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ESTIMATION OF CRITICAL LOADS AND LOW-CYCLE FATIGUE OF LAMINATED PLATES WITH DELAMINATION REGIONS

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The results of experimental investigation into the problem of effect of delamination on the critical load and the low-cycle fatigue of a laminated plate are presented. The rectangular plates tested were composed of epoxy-glass composite facings and a core of foamed polyvinyl chloride, with circular delaminations between one of the two facings and the core.

1. Introduction

The practical importance of the study of the problem of influence of the size of delamination on the strength of a laminated plate is considerable, it being difficult to obtain a product without unglued regions under industrial production conditions of laminated structures. Delamination may also occur under operation conditions of a produced object as a result of overloads or impacts. Publications concerned with studies of the influence of delaminations on the strength characteristics of laminated sandwich plates are scarce. The problem of stability of sandwich plates with delamination regions was analysed in [1], but only for strips of various widths. The subject of the studies were plates with facings with identical or different thickness and the influence of the stiffness and thickness of the core on the development of delamination regions. The results of the analysis are confronted with those of experiments. The publications concerned with the influence of delamination on the critical loads of laminated plates in the cases, in which the values of mechanical properties of the particular layers do not differ very much from each other are more numerous. The paper [2] discusses the influence of the presence of delamination regions of various forms and size on the stability of a plate. This influence is determined on the basis of the classical theory of plates, by means of the method of finite elements. In [3] the delamination regions in a plate are assumed to have the form of a strip or a finite form (such as a circle, an ellipse or a rectangle). The results of stability analysis obtained by the Rayleigh-Ritz method are confronted with those obtained by the method of finite elements. The results of the latter analysis of the stability problem of plates with a delamination are confronted in [4] with experimental results, the agreement being found to be good. The influence of the delamination region in the form of a strip on the critical load is determined in [5, 6]. The results obtained by the method of finite elements are confronted with those of experiments. A new theory of modelling laminated plates with delamination regions is presented in [7], the theoretical results being confronted with those obtained on the grounds of the classical theory of plates and those obtained by experimental means. On the contrary, no publications concerned with the influence of delamination on the fatigue strength are available. The aim of the work reported here was to determine by experimental means the influence of the presence of delamination on the value of the critical load and the low-cycle strength of sandwich plates of 12 and 24.5 mm in thickness.

2. Subject of investigation

The object of the tests reported here were $280 \times 180 \times 12$ mm and $280 \times 180 \times 24.5$ mm sandwich plates, 12 and 24.5 mm in thickness, composed of epoxy-glass facings of an equal thickness of 1 mm and a core of foamed polyvinyl chloride. They had circular delaminations between one of the facings and the core, of a relative delamination area $S_n = S_0/S = 0$; 0.1; 0.2; 0.3 and 1.0, where S_0 is the area of the delamination region and S – that of the plate.

The facings were made of an orthotropic composite of two layers of STR-53 glass fabric and E-53 epoxy resin. The direction of the warp coincided with that of the plate length denoted by the index 1, Fig. 2 presenting that of the weft. Direction 3 was normal to the plane of the layers. The weight content of glass in the composite was 0.503. The mechanical properties of a facing were as follows:

The moduli of elasticity were $E_{11} = E_{22} = 13900$ MPa, $E_{33} = 6560$ MPa, $E_{12} = 1134$ MPa, $E_{13} = E_{23} = 1869$ MPa; Poisson's ratios $\nu_{12} = \nu_{21} = 0.1628$, $\nu_{13} = \nu_{23} = 0.3459$, $\nu_{31} = \nu_{32} = 0.163$; tensile strength $R_{11} = 308.2$ MPa and shear strength $R_{12} = 5.66$ MPa.

The core, 10 and 2.5 mm in thickness, was made of foamed PChW-1-115 polyvinyl chloride. The indices determined by tests of the core were as follows:

Young's modulus in the longitudinal direction 92.4 MPa for tension and 80.6 MPa for compression; Young's modulus in the transverse direction 34.0 MPa, Poisson's ratio 0.26, tensile strength – 1.82 MPa, compressive strength – 0.91 MPa, shear strength – 1.32 MPa. The facings were glued to the core with E-53 epoxy-resin hardened with Z-1. Circular delaminations were made by inserting circles of thin teflon foil in the course of the gluing operation between the core and the facing. In order to prevent crushing of the facings during the test, the grip segments of the core were replaced with wooden blocks. A diagrammatic view of a test specimen is presented in Fig. 1.

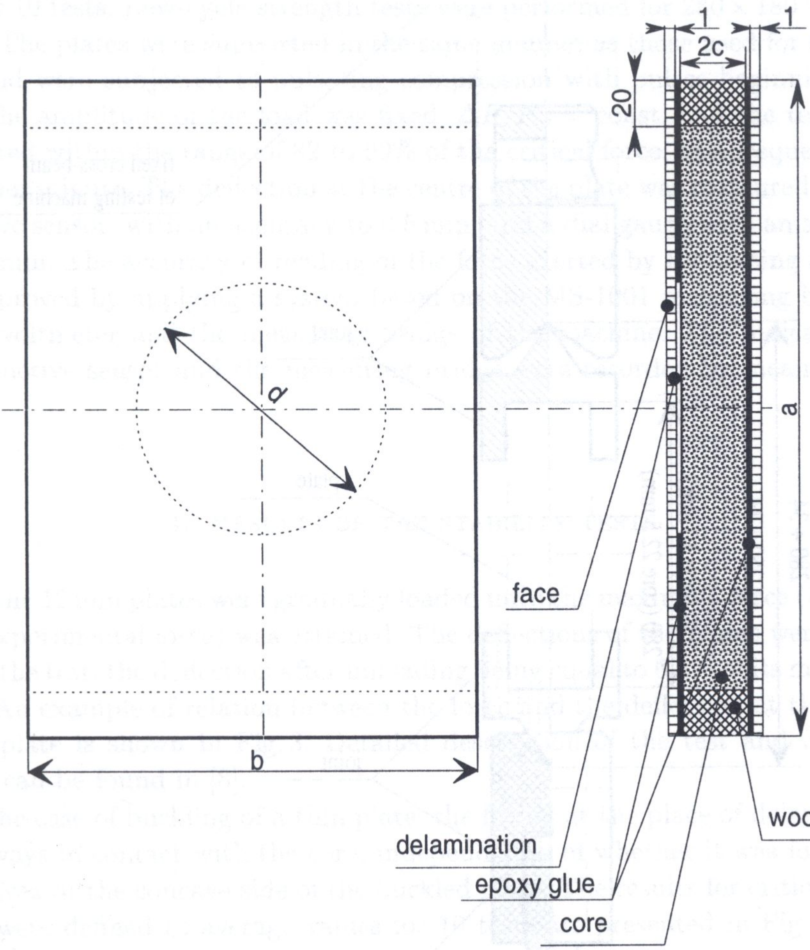
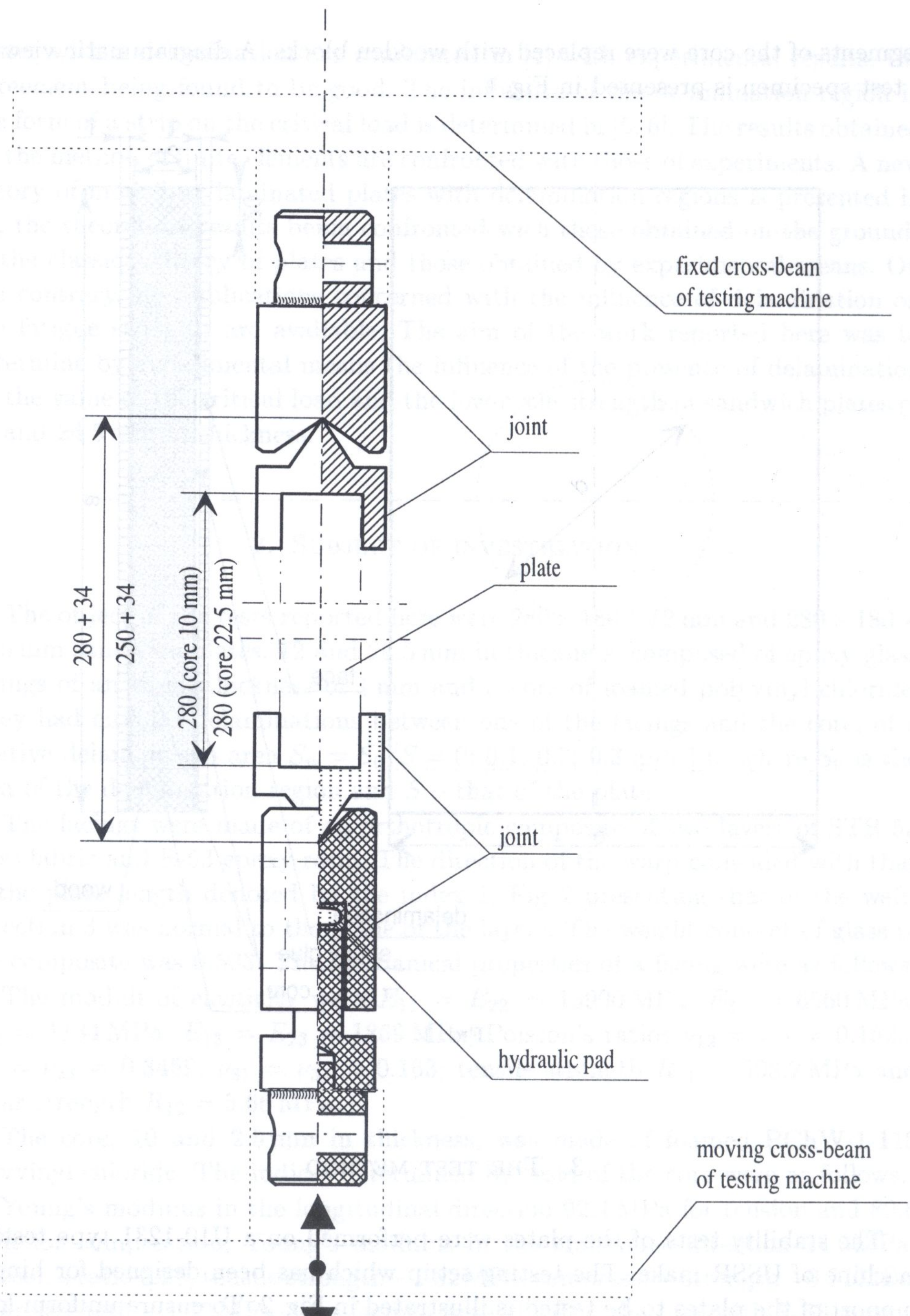


FIG. 1.

3. THE TEST METHOD

The stability tests of the plates were performed on a U10-1231 type testing machine of USSR make. The testing setup which has been designed for hinged support of the plates to be tested is illustrated in Fig. 2. To ensure uniform load distribution along the edge, a rubber cushion filled with hydraulic liquid was used. The deflection of the test specimen were measured with dial gauges and inductive sensors. The rate of travel of the holder of the machine was 0.5 mm/min



fixed cross-beam
of testing machine
joint
plate
joint
hydraulic pad
moving cross-beam
of testing machine
280 + 34
250 + 34
280 (core 10 mm)
280 (core 22.5 mm)

FIG. 2.

for all the tests. The program was made up for plates of 12 and 24.5 mm in thickness, with delaminations of six sizes. Each result was computed as a mean value of 10 tests. Low-cycle strength tests were performed for $280 \times 180 \times 12$ mm plates. The plates were supported in the same manner as those used for stability tests and were subjected to pulsating compression with pulses beginning from zero. The amplitude of the load was fixed, $\Delta P/P_{\text{cr}} = \text{const}$, and the tests were conducted within the range of 82 to 99% of the critical force, at a frequency of 4 cycles per minute. The deflection at the centre of the plate was measured with an inductive sensor, with an accuracy to 0.5 mm, and a dial gauge with an accuracy to 0.01 mm. The accuracy of reading of the force exerted by the testing machine was improved by applying a system based on the MS-1001 measuring bridge, a digital voltmeter and the measuring bridge of the machine. The indications of the inductive sensor and the measuring bridge were recorded by means a X-Y plotter.

4. Results of the stability tests

All the 12 mm plates were gradually loaded until the maximum force (assumed as an experimental force) was attained. The deflections of the plates were elastic during the test, the deflection after unloading being equal to 0.1% of its maximum value. An example of relation between the force and the deflection at the centre of the plate is shown in Fig. 3. Detailed description of the test and complete results can be found in [8].

In the case of buckling of a thin plate, the facing at the place of delamination was always in contact with the core, independently of whether it was formed on the convex or the concave side of the buckled plate. The results for critical loads, which were defined as average values for 10 tests are presented in Fig. 4 in the form of a function of the size of the delamination.

From the relation $P_{\text{cr}} = P_{\text{cr}}(S_n)$ in Fig. 4 it can be inferred that the influence of the delamination area of up to 5% on the value of the critical force is lower than the value of the dispersion of the measurement results. The influence of delamination is the highest within the range of 5 to 15% and amounts to 10% of the critical force for $S_n = 0$, the decrease in the critical force being 23.2% for $S_n = 30\%$ and 53.1% for $S_n = 100\%$. The results of statistical processing of the results obtained from the tests of the critical force showed that the dispersion of P_{cr} was small and the mean error was contained in particular cases ($S_{ni} = (0$ to $30\%)$) between 5% and 7.5%. Plates of 24.5 mm in thickness were loaded to failure. In plates without delamination, local buckling of the facings occurred just before failure, in the form of a dozen of semi-waves or so. The critical force

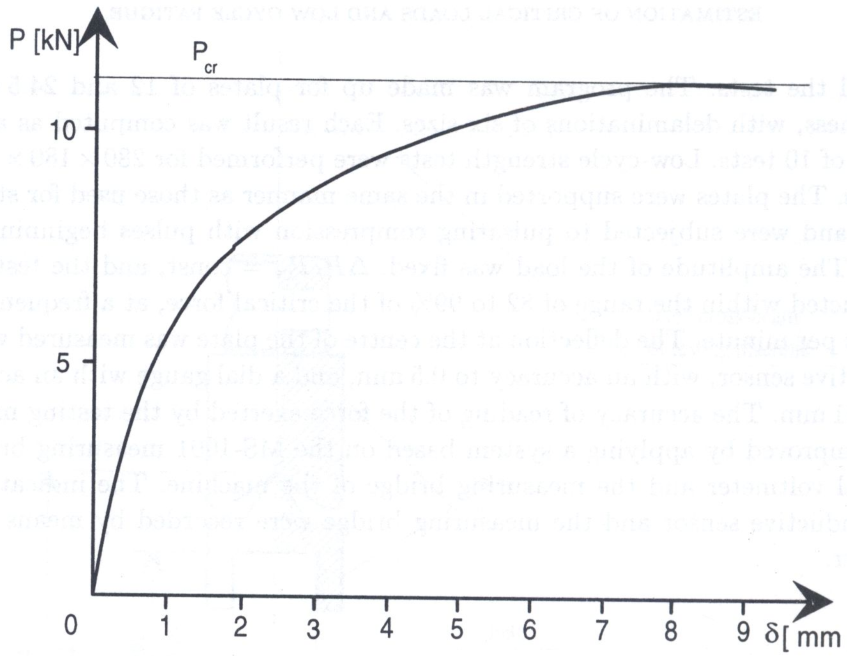

P [kN]
P_cr
10
5
0
1
2
3
4
5
6
7
8
9
δ[mm]

FIG. 3.

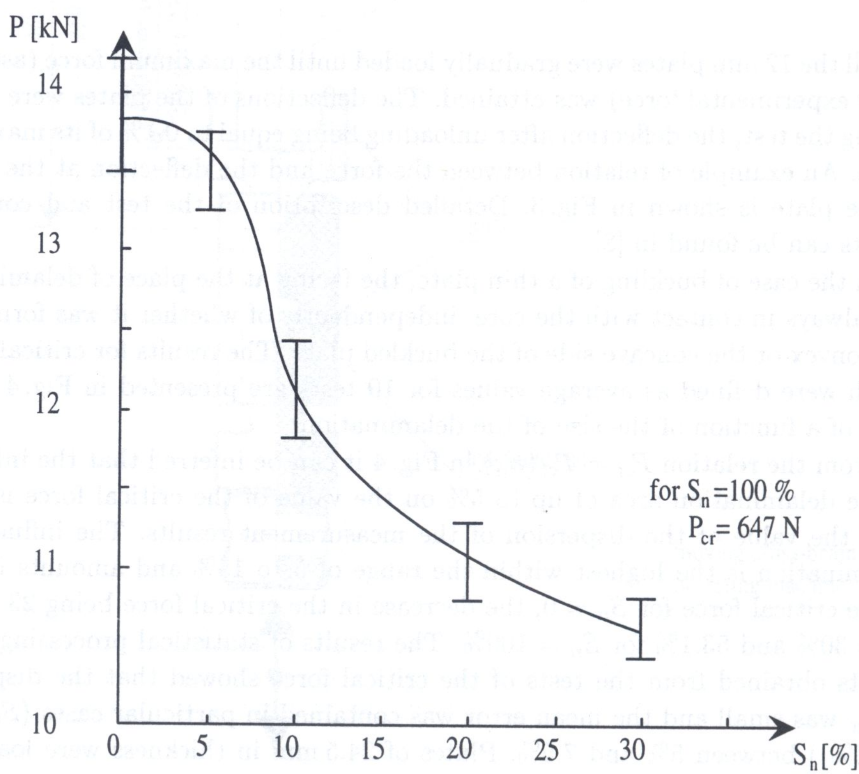

P [kN]
14
13
12
11
10
0
5
10
15
20
25
30
S_n[%]
for S_n=100 %
P_cr= 647 N

FIG. 4.

and the maximum failure force were recorded. In plates with delaminations, the facing was deformed at the place of delamination to take the form of spherical cap with a diameter equal to that of the delamination region. The beginning of this phenomenon was treated as that of local stability loss. For higher loads the spherical cap became an ellipsoid expanding towards the edges of the plate to fail when those edges were attained. An SVHS camera was used to record the type of failure and to play the role of an additional device for recording the force of failure (destructive force). This was done by arranging, within the frame of the camera, another voltmeter with a large digital display, to indicate the transient value of the force. The results of tests of the maximum force, which have undergone statistical processing are presented in Fig. 5, showing also the critical force and the maximum force as functions of the size of the delamination.

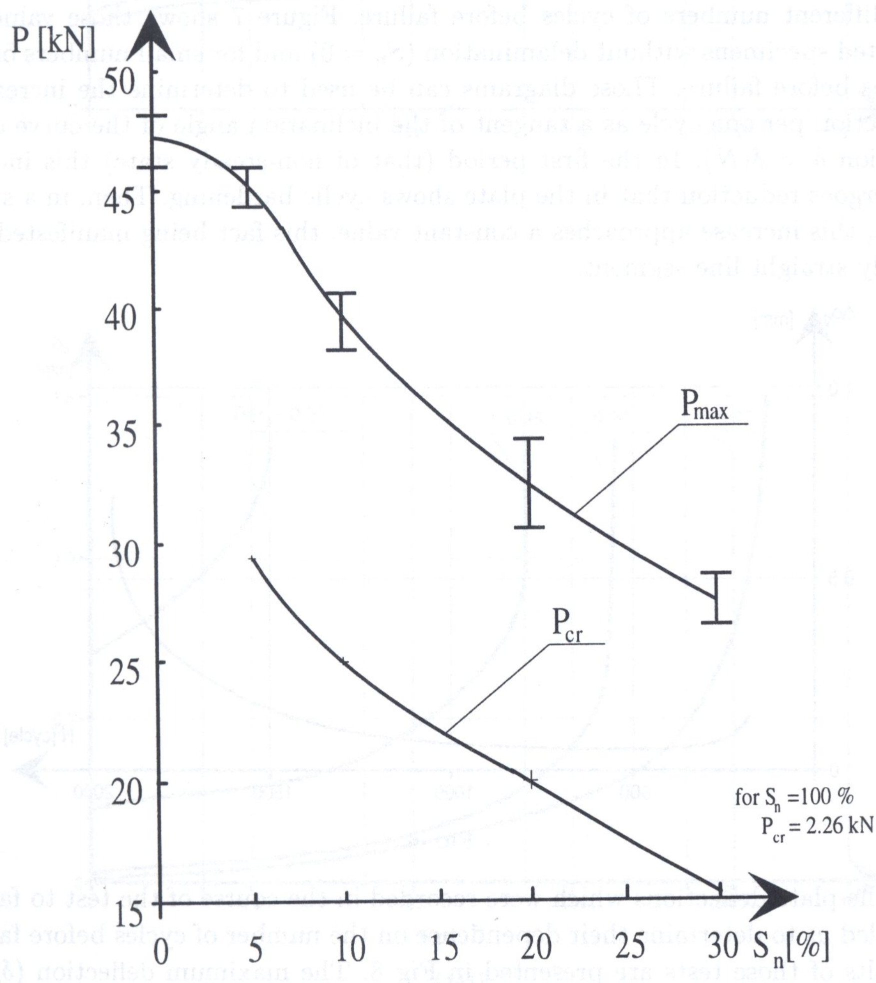


FIG. 5.

5. Results of low-cycle strength tests

The tests performed under a constant load, $\Delta P/P_{\mathrm{cr}} = \mathrm{const}$, showed distinctly a cumulation of deformations. In the initial period of the test (period 1), that is during the first dozen cycles or so, the increases in deflection of a plate become gradually smaller. Then, with increasing number of cycles (period 2), the growth of deflection $\Delta\delta$ has a practically constant value, but it increases rapidly (period 3) just before failure. As an example, Fig. 6 shows a typical relation $\Delta\delta = \Delta\delta/(N)$ for one test specimen. If the number of cycles before failure is small those periods are reduced, often with overlapping. Those periods are also distinct in the relations expressing the dependence of the total deflection of the plate on the number of cycles, for different values of the load, that is for different numbers of cycles before failure. Figure 7 shows those values for selected specimens without delamination ($S_n = 0$) and for small numbers of load cycles before failure. Those diagrams can be used to determine the increase in deflection per one cycle as a tangent of the inclination angle of the curve of the relation $\delta = \delta(N)$. In the first period (that of non-steady state) this increase undergoes reduction that in the plate shows cyclic hardening. Then, in a steady state, this increase approaches a constant value, this fact being manifested by a nearly straight line segment.

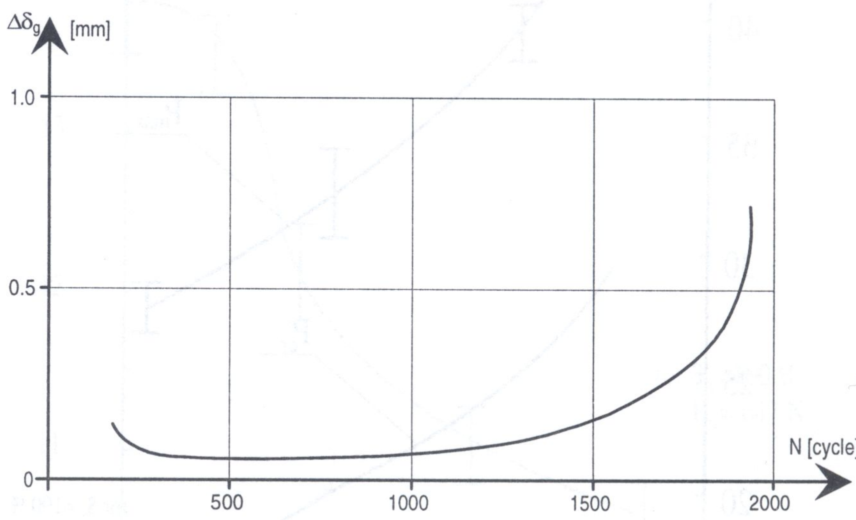
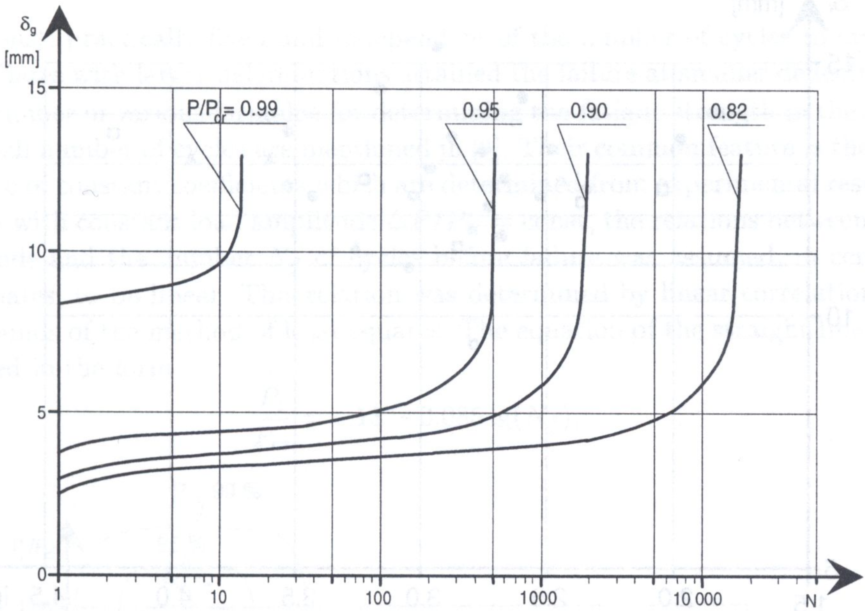


Fig. 6.

The plate deflections which were recorded in the course of the test to failure, enabled us to determine their dependence on the number of cycles before failure. Results of those tests are presented in Fig. 8. The maximum deflection $(\delta_g)_{\max}$ of a plate during the destruction process is, for all the specimens tested for


δg
[mm]
15
10
5
0
1
10
100
1000
10 000
N
P/Pcr= 0.99
0.95
0.90
0.82

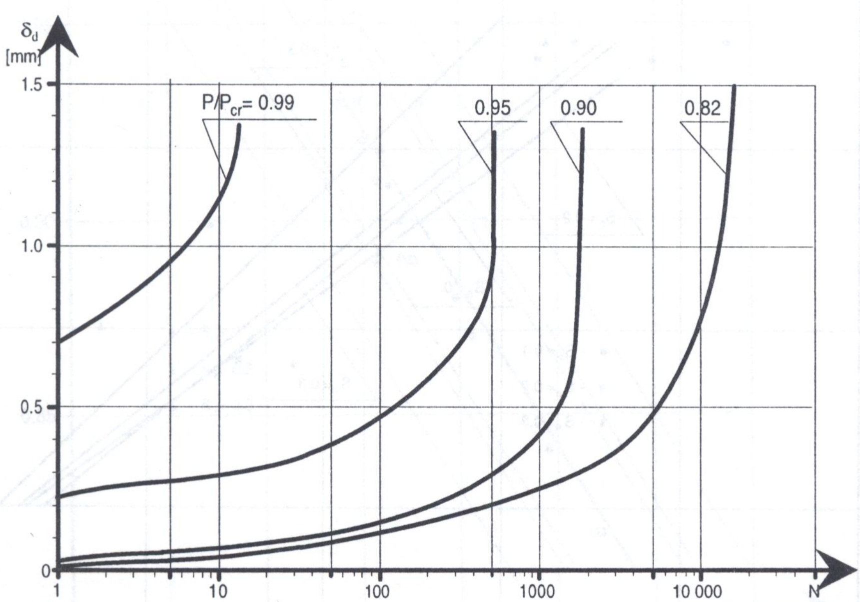

δd
[mm]
1.5
1.0
0.5
0
1
10
100
1000
10 000
N
P/Pcr= 0.99
0.95
0.90
0.82

FIG. 7.

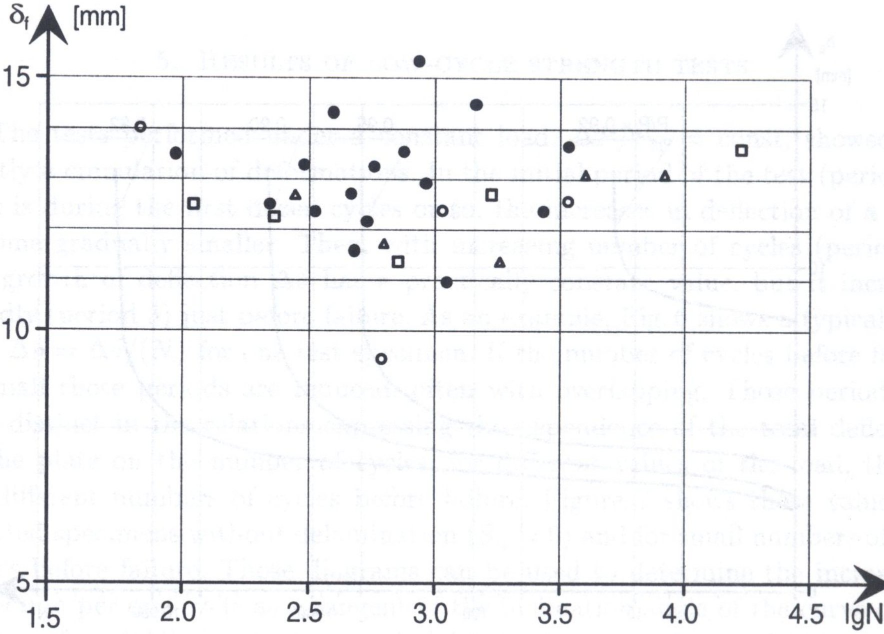

δf [mm]
15
10
5
1.5
2.0
2.5
3.0
3.5
4.0
4.5
lgNf

FIG. 8.

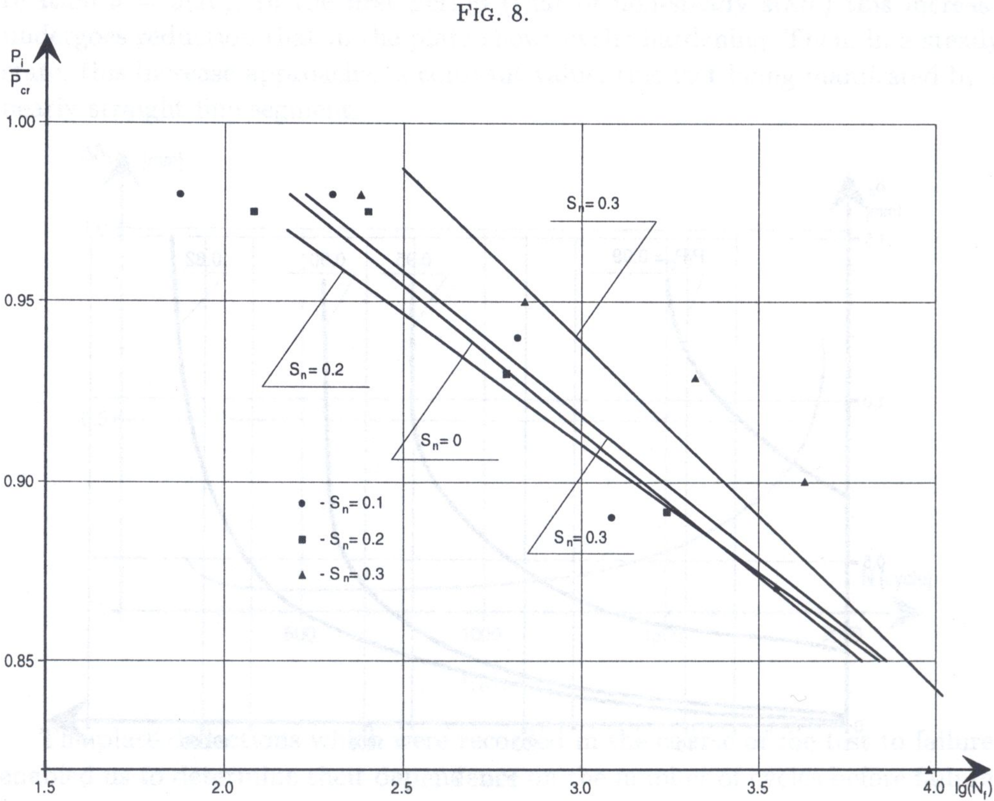

Pi/Pcr
1.00
0.95
0.90
0.85
1.5
2.0
2.5
3.0
3.5
4.0
lg(Nf)
Sn= 0.3
Sn= 0.2
Sn= 0
Sn= 0.3
- Sn= 0.1
- Sn= 0.2
- Sn= 0.3

FIG. 9.

$S_n =$ const, practically fixed and independent of the number of cycles to failure (N_f). Plates with larger delaminations attained the failure at smaller deflections.

A number of various formulae for determining the fatigue strength in the case of a small number of cycles are mentioned in [9]. Their common feature is the occurrence of constant coefficients which are determined from experimental results. In tests with constant load amplitude $\Delta P/P_{\rm cr} =$ const, the relations between the amplitude and the number N_f of cycles before failure was assumed, in certain coordinates, to be linear. This relation was determined by linear correlation on the grounds of the method of least squares. The equation of the straight line was obtained in the form

$$\frac{P_i}{P_{\rm cr}} = 1.18 - 0.085\lg(N_f),$$

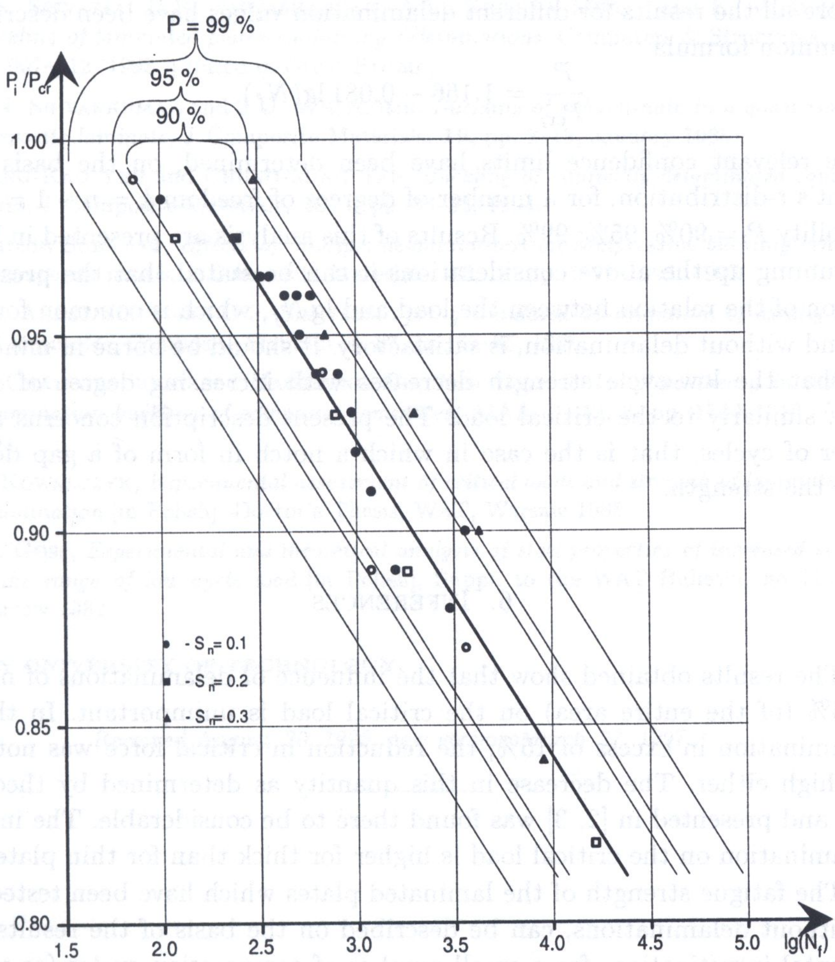


FIG. 10.

where P_i/P_{cr} is the (constant) amplitude of the pulsating load (from zero), P_{cr} – critical buckling load for plate buckling, N_f – number of cycles before failure.

The high value of the correlation coefficient $r = -0.9733$, confirms the fact that the relation between the load and the number of load cycles before failure can be approximated by a straight line. It has been found by statistical analysis that 94.7% of the measurement results can be described by a linear relation.

The test results are presented in Fig. 9. From the above set of simple regressions it follows that the agreement between them is good, except the case of $S_n = 0.3$, and the regression coefficient b (the inclination angle of the straight line) differs only by 9.17% from the coefficient b for $S_n = 0$. Thus, the relation $P = \Delta P(\lg N_f)$ can be approximated for all the values of the area of delamination S_n, by linear functions with regression coefficients of nearly the same value, therefore all the results for different delamination values have been described by the common formula

$$\frac{P_i}{P_{\mathrm{cr}_i}} = 1.166 - 0.081 \lg(N_f).$$

The relevant confidence limits have been determined, on the basis of the Student's t-distribution, for a number of degrees of freedom $k = n - 1 = 30$ and probability $P = 90\%$; 95%; 99%. Results of this analysis are presented in Fig. 10.

Summing up the above considerations it can be stated that the present description of the relation between the load and $\lg N_f$, which is common for plates with and without delamination, is satisfactory. It should be borne in mind, however, that the low-cycle strength decreases with increasing degree of delamination, similarly to the critical load. The present description concerns a small number of cycles, that is the case in which a notch in form of a gap does not reduce the strength.

6. Inferences

1. The results obtained show that the influence of delaminations of no more than 5% (of the entire area) on the critical load is unimportant. In the case of delamination in excess of 15%, the reduction in critical force was not found to be high either. The decrease in this quantity as determined by theoretical means and presented in [2, 3] was found there to be considerable. The influence of delamination on the critical load is higher for thick than for thin plates.

2. The fatigue strength of the laminated plates which have been tested, with and without delaminations, can be described on the basis of the results of experimental investigation, for a small number of compression cycles (as was the case of static tests), by a linear relation in semi-logarithmic coordinates.

3. The dependence of the low-cycle fatigue strength and the critical load on the degree of denomination is similar.

4. Within the range of usual loads and small numbers of cycles, the laminated plates with delamination which were tested did not show susceptibility to the action of a notch.

5. Plates of identical delamination failed for nearly identical deflections, independently of the number of cycles before failure.

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