QUASI-BRITTLE FRACTURE OF FOAM-POLYSTYRENE PLATES WITH HOLE

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ABSTRACT

Experiments were performed to determine the quasi-brittle fracture of foam-polystyrene plates of trademark PSB-25 involving some holes, cuts and also without them. The plates of dimensions 1×1 m and thickness 5 cm are used. The ultimate strength of material, Young's modulus, Poisson's ratio, pre-fracturing strain and critical coefficient of stress intensity were determined. All holes in plates are made as central holes having circular, elliptic and square shapes. A major axis of elliptic holes is located both normally to the stretching directions and at angle 45° to this direction. To analyze experimental data, a numerical algorithm is used because the relation among the sizes of holes and plates does not correspond to the known problems on stress concentrations for infinite planes. Using the gradient fracture criterion (Legan [1, 2]) as the base and the boundary element method (the fictitious stress method), the above computational strength algorithm is constructed (Sheremet [3]). The key feature of the numerical algorithm is that in calculating it is necessary to determine not only components of stress state but also their derivatives with respect to space coordinates as well for them to be used in the gradient fracture criterion. The experimental data are compared with the calculation results. The application of classic strength criterion resulted in lower evaluations of critical stresses and loads. In comparison with the classical criterion, the use of the gradient fracture criterion leads to better agreement between estimates and experimental data.

1 INTRODUCTION

A numerical algorithm for strength analysis of plane structural members with stress concentrators was developed in (Sheremet [3]). This algorithm uses the gradient fracture criterion (Legan [1, 2]) and the boundary-element method (the method of fictitious loads) (Crouch [4]). In the present paper, this algorithm is applied to analysis of fracture of foam-polystyrene plates of finite dimensions.

The essence of the gradient approach to evaluation of fracture is that non-uniformity of a stress state leads to reduction in the breaking ability of stress in the range of maximum values. According to gradient fracture criterion, to determine the onset of fracture, one should compare not the first principal stress σ_1 (used as the equivalent stress) but a certain effective stress $\sigma_e = \sigma_1 / f(g_1, L_1, \beta)$, which is less than the equivalent stress, with the ultimate strength of material σ_b. The denominator $f(g_1, L_1, \beta)$ is a function of the stress-field non-uniformity at a point of the body considered as well as two parameters that depend on the material properties. The stress-state non-uniformity is characterized by the relative gradient of the first principal stress $g_1 = |\mathrm{grad}\,\sigma_1| / \sigma_1$ and is determined from elastic solution of the corresponding problem. The parameter L_1 has the dimension of length and it is determined from the condition that the gradient criterion agrees with linear fracture mechanics: $L_1 = (2/\pi) K_{\mathrm{Ic}}^2 / \sigma_b^2$, where K_{Ic} is the critical coefficient of stress intensity. The dimensionless parameter $\beta = \sigma_b / (E\varepsilon_*)$, which varies from 0 to 1, takes into account the quasi-brittle nature of fracture ($\beta = 1$ for brittle fracture). Here E is

Young's modulus, ε_* is a pre-fracturing strain. The effective stress is calculated by the formula $\sigma_e = \sigma_1 \Big/ \left(1 - \beta + \sqrt{\beta^2 + L_1 g_1}\right)$. Let the fracture begin at the point of concentrator contour when $\sigma_e = \sigma_b$ and extend by perpendicular to the contour.

2 SCHEME OF LOAD

All experiments have been performed on the PSB-25 foam-polystyrene plates whose size was 1×1 m and 5 cm thickness. The plates were loaded in vertical direction by clamps of original construction in which the upper and lower parts of the plate were fixed (Fig.1). Distance between upper and lower clamps was 0.7 m. Fracture force P_* was measured by dynamometer.

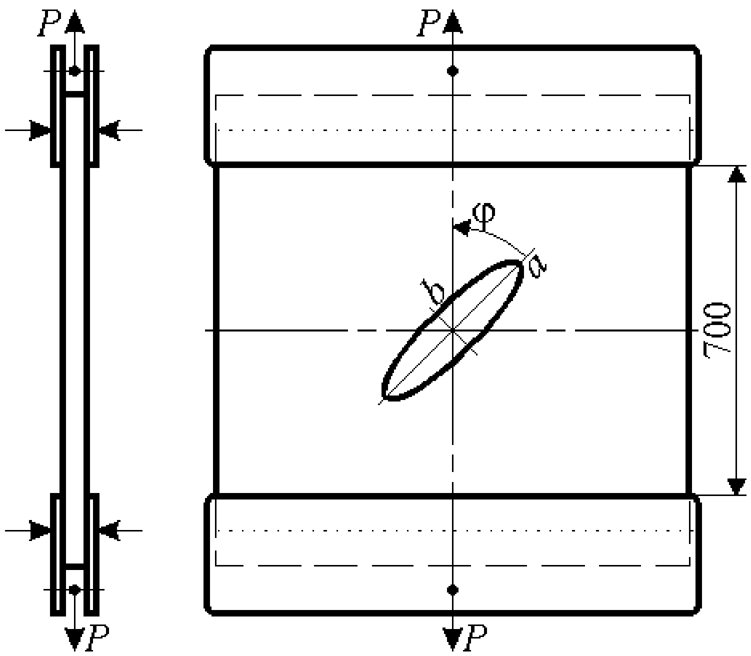

Figure 1: Scheme of load

Every clamp was made of 2 sheets of firm plywood, which were loaded by pressure from bicycle tube and fixed the rim of foam-polystyrene plates. In places of contact with specimens the sheets of plywood were covered with abrasive material. Bicycle tube enclosed in a steel frame to avoid the excessive blowup was placed along clamp perimeter and created the uniform pressure on sheets of plywood. The force of loading was transmitted from testing machine to sheets of plywood through the hinge connection. Further, by friction this force was transmitted to foam-polystyrene plates. Such locking and loading conditions better correspond to the constant vertical displacement along the width of the plate but not to the constant loading along the plate width. This circumstance was mentioned in establishing the boundary conditions in the boundary element method.

3 VARIETIES OF TEST

Let us characterize of the main tests.

A. To determine the ultimate strength of material, elasticity module and ultimate deformation, the specimens of special form representing two parallel-connected specimens of usual form were tested (Fig.2). Such geometry allowed decreasing the parasitic bending stress in specimens and providing the main fracture on the working part with constant section, but not in the fillets.

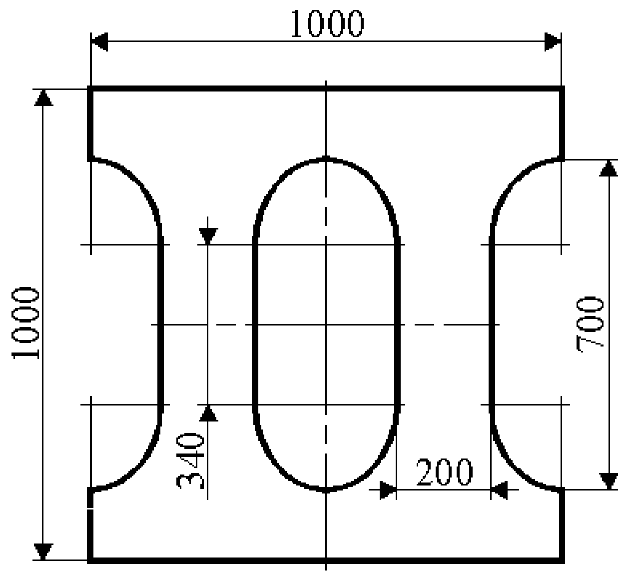

Figure 2: Specimen for determination of the ultimate strength material

Obtained in 11 experiments, the following average values are:

– the ultimate strength of material $\sigma_b = 105.21$ kPa ;

– Young's modulus $E = 7.957$ MPa ;

– the ultimate deformation $\varepsilon_* = 1.7 \cdot 10^{-2}$.

Note that in diagram of the PSB-25 foam-polystyrene a rejection from linear trajectory under stress conditions exceeding 2/3 of σ_b is observed. For gradient criterion, the parameter $\beta = \sigma_b / \left(E\varepsilon_* \right) = 0.778$ was calculated. The fracture of this material is considered to be quasi-brittle.

B. To determine the critical stress intensity coefficient, we used the plates with central cut whose total length was 0.2 of the plate width. The value $K_{\mathrm{Ic}} = 17.354\ \mathrm{kPa} \cdot \mathrm{m}^{1/2}$ was obtained in 6 experiments using Feddersen formula (Brown [5]).

C. To determine Poisson's ratio square plates with 2 sensors were strained. One sensor was for measuring the displacement in strain direction and another one was for measuring the displacement in perpendicular direction. As a result $\nu = 0.26$ was found.

D. To determine the critical load, the experiments of fracture of foam-polystyrene plates with central holes of the following forms were performed:
– circular form;
– elliptical form of different sizes and angles of inclination φ of large axis of ellipse in direction of strain (Fig.1);
– curvilinear form close to square with round angles obtained by conform transformation of single circumference (Savin [6]). Strain is directed along opposite sides of square.
Geometric parameters of the holes-concentrators are shown in Table 1, where a and b are large and small semi-axes of elliptic hole.

Table 1: Parameters of holes

Variety of test	Form of the hole	a, m	b, m	φ, grad
D.1	Circular	0,1	0,1	—
D.2	Elliptic large	0,2	0,05	90
D.3	Elliptic	0,1	0,025	90
D.4	Elliptic inclined	0,1	0,025	45
D.5	Square curvilinear hole in which the minimal distance between sides is equal 0.2 m			

From characteristics obtained in tests **A** and **B** we determined the parameter of the gradient fracture criterion $L_1 = (2/\pi)K_{\mathrm{Ic}}^2 / \sigma_b^2 = 17{,}321$ mm .

4 EXPERIMENTAL RESULT AND NUMERICAL EVALUATIONS

The mean results of some experiments with specimens with stress concentrators are shown in Table 2 as an average value of critical stress in brutto-section of plate. The boundary element method and the gradient fracture criterion were used to get the evaluations in Table 2. The total number of elements was 600: 200 elements were for the hole and 100 elements were for each side of the plate. The decreasing number of elements by two resulted in the insignificant change of the results (less than 4 % of the gradient criteria evaluation).

Table2: Results and evaluations

Variety of test	Number of experiments	Experimental data σ_*, кПа	Classic criterion σ_c, кПа	Gradient criterion σ_g, кПа	Conditional stress $\sigma_\beta = \frac{\sigma_g}{\beta}$, кПа
D.1	6	53,209	35,671	43,529	55,950
D.2	6	31,176	11,310	23,177	29,790
D.3	6	41,791	11,534	30,571	39,294
D.4	8	57,251	17,975	39,751	51,094
D.5	8	59,645	27,612	59,200	76,093

Note that conditional stress σ_β better than other evaluations correspond to the experimental data (see the errors in Table 3), because it takes into account the rejection from the linear character of the deformation diagram. As the boundary element method uses the linear elasticity theory, the stress values in small zone of stress concentration are higher than these when taking into account the real properties of material in high strain. It results in the lower values of evaluation of average stress in brutto-section of the plate in comparison with the experimental data even when using the gradient fracture criterion taking into account the inhomogeneous stress state. When using the classic strength criterion according to which the fracture begins when maximal value of the first main stress σ_1 reaches the ultimate strength of material σ_b, the evaluations of average critical stress in brutto-section are significantly lower.

Table 3: Evaluation errors

Variety of test	Error of classic criterion	Error of gradient criterion	Error of conditional stress
D.1	-0,3296	-0,1819	0,0515
D.2	-0,6372	-0,2566	-0,0445
D.3	-0,7240	-0,2685	-0.0597
D.4	-0,6860	-0,3057	-0,1075
D.5	-0,5371	-0,0075	0,2758
Mean value	-0,5828	-0,2040	0,0231

5 CONCLUSION

A series of experiments with specimens made of foam-polystyrene of trademark PSB-25 were performed. There were determined its following characteristics: ultimate strength of material, Young's modulus, Poisson's ratio, pre-fracturing strain and critical coefficient of stress intensity. Experimental values of breaking load for specimens having concentrators in the form of different holes were obtained.

The comparison of numerical evaluations with experimental values showed that the application of classic strength criterion resulted in lower evaluations of critical stresses and loads. The use of gradient fracture criterion taking into account the non-uniformity of a stress state results in higher evaluations of critical loads that remain less than those of experimental loads.

We get evaluations the closest to experimental values if we take into account both non-uniformity of a stress state and rejection from the linearity of the deformation diagram, i.e., the effective stress σ_e in the gradient criterion may be multiplied by the parameter β that is below unity in quasi-brittle fracturing. This recommendation does not concern the developed plastic flow when for evaluation of critical loads it is necessary to apply other methods.

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