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NONDESTRUCTIVE DETERMINATION OF THE CRITICAL LOAD OF COLUMN-TYPE STRUCTURES

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In [2] a highly developed analysis of methods for investigating the stability of columns under pressure as well as for determining the critical force for columns and column-type structures is given. In particular, it is shown that the onset of static instability in a column is marked by a zero natural vibration frequency.

It is of great practical importance to determine the stability of the elements of structures formed from multilayer composite materials which satisfy specific requirements of durability against a variety of effective factors. Often the supports of a real-world structure, understood as elements of the structure itself, are themselves complex structures possessing all the technological types of irregularities inherent to real-world structures, a fact which leads to significant spread of the actual critical loads of the structure within one and the same series.

Sampling testing of several such structures to determine the critical loads and extending these tests to an entire series of such structures in principle allows for the likelihood that there will be structures in the working series which may lose stability when subjected to loads which are much less than the predicted value. Thus, it is important to make a nondestructive determination of the critical load for each support so as to exclude from the working series inadmissibly weakened structures.

A coupled beam-column mechanical system has been used to model the mechanics of the behavior of a column-type support subjected to a pulse axial load [1]. A symmetric beam which restrains the transverse displacement of a column attached at one of its ends when the column experiences bending was selected as the element for transmitting an oscillating shock load to the column. The beam, which was rigidly restrained at both ends, rested on a column which was attached to the beam at its middle section, while the other end of the column was rigidly set in a fixed support. The parameters of the column and beam were selected so that in the unloaded state the vibration frequency of the column Ω_0 in bending with respect to the first normal mode in the direction of least rigidity would be less than the transverse vibration frequency of the attached beam. Tests of beams and columns were designed so that the ratio of these frequencies would be in the range 1.6-2.5.

Beams and columns made of fiber glass laminate (SF-1-150; All-Union State Standard 10316-78) 2.5 mm thick were subjected to the tests. The modulus of elasticity of the material was equal to $2.6 \cdot 10^{10}$ Pa, and its density 1.7 g/cm^3.

A beam restrained at both ends was mounted transverse to the measurement cross-section of a diaphragm-covered tube. A section of the tube which was not spanned by the beam was plugged in such a way that the caps did not touch the beams, but nevertheless prevented any waves from escaping from it. In all three variants of the system which were subjected to testing the beams were of the same dimension, with width of 59.5 mm and length of 210 mm. The geometric dimensions of the three tested columns are presented in Table 1, where l is the length and b the width of the column. In the last column may be found the approximate ratio of the first natural bending frequency ω of the beam to the first natural roll frequency Ω_0 of a column of length l and thickness h rigidly restrained at both ends.

The numerals in the first column of the table will be assigned in the text below to both columns and, in general, the corresponding beam-column system.

In a number of the experiments an initial camber was imparted to the column by means of a thin rubber strut. The magnitude of this camber did not exceed the thickness of the column and was measured by means of a dial gauge head with scale divisions every 0.01 mm.

Foil-covered resistance strain gauges with a base of 1 or 3 mm (type KF 4P1-3-100 V-12) were pasted along the wide faces of the beams and columns. The strain gauges were placed along the axial lines of each side in pairs facing each other, making it possible to record either the bending ε^b or the membrane ε^m deformations in the dynamic tests.

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TABLE 1

System	l, mm	b, mm	$\frac{\omega}{\Omega_0}$
1	158	18,0	2,5
2	150	17,5	2,2
3	125	12,5	1,6

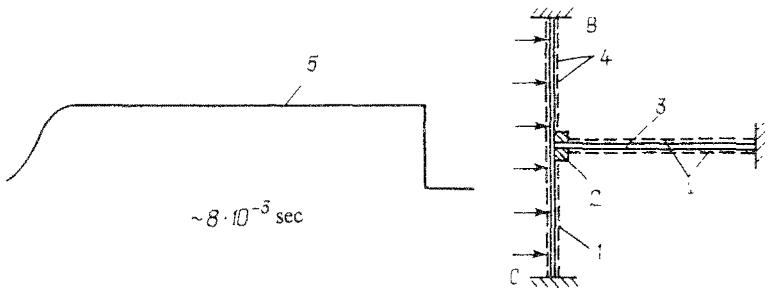

Fig. 1

Static tests were conducted following the technique of [3], with each system subjected to the effect of a constant load with pressure P on the beam increasing right up to levels at which the column-type support experienced a loss of stability. The pressure at which a loss of stability was observed was established on a class 0.4 indicating pressure gauge. It was not possible to establish the critical pressure in the concluding test with system 2 before it became unstable, since as the load was increased, the flexure of the column increased gradually to very high values (on the order of 10h) without any abrupt change in shape which is otherwise typical for a loss of stability.

The system is depicted schematically in Fig. 1, where the arrows denote the load acting on the beam, with 1 denoting the beam, 2 a center plate which is used to attach the column to the beam, 3 the column-type support, 4 the resistance strain gauges, and 5 the shock wave. The cascade-type shock waves had a duration on the order of $8 \cdot 10^{-3}$ sec.

The amplitude of the incident wave was allowed to vary over the range $(0.07\text{-}1.0) \cdot 10^5$ Pa.

In testing elastic beam-column systems subjected to static loads P of different strengths, the natural frequencies of the supporting column was determined in two ways. In the first approach the most generally accepted method of determining the natural frequencies in terms of resonances, a method which involved subjecting the column to constrained transverse vibrations, was employed. In addition, a thin plate made of a ferromagnetic substance was pasted to one side of the column midway with respect to its longest edge; a vibration excitation coil was mounted near the plate. The coil was connected to a type GZ-109 power generator. On the opposite side a thin piezoceramic plate was pasted to the support also midway with respect to its longest edge, and the signal from this plate was fed to an electronic oscillograph as well as to a frequency meter equipped with a digital display.

The second method involved establishing the free vibrations of the column which was first loaded with a constant force after it had been subjected to a single transverse impact at its central section caused by a steel ball with diameter $\approx$ 5 mm. The signal from the piezoceramic plate was fed to the oscillograph operating in automatic start mode and photographed in still frames.

In the course of testing the response of the system to the effects of a shock wave [1] it was shown that as it vibrates, the beam transmits an axial compressive load to the column. As in the case of a beam subjected to bending strains, the axial strains experienced by the column possess a stepped and a decaying oscillatory component. Throughout the entire period of investigation the column was in a compressed state against the background of a constant compressive load P_+ which depended on the strength of the wave incident on the beam. It was also subjected to a periodic damping load. Analysis of the oscillograms demonstrated that the process in which the column-type support was subjected to flexural vibrations was basically dual-frequency in nature: vibrations with the excitation frequency, which is determined by the frequency of the flexural vibrations of the beam, were superimposed on the vibrations of the column, which had a frequency of ω.

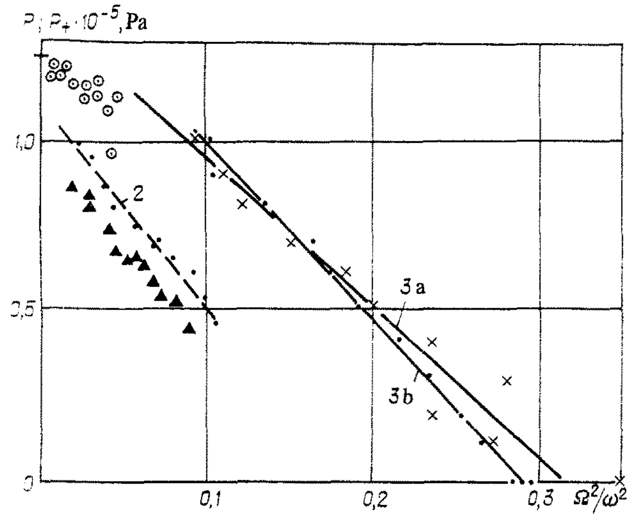

Fig. 2

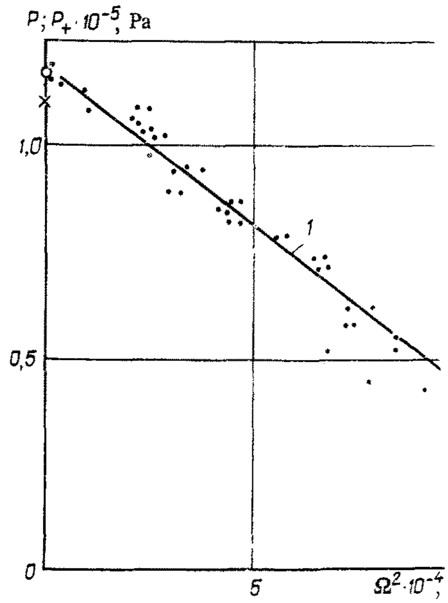

Fig. 3

The nonsteady-state bending vibrations which the column experienced under the effect of the compressive load may be considered from the standpoint of parametric vibrations, inasmuch as the rigidity of the column varies starting from the moment the load is applied as a function of the magnitude of the load P_+.

Figure 2 shows the values of the square of the fundamental oscillation frequency of the column 3 determined as a function of the axial load using three separate methods. The points in the figure denote measurements of the frequencies of the column determined on the basis of the resonances in the case of a stationary excitation of vibrations, while the crosses denote results obtained in experiments involving the excitation of vibrations by means of a micro-impact. The small circles with dots inside represent results from processing the oscillograms of the nonsteady-state vibrations experienced by the same column when the beam was affected by shock waves of different strengths. The results obtained in the first two approaches r· .y be sufficiently closely approximated by means of linear dependences (line 3a in the figure represents the resonance measurements, and line 3b the measurements by means of the micro-impact). The extensions of these lines to their intersection with the load axis determines the critical load for the particular column, or roughly $1.5 \cdot 10^5$ Pa (determination of frequencies from resonances) and $1.4 \cdot 10^5$ Pa (micro-impact method). The actual value of the critical static load for the particular column proved to be equal to $1.25 \cdot 10^5$ Pa and is labeled by a short horizontal bar on the vertical axis. The points closest to the bar are the experimental

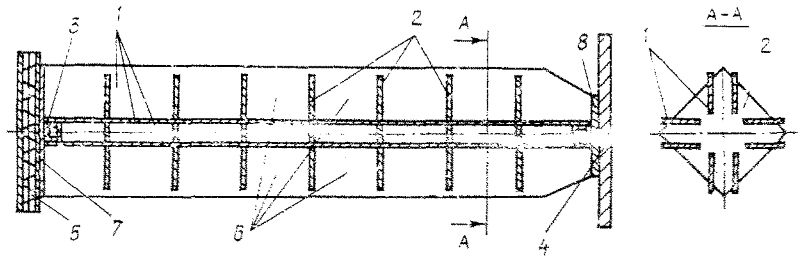

Fig. 4

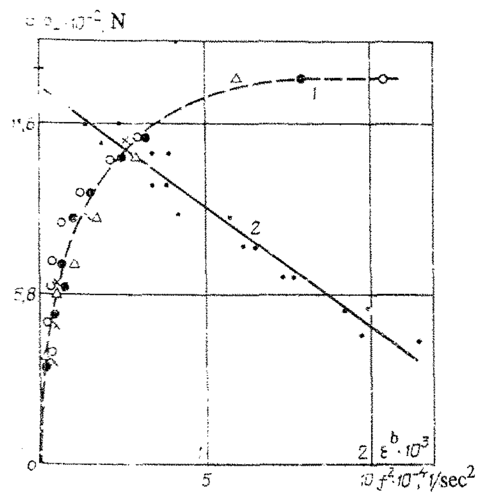

Fig. 5

points which were obtained by determining the frequencies of the column's flexural vibrations on the basis of oscillograms of the nonsteady-state process when the column was affected by shock waves of different strengths.

For column 2 the ratio of the square of the frequency of the column measured from oscillograms of the flexural vibrations to the square of the frequency of the vibrations of the beam as a function of the dynamic load is shown in Fig. 2. The points and broken line denote the results of experiments with the column in its initial state, respectively, while the triangles denote measurements made when an additional initial camber of 0.38 mm ($\delta/h \approx 0.15$) was imparted to the column. The downward shift in the results denoted by the triangles below the broken line constructed from the points confirms the well-known fact that the critical load drops as the initial camber of the column is increased, and illustrates the rather high sensitivity of the nondestructive method of determining critical loads.

Experimental results designed to determine the frequency of the base vibrations of column 1 when the beam is affected by shock waves are denoted by means of points in Fig. 3 using the same coordinates. At its intersection with the load axis, the straight line which averages the experimental points predicts the dynamic critical load for this support, which is equal to $1.18 \cdot 10^5$ Pa. Using the same column, the dynamic load on the beam at which the process of strain the column is subjected to is shown on the oscillogram to be aperiodic ($P_+ = 1.17 \cdot 10^5$ Pa) is indicated by a small circle on the vertical axis. The static load under the influence of which the column experiences an actual loss of stability $P_+ = 1.10 \cdot 10^5$ Pa) is indicated by a cross on the vertical axis.

Despite the fact that the three values of the critical load determined by the three different methods do not coincide, their difference is no more than 7% and, within the experimental precision, may be assumed to coincide. The error may be reduced through a more rigorous harmonic analysis of the oscillograms of the flexural strains.

A full-scale column-type support (Fig. 4) consisting of eight fiberglass plastic pedestals (1) measuring 635 × 55 × 1.2 mm glued by means of seven square plates (2) measuring 110 × 110 × 1.2 mm affixed uniformly along the length of each pedestal were tested for the effect produced by a shock wave. At one end the pedestals were truncated at an angle of 45° so as to give the end-face of the support dimensions of 65 × 65 mm. The plates 2 contained sections 1.5 mm wide and 45 mm in length to which supporting struts were pasted. Plates 7 and 8, which have the same dimensions as the support cross-section, were pasted to the end-faces of the struts. At their end-faces each pair of struts was bonded to small chambers 3 measuring 50 × 28 × 28 mm in dimension and pasted on with glue to the end plates 7 and 8.

The supporting end-face of the column-like structure was rigidly attached to a solid steel plate 4 and a piston 5 was pasted to the other end-face. The piston was in the form of a five-layer fiberglass plastic panel 60 mm thick. As designed, the panel was rectangular in shape with dimensions that allowed it to fit in the end-face of the measurement section of the diaphragm-covered shock tube leaving a gap of around 1 mm [3]. The shock wave which had been created as a result of the rupture of the diaphragm was incident on the piston (panel) at a right angle, and by means of the piston the nonsteady-state axial load was transmitted to the support.

The strain experienced by the elements of the support was studied by recording the signals from KF4P1-1-3-100 V12 resistance strain gauges connected by means of a full-wave circuit on the screens of electronic oscillographs using wide-band ($0\text{-}2\cdot10^5$ Hz) amplifiers. A flow chart showing how the strains are recorded using a pulse power source is presented in [3].

Before testing the support two pairs of resistance strain gauges facing each other were pasted on each of the eight supporting struts midway with respect to the lengthwise direction. The position of the resistance strain gauges on the support is labeled 6 in Fig. 4. Preliminary tests of the support by means of low-intensity shock waves were initially carried out for the purpose of identifying the weakest sections. Three of the eight sections were selected on the basis of readings from the sensors; the magnitude of the strain experienced by these sections exceeded that experienced by the other sections. Subsequently, the strains experienced by these three sections were recorded in the course of testing. The resistance strain gauges pasted on two of the sections were connected into a circuit designed to measure the flexural vibrations, while those pasted onto the third support were intended to measure the strain experienced by the diaphragm. The support was subjected to pulse compression by means of shock waves with the pressure behind the front of the reflected wave in the range $0.1\cdot10^5\text{-}0.45\cdot10^5$ Pa, while the impact load on the piston varied from 229 to 1305 N.

The strain experienced by the elements of the support was complex and oscillatory in nature, and, as in the tests of column-type supports, the vibrations occurred relative to the state of strain in which the support was subjected to a static load equal to the load behind the shock wave reflected from the piston.

Figure 5 shows the results obtained from processing the oscillograms. The magnitude of the flexural vibrations ε^b of the elements of the support and the square of the frequency of their vibrations f are laid out along the horizontal axis, while the magnitude of the load experienced by the support when it was affected by a shock wave with stepwise profile is laid out along the vertical axis. The flexural vibration curve (1) was constructed from the readings of four pairs of resistance strain gauges (represented by means of crosses, triangles, and dark and light circles, respectively) when the first flexural vibration maximum appeared. The linear dependence (2) of the square of the frequency of the flexural vibrations on the load was constructed from the experimental points. The short horizontal bar on the vertical axis denotes the critical load (1340 H) at which the support was observed with the naked eye to have experienced a loss of stability as a result of the influence of the static load P.

From the results presented here we are led to conclude that the extension of the straight line (2) until it intersects the load axis determines the critical force for this support (1290 H), moreover it lies in a region of loads where a small increment in the load leads, according to the experimental curve (1), to large increments in the flexural vibrations.

Thus, it has been shown that subjecting complex supports to axial loading, such as that produced by a stepwise shock wave, together with measurements of the square of the flexural vibration frequency of the supporting elements in the subcritical region makes it possible (depending on the strength of the axial load) to determine, using a nondestructive method, the critical load of a multi-element, full-scale support.

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