularity), it is possible to show that, when in selecting the characteristic size

$$d = \frac{2}{\pi}\frac{K_{IC}^2}{\sigma_c^2}, \quad (2)$$

where K_{IC} is the critical stress intensity coefficient for the cracks loaded in mode I, criterion (1) becomes equivalent to the classical Irwin condition for the critical stress intensity coefficient ($K_I \geq K_{IC}$). An important feature of criterion (1) (equivalent to the Neuber–Novozhilov criterion under the quasi-static conditions) is the possibility of correctly describing the fracture of solids with small cracks. By these we mean the cracks that are too large to neglect their effect on the external field, but insufficiently large for assuming that the intensity coefficient completely determines the field near the tips. In addition, criterion (1) can be applied in the absence of the root-type singularity (for example, in the case of angular cuts).

Numerous investigations (see, e.g., [2, 3]) have shown that, using criterion (1), it was possible to describe quite accurately the start of dynamically loaded cracks. Applying this criterion to estimations of the brittle fracture processes with the time to failure comparable with τ, it is possible both to describe the whole variety of the experimentally observed dynamic fracture phenomena (see, e.g., [8–11]) and to predict new effects in fracture dynamics (see, e.g., [4–7]). Recently, we used [6, 7] the finite element method (FEM) to apply the incubation-time criterion for simulating the start, propagation, and arrest of dynamically loaded cracks. The results obtained with using criterion (1) in the numerical simulations coincide well with the data of natural experiments.

In the present study, we have applied a FEM scheme incorporating the incubation time criterion to solving the problem of penetration related to the dynamic fracture of an initially defect-free medium.

[a] Institute of Problems in Machine Science, Russian Academy of Sciences, St. Petersburg, 199178 Russia
[b] St. Petersburg State University, St. Petersburg, 198504 Russia
*e-mail vladimir@bratov.com

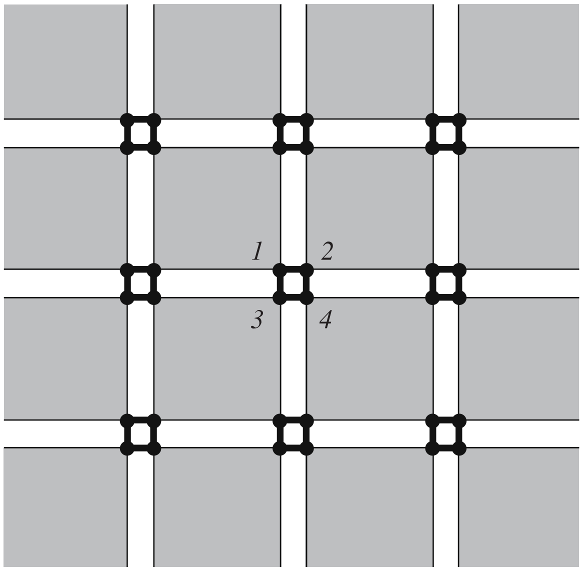

Fig. 1. Finite-element model with elements having no common nodes.

NUMERICAL SIMULATION OF THE ORBITER IMPACT ON THE MOON'S SURFACE

On September 3, 2006, the SMART1 orbiter of the European Space Agency made impact on the Moon's surface [12, 13, 15]. The contact of the satellite with the lunar surface took place at a velocity of about 2000 km/s; the satellite had an almost cubic shape with a characteristic size of ~1 m and a mass of 366 kg. The observed defect (crater) formed on the Moon's surface as a result of the impact was about 6–10 m in diameter and 3 m deep. The purpose of our investigation is to compare the actual sizes of the crater with the values obtained in simulations of the impact by the FEM scheme incorporating the fracture incubation time criterion.

The traditional method of constructing a new surface in the FEM is related to node separation. This approach is most convenient in many cases; however, it is associated with rather time-consuming procedures of redividing grids and recalculating displacements, strains, and velocities for the new nodes. To guarantee the correct integration in Eq. (1), it is necessary to use small time steps. Under these conditions, the node separation seems to be not the best solution. In the method employed in this study, the finite elements representing the Moon initially have no common nodes. Before the fracture moment, the degrees of freedom of nodes located at the same point are rigidly interrelated (Fig. 1). In this case, the solution of the problem coincides with that for the elements with a common node. The size of each element was exactly equal to the d value determined from Eq. (2). If the fracture condition is fulfilled, the limitation on the degrees of freedom of the corresponding nodes is removed and a new surface is formed.

Figure 1 shows a schematic representation of internal points of a body to be fractured. Initially, the degrees of freedom of the nodes located at one point are

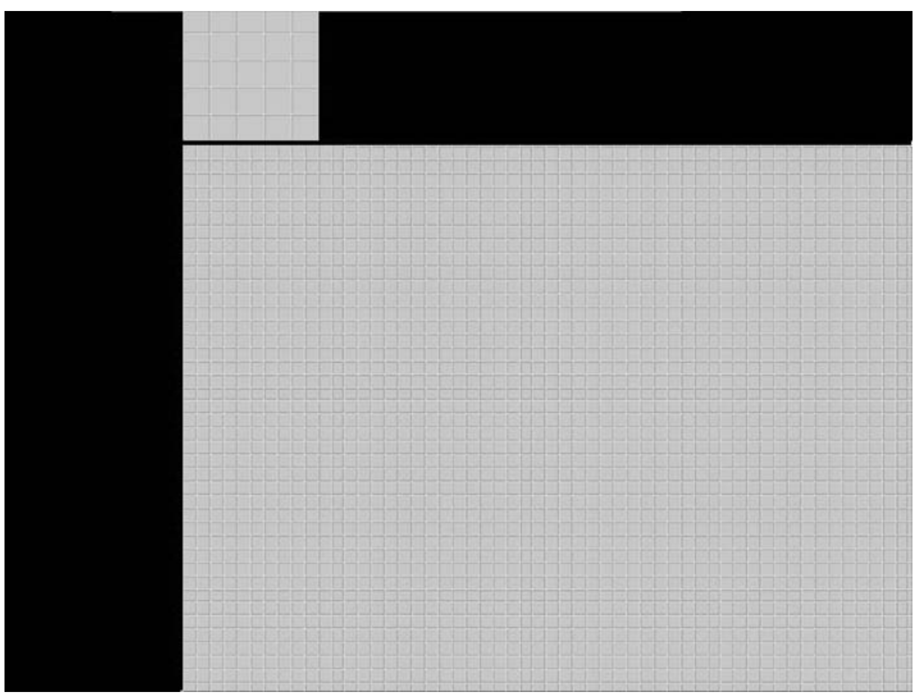

Fig. 2. General view of the finite-element model.

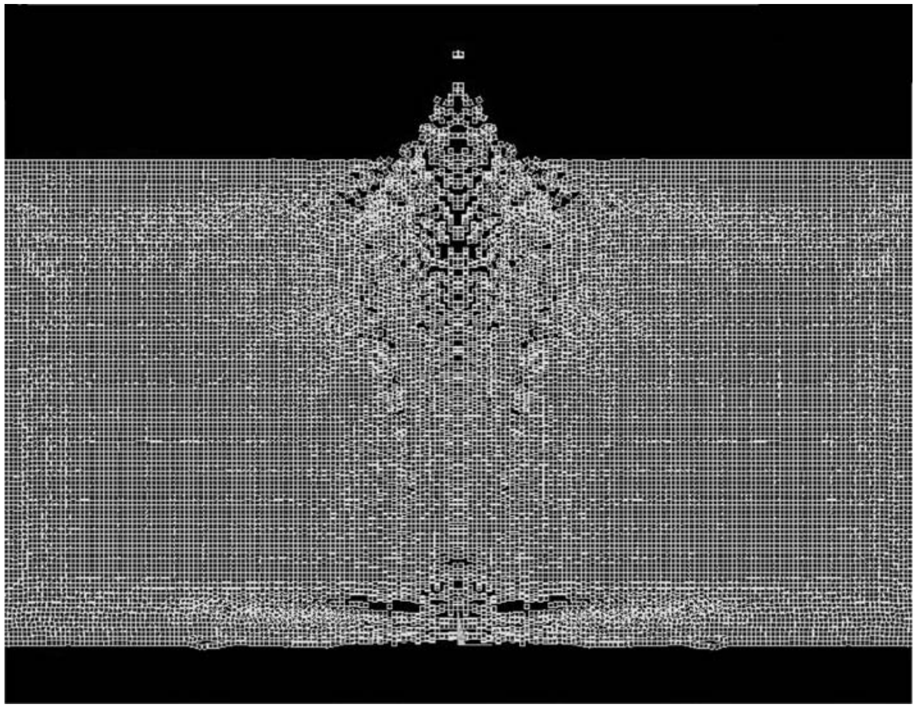

Fig. 3. Sample structure after the orbiter impact.

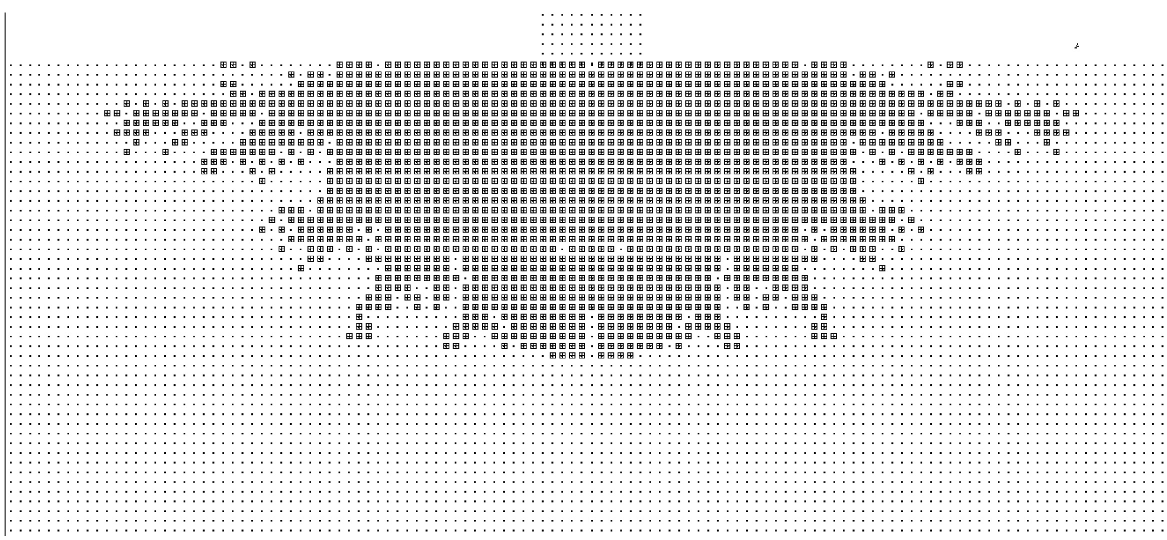

Fig. 4. Initial grid with marked nodes at which the fracture occurred.

mutually related. Fracture condition (1) for such a point can be rewritten as

$$\frac{1}{\tau}\int_{t-\tau}^{t}\sigma_{ii}(t')dt' \geq \sigma_c, \tag{3}$$

where i takes the values 1 and 2. The spatial integration disappears because, in the FEM, the stresses at a given node are already averaged over a distance about the element size.

The problem is solved for the half-space $y < 0$. The behavior of the target material is determined by the linear theory of elasticity. At the initial instant of time, there are no stresses in the material representing the Moon, and all points are at rest. The problem is treated as axisymmetric. The properties of the material representing the Moon are taken equal to the average values typical of the

Earth's basalt: $\sigma_c = 10.5$ MPa, $K_{IC} = 2.94$ MPa $\sqrt{m}$, $\tau = 80$ μs, $E = 60$ GPa, $\rho = 2850$ kg/m^3, and $\eta = 0.25$. In this case, $d = 5$ cm. The impact was simulated for a cylinder 1 m in diameter and 1 m in height incident on the half-space at a velocity of 2000 m/s. The cylinder material density was chosen such that the projectile total mass was 366 kg. Figure 2 illustrates the finite-element model employed. The sizes of elements were selected so that no waves reflected from the sample boundaries would return to the fractured area during the experiment.

For solving the problem of the linear elasticity theory, we used the FEM package ANSYS [14]. The fulfillment of condition (3) in all nodes of the sample was checked by a separate subroutine written in the ANSYS ADPL language.

Figure 3 shows the state of the sample after completion of the numerical experiment. The fracture in the lower part of the sample appeared due to cleavage of the sample material as a result of the reflection of elastic waves from its lower boundary. Figure 4 shows the nodes of the undeformed grid in which separation of the material took place. Thus, it is possible to estimate the size of the imprint (crater) formed as a result of the orbiter impact on the Moon's surface. The damaged zone is about 10 m in diameter and approximately 3 m deep. The region of complete fragmentation of the material can be estimated as 7–10 m in diameter and 3 m deep. These results coincide with the dimensions of the crater as estimated by the ESA [12, 13].

The results of our investigation show that the applicability field of the fracture criterion formulated on the basis of the fracture incubation time concept is quite wide. The majority of applied problems related to dynamic elasticity have no explicit analytical solutions, and, hence, it is necessary to use numerical calculation schemes. In this context, the approach associated with the incubation time has considerable advantages—it can be used for describing both the fracture dynamics and statics. Hence, there is no need to introduce different fracture criteria for various load application rates. Previously, it was shown that, using the incubation time criterion incorporated into the scheme of finite-element calculations, it is possible to describe correctly the beginning (see, e.g., [1–5]), the propagation, and the end [6, 7] of dynamic cracks. In this paper, we demonstrated that a similar approach can be used to predict the fracture of an initially defect-free medium.

We understand that the linear model of elasticity and quasibrittle fracture is incompletely adequate for the problem of space mechanics under consideration. Nevertheless, even in such primitive simulation, the application of the incubation time concept and structural time approach makes it possible to efficiently forecast some important characteristics of the collision of celestial bodies.

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