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Effect of Structure Defects Distribution on the Fragmentation Spectrum in the Simulation of Explosive Destruction of Thick-walled Cylindrical Shells

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Abstract. The destruction of thick-walled cylindrical shells under explosive loading is a typical example of a problem that cannot be solved without taking into account the heterogeneity of the material's internal structure. A probabilistic approach to numerical simulation of dynamic fracture is described. Fragmentation spectrum of shells fracture under explosive loading (flat 2D modeling) is compared for different distributions of the strength properties. Using numerical simulation results, it is shown that increasing of strength properties dispersion leads to an increase in the spectrum part of medium and large fragments. It is shown that the fragmentation spectrum is determined mainly by dispersion of the distribution law, but not its shape.

INTRODUCTION

In many fracture problems, fragmentation is an essentially probabilistic process that cannot be described without taking into account the heterogeneity of the internal structure of the material. Most clearly the probabilistic nature of fracture manifests itself to axisymmetric problems. Despite the uniformity and symmetry of the loading, in reality, the localization of deformations on the inhomogeneities of the material structure begins quite quickly. A relaxation zone is formed near the growing cracks, which depends on the strain rate and determines the characteristic size of the fragment, which is clearly manifested in the explosive destruction of the shells of rotation or cylindrical containers [1-3]. To give a probabilistic character to the crack formation process, close to reality, the distribution of strength characteristics in the volume of the sample should provide a certain distribution of the limiting states of the material, in which the localization of deformations or the formation of a microfracture begins. In numerical modeling, the material is represented by discrete parameters tied to the nodes and cells of the computational domain, so the initial distribution of these parameters on the computational grid must be made with some variance from the mean value.

For a long time, the probabilistic approach to solving such problems was limited to the analytical dependences of the fragmentation spectrum parameters on the strain rate determined by the Mott's statistical theory of fragmentation and its variants proposed by Grady, Gilvarry and other researchers [4]. A large number of researchers in the modeling of fracture processes [1, 5-7] rely to some extent on the approach of Mott, which, in fact, is the evolution of a simplified one-dimensional model problem, which makes it insufficiently justified and difficult to apply in practical terms to determine fragmentation spectrum or fragments velocities of real structures destroyed by an explosion. Currently, the development of computer technology makes the most promising approach that allows for numerical simulation of destruction to take into account the heterogeneity of the body's internal structure by distributing the physical and mechanical characteristics responsible for strength [1, 2, 6, 7]. Moreover, the regular ability to specify the distribution of structural inhomogeneities is already included in some popular software designed to calculate the destruction [7].

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The probabilistic approach described in this article allows modeling structural heterogeneities of the material in fracture problems, thereby increasing accuracy, removing the limitations of the classical approach and solving problems in the most realistic formulation. This technique allows us to simulate the effect of initial inhomogeneities and structural defects on the nature of the dynamic destruction of solids in a simple form, almost without complicating the material model.

MATHEMATICAL FORMULATION OF THE PROBLEM

To assess the effect of the law of distribution of strength properties, a number of numerical experiments were conducted to undermine the thick-walled copper cylindrical shell [8] with different laws of distribution of structure defects. Being axisymmetric, with a pronounced probabilistic nature of destruction, this problem is well suited for comparing the influence of different factors on the fragmentation spectrum. The numerical simulation of this problem was carried out in a two-dimensional plane formulation, which corresponds to the plane-deformed state of the middle crosssection of the tubular shell. The external radius of the shell is 3 cm, the inner 2 cm. As an explosive, RDX selected, as the initial data for the detonation products, a self-similar distribution of parameters is taken (it is assumed that the cylindrical charge of the explosive filling the inner volume of the shell completely detonates as a result of axial detonation). The equivalent plastic deformation was used as the damage, the formation of cracks was modeled using the method of local regeneration of the grid [9]. The problem was solved using the probabilistic approach; the initial heterogeneities of the structure were modeled by the distribution of critical values of equivalent plastic deformation in the cells of the computational domain; used modified random generator produces a random variable that obeys the chosen distribution law. The normal distribution law was chosen as the basic one. The distribution interval was limited by the 3σ-rule, thus excluding non-physical values of random variables.

INFLUENCE OF STRENGTH PROPERTIES DISPERSION ON THE FRAGMENTATION SPECTRUM

To assess the influence of damage critical value dispersion on the fragments spectrum, a few problems were solved. In that calculations the value of the critical equivalent plastic deformation was distributed with normal law in the intervals $3\sigma = 5\%\ x_0$; $3\sigma = 10\%\ x_0$; $3\sigma = 15\%\ x_0$, where x_0 is a material reference value. Characteristic fragmentation spectrum in the coordinates "the total mass of fragments of a given size – the mass (size) of the fragment" ("mass by mass") qualitatively confirms numerous experimental data with the bimodality of the distribution. Calculations show (Fig. 1) that the increase in the dispersion of critical damage value leads to an increase in the spectrum part of medium and large fragments and to a decrease in the small fraction maximum, so average size of the fragment increases. The maximum size of the fragment also tends to increase, which leads to an increase in the number of fragments containing portions of both initial surfaces (internal and external). This is because that the number of large defects implemented in microcracks in the initial stages of destruction increases with increasing dispersion, and stress relaxing from the newly formed surfaces reduces the risk of smaller defects.

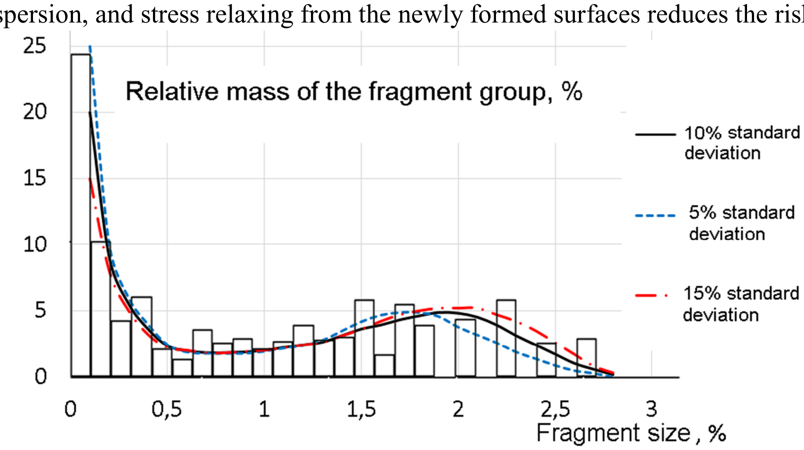

FIGURE 1. Averaged fragmentation spectra for normal distribution with different dispersion, compared to some a typical single fragmentation spectra (shown as histogram). Large fragments exists not in every experiment, so averaged spectra value for large fragments is less than fragment size

We have compared the fragmentation spectra obtained using different critical value distribution laws. Reference value x_0 was the same; standard deviation for all laws was taken equal to 10%.

Normal distribution law:

$$\frac{dp}{dx} = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-x_0)^2}{2\sigma^2}}$$

Exponential distribution law:

$$\frac{dp}{dx} = \frac{\sqrt{2}}{\sigma} e^{\frac{-\sqrt{2}(x-x_0)}{\sigma}}$$

where $(x_0 \le x \le \infty)$

Three-parameter Weibull distribution:

$$\frac{dp}{dx} = \frac{\lambda}{m_0}\left(\frac{x}{m_0}\right)^{\lambda-1} e^{-\left(\frac{x}{m_0}\right)^{\lambda}}$$

Weibull distribution was used with parameter λ=2 (Rayleigh distribution), which in variables x_0 and σ gives:

$$\frac{dp}{dx} = \frac{2(x - x_0 + c_2)}{\sigma^2 c_1} e^{\frac{-(x-x_0+c_2)^2}{\sigma^2 c_1}}$$

where $(x_0 - c_2 \le x \le \infty)$, $c_1 = \frac{4}{4-\pi}$, $c_2 = \frac{\sigma}{2}\sqrt{\pi c_1}$.

For each of the three laws, the averaging for implementation was carried out (Fig. 2). The number of numerical experiments used in averaging was 10. The obtained results showed that in the sense of the standard deviation metric, the difference between the averaged spectra is much smaller than between the results of one experiment and its averaging.

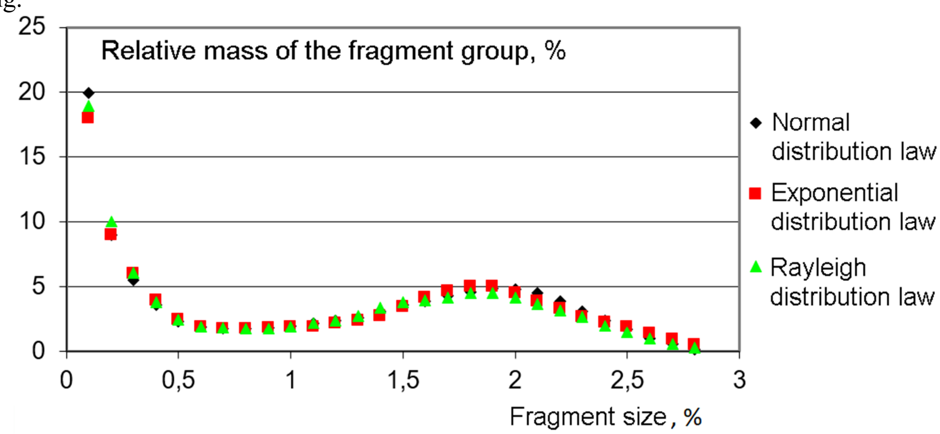

FIGURE 2. Average fragmentation spectra for different distribution laws (standard deviation 10%)

The difference between the implementation averaging for normal and Weibull laws was

$$\sigma^*_{weibull} = \sqrt{\sum_{i=1}^{n} \frac{(\overline{f_i^{weibull}} - \overline{f_i^{normal}})^2}{n}}$$

$\sigma^*_{weibull}$ =1.5% by weight of the shell.

The difference between the implementation averaging for normal and exponential laws was

$$\sigma^*_{\exp} = \sqrt{\sum_{i=1}^{n} \frac{(\overline{f_i^{\exp}} - \overline{f_i^{normal}})^2}{n}}$$

$\sigma^*_{\exp}$ =1.8% by weight of the shell.

The average difference between the results of one experiment and its averaging was

$$\overline{\sigma^*_{normal}} = \frac{1}{m}\sum_{j=1}^{m}\left(\sqrt{\sum_{i=1}^{n}\frac{(f_i^{j\_normal} - \overline{f_i^{normal}})^2}{n}}\right)$$

$\overline{\sigma^*_{normal}}$ =2.3% by weight of the shell.

Here n=30 is the number of intervals into which the fragmentation spectrum is divided; m=10 - number of experiments used for averaging over implementation;

$\overline{f_i} = \frac{1}{m}\sum_{j=1}^{m} f_i^j$ - the value of the averaged spectrum function (in mass-by-mass coordinates) in the i-th interval;

f_i^j - the value in the i-th interval of the spectrum function obtained in the j-th experiment;

The results show that $\overline{\sigma^*_{normal}}$ is much larger than $\sigma^*_{weibull}$ and $\sigma^*_{\exp}$, which allows us to conclude that the fragmentation spectra obtained using different laws of the distribution of initial inhomogeneities coincide (with the same variance of the initial distribution), up to the probability factor

Thus, we can assume that the dispersion of the distribution plays a main role in the choice of the law of distribution of strength properties. This is quite consistent with the theoretical ideas about the heterogeneities influence - not all of them will be able to be realized in macro cracks, but only those whose deviation from the average value exceeds a certain value.

The conclusion that the dispersion of the initial distribution of strength properties has a stronger influence on the formation of the fragmentation spectrum than its shape reduces the requirements for the choice of the distribution law and allows the use of almost any law in analytical and numerical calculations. It should be noted that Diep [2] also concluded that choice of the distribution law does not have a significant influence on the fragmentation spectrum in exploding cylinder tests.

Despite the fact that recently the probabilistic approach with the distribution of strength properties is gaining popularity, its application is largely limited to the inconvenience of the generally accepted Weibull distribution, which is derived from the power "hazard function" in Mott's statistical theory of fragmentation [4]. The Weibull distribution is not symmetric, so the parameters of the Weibull distribution do not have a clear physical meaning and setting the boundaries of the distribution is inconvenient. Using the normal distribution law for the distribution of ultimate strength properties is more convenient and makes available the use of probabilistic approach to each researcher. The normal law makes it quite easy to mathematically select the working interval, exclude non-physical values of random variables and vary the variance.

CONCLUSION

Thus, the introduction of only one additional parameter (dispersion of the distribution of strength properties) into the material model makes it possible to give the process of crack formation a probabilistic character at any scale level of the structure modeling, which corresponds to theoretical concepts and experimental data. Thus, the limitations of the classical approach to numerical simulation of fracture are removed and the calculation results are close to the natural form of crushing. The described probabilistic approach can be used at any mesh step and at any level of multilevel modeling, providing the distribution of inhomogeneities of the characteristic size. This approach can be applied to any material models and fracture criteria.

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