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EXPERIMENTAL STUDIES OF FLUTTER OF BUCKLED RECTANGULAR PANELS AT MACH NUMBERS FROM 1.2 TO 3.0 INCLUDING EFFECTS OF PRESSURE DIFFERENTIAL AND OF PANEL WIDTH-LENGTH RATIO

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EXPERIMENTAL STUDIES OF FLUTTER OF BUCKLED RECTANGULAR PANELS AT MACH NUMBERS FROM 1.2 TO 3.0 INCLUDING EFFECTS OF PRESSURE DIFFERENTIAL AND OF PANEL WIDTH-LENGTH RATIO

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SUMMARY

Experimental panel flutter data have been obtained at Mach numbers from 1.2 to 3.0 for buckled rectangular panels and the effect of a pressure differential has been determined. Increasing the pressure differential was effective in eliminating flutter on most of the panels tested. The effects of the variables in the panel flutter parameter,

$\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3} \frac{t}{l}$ (where M is the Mach number, q is the dynamic pressure, E is Young's modulus, and t and l are the panel thickness and length, respectively), were investigated for buckled panels clamped on the front and rear edges and a critical value of this parameter of 0.44 is indicated at zero pressure differential when the panel width-length ratio is 0.69. An estimated flutter boundary is presented for buckled panels clamped on four edges and having width-length ratios of 0.21 to 4.0. This boundary shows that the panel width is more significant than the panel length when the ratio of width to length is less than approximately 0.5. Panels clamped on four edges and buckled in two half waves in the direction of flow were found to be particularly susceptible to flutter. The results of limited tests on panels with applied damping, curvature and lengthwise stiffeners are also presented and discussed.

INTRODUCTION

The possibility of panel flutter at supersonic speeds has been indicated theoretically and demonstrated experimentally, and continues to cause some concern as more airplanes and missiles are being designed to operate in this speed range. The results of initial NACA panel

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flutter experiments at Mach number 1.3 (ref. 1) showed that aircraft panels with practical dimensions can be subject to flutter, and that buckled panels were more susceptible to flutter than flat panels or panels with tension. The experimental tests were therefore extended to make a more comprehensive study of the flutter of buckled panels. Some results of this study, together with a brief review of recent theoretical work, are reported in reference 2. These results include an extension of the Mach number range from 1.2 to 3.0 as well as an indication of the effects of a pressure differential across the panel and an investigation of the effects of panel width-length ratio.

The present paper further amplifies some of the material in reference 2, discusses the results of tests on additional panel configurations, and summarizes the results of experimental flutter tests on buckled panels. These results include a study of flutter trends of buckled panels clamped on the front and rear edges, an investigation of some factors affecting the flutter of buckled panels clamped on four edges, and a discussion of the effects of several modifications to the basic panels or their boundary conditions.

The flutter-trend studies of panels clamped on the front and rear edges indicate the effects of Mach number, dynamic pressure, panel stiffness, length and width-length ratio, and pressure differential. This simplified panel configuration was used in the flutter trend studies since better control of the test conditions could be maintained.

Panels clamped on four edges and having several types of buckling modes as well as various width-length ratios were investigated to determine their flutter characteristics and to indicate the extent to which the results of tests on simplified panels may apply to this more practical panel configuration.

The modifications to the panels or their boundary conditions included applied damping, the addition of lengthwise stiffeners, and the addition of "two-dimensionalizing fences" along the tunnel wall adjacent to the free edges of a panel. A few panels with simple curvature, either perpendicular or parallel to the stream flow, were also tested.

SYMBOLS

c damping coefficient, lb/ft/sec

d maximum panel buckled depth with no air flow, in.

E Young's modulus of elasticity, lb/sq in.

M	Mach number
n	number of approximate half waves in panel buckled mode in direction of flow
m	number of approximate half waves in panel buckled mode perpendicular to flow
p	free-stream static pressure in test section, lb/sq in.
p_1	chamber static pressure (behind panel), lb/sq in.
q	dynamic pressure, lb/sq in.
V	air velocity in test section, ft/sec
ρ	air density in test section, slug/cu ft
t	panel thickness, in.
l	panel length in direction of flow, in.
w	panel width measured perpendicular to flow, in.

APPARATUS AND TEST METHODS

Test Facilities

The panels were flutter tested in the Langley supersonic flutter apparatus. Part of the panel flutter program was conducted with this tunnel operating from atmospheric pressure to a vacuum as described in detail in reference 3. Interchangeable nozzles gave Mach numbers of 1.2, 1.3, and 1.6; and the flow conditions at the test section were, of course, fixed for each Mach number. The remainder of the panel flutter program was conducted with the tunnel modified by the addition of a 2500-cubic-foot air storage tank with a working pressure of 100 pounds per square inch. This tank was connected to the nozzle entrance through an adjustable control valve, which provided some control over the stagnation (and test section) flow conditions. These flow conditions were usually adjusted (insofar as possible) to be comparable with those obtained in the initial part of the test program. The increased stagnation pressure made it possible to extend the range of the tests to Mach numbers 2.0 and 3.0.

Panel Mounting Apparatus

The panel mounting apparatus is shown in figures 1 and 2 and is described in detail in reference 1. Figure 1 shows the panel clamped in the tunnel side wall. Although not shown in the figure, provision was made for fairing the panel and clamps smoothly into the side wall of the tunnel. Figure 2 shows the panel beveled-edge clamps and the induction pickups. Each of the four panel clamps could be moved independently of the others to make it possible to apply compressive, tensile, and shear forces (or combinations of these forces) to the panel edges. The panel clamps could also be moved to adjust for panels of widely different dimensions. In testing panels with curvature, the front and rear clamps shown in figure 1 were replaced with curved panel clamps having a radius of curvature of either 12 inches or 48 inches and these were faired into the tunnel side-wall plate as shown in figure 3. The tunnel side-wall plate could be rotated to obtain test results with the flow over the panel from two directions as indicated by the arrows in the figure. The space behind the panels was enclosed to give a chamber in which the pressure could be controlled.

Panel Models

The panels used in the tests were thin rectangular sheets of steel, aluminum alloy, magnesium, Monel, and brass. These panels are listed in tables I to IV along with the pertinent panel dimensions. The panels were clamped on either two or four edges and a drawing of a buckled panel clamped on two edges is shown (with clamps omitted) in figure 4 to indicate the notation used in discussing the panels.

Modifications to the basic panels or their boundary conditions are illustrated in figures 5 to 7. These modifications, for panels clamped front and rear, consisted of lengthwise stiffeners added to a 0.0165-inch-thick aluminum-alloy panel as shown in figure 5 and "fences" attached to the tunnel wall along the free edges of a 0.039-inch-thick aluminum-alloy panel as shown in figure 6. For panels clamped on four edges the modifications consisted of curving the panel, attaching stiffeners to a panel (fig. 5), attaching three viscous dampers along the center line of a panel at $0.25l$, $0.50l$ and $0.75l$ (fig. 7), and bonding hard rubber to the rear surface of a 0.025-inch-thick steel panel. The dampers were of the rod-cylinder type and the damping constant was varied by changing the viscosity of the oil between the rod and cylinder. The curved panels with a radius of 12 inches were rolled to the proper radius before being clamped in place but those with a radius of curvature of 48 inches were simply formed to the proper curvature with the clamps.

The dimensions of the panels tested were such that they would be free of the shock wave reflected from the opposite tunnel wall.

Method of Buckling Panels

The buckling forces were induced in the panels by thermal stresses resulting from heating the panel, by application of forces with the panel clamps, or by a combination of these two methods. When possible the type and amount of buckle were adjusted when the panel temperature was approximately equal to the tunnel stagnation temperature. This temperature was about 180° F for the original tunnel configuration and was in the range between 80° and 120° F for the modified tunnel. Examples of the types of buckling modes tested are shown in figure 8 and are discussed in the appendix.

Instrumentation

Quick response strain-gage-type pressure cells were used for pressure measurements to determine the dynamic pressure and the pressure in the chamber behind the panel. This latter pressure was measured relative to a constant-reference static pressure in the tunnel by connecting a sensitive pressure cell differentially between the chamber and a static pressure orifice on the opposite tunnel wall.

Motions of the panels were detected by inductance-type pickups which were mounted in the chamber behind the panel (see fig. 2). A strain gage was located 3/16 of an inch from the trailing edge of one panel, midway between the sides, to indicate the magnitude of the flutter stresses at this location. A thermocouple was taped to the back of each panel to indicate the approximate panel temperature.

The signals from the pressure cells, inductance pickups, strain gage, and thermocouple were all recorded simultaneously along with a 60-cycle-per-second timing signal by a recording oscillograph.

Testing Technique

The panel was clamped in place in the tunnel side-wall plate, mounted in the tunnel, and the amount and type of buckling were adjusted and noted. The chamber cover was then put in place and the valve for adjusting chamber pressure was opened to give a chamber pressure which was estimated to give a sufficient pressure differential across the panel to suppress flutter. A series of runs was then made, decreasing the chamber pressure by discrete steps in each succeeding run until flutter was obtained and the positive value of the measured pressure differential required to prevent flutter was determined. A similar series of tests was then made to determine the negative value of the measured pressure differential required to prevent flutter. Immediately prior to each flutter test, the panel was heated to the temperature (usually tunnel stagnation temperature) at which the buckling mode had been previously adjusted. This was done so that the stresses, induced in the panel by temperature changes during the run, would be minimized.

The panels were observed before and after each test to estimate the maximum panel buckle depth and during each test to note the panel flutter characteristics and to determine which way (i.e., towards or away from the stream) the panel buckled during the run.

The term "panel flutter," as used in referring to the present experimental results, includes all sustained panel vibrations of sufficient amplitude and persistence as to reasonably indicate an unstable panel configuration. Some types of these panel flutter oscillations are described and illustrated in reference 1.

RESULTS AND DISCUSSION

The results of most of the flutter tests on buckled panels are listed in tables I to IV along with the associated test section flow conditions (M, q, and ρ) and the pertinent panel parameters. Some of these results are presented in figures 9 through 14 and are discussed with the aid of several panel parameters and the pressure differential across the panel. The panel length flutter parameter, $\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3}\frac{t}{l}$, is used to correlate the results of tests on buckled panels clamped on the front and rear edges and is also used, in conjunction with the panel width flutter parameter, $\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3}\frac{t}{w}$, to discuss the results of tests on buckled panels clamped on four edges. These parameters were introduced in reference 2 and are nondimensional groupings of aerodynamic and stiffness factors.

The positive and negative values of the measured pressure differential required to stop flutter on panels with no curvature prior to buckling were not, in general, equal. The difference in these values was not consistent and appeared to be largely the result of imperfections in the panels and their edge conditions. In order to eliminate some of the scatter in the data due to these imperfections, the values of the measured pressure differential required to stop flutter were averaged. (For example, if the negative and positive values of the measured pressure differential required to stop flutter were -0.20 and +0.10 pound per square inch, then the average values would be ±0.15 pound per square inch. These averaged values are listed in the tables and used in discussing the results. Because of the scatter in the pressure differential data, the general magnitude of these data and the trends shown should be emphasized rather than the actual values of the pressure differential.

Buckled Panels Clamped on the Front and Rear Edges

The results of the studies to investigate the effects of panel stiffness, panel length, panel width-length ratio, Mach number, and a pressure differential on the flutter of buckled panels clamped on the front and rear edges are listed in table I along with the pertinent panel parameters.

These panels were buckled in the one-half-wave type of buckle (fig. 8(a)) and the buckle depth, within the limits tested, did not appear to have any significant effect on the flutter results. This fact is shown by a comparison of the flutter results of tests on panels 7a, 7b, 8a, 8b, 12a, 12b, 18a, 18b, 28a, 28b, 42a, 42b, 43a, 43b, 49a, and 49b. Each of these panels was tested with two different values of the estimated ratio of buckle depth to length, d/l, and the corresponding flutter results indicate that these changes in the buckle depth had no appreciable effect on the panel flutter characteristics. Nevertheless, the ratio of buckle depth to length was maintained as constant as possible throughout the flutter tests on this panel configuration.

Observations of the flutter tests and an investigation of the flutter records indicated that the predominant flutter mode on buckled panels clamped on the front and rear edges was generally of the "oil canning" or modified traveling wave type (i.e., relatively low frequency, high amplitude oscillations occurring between the two buckle extremities with the front portion of the panel leading the rear portion). However, higher order modes occasionally occurred or were superposed on the lower frequency mode, particularly for panels with relatively low values of the flutter parameter. In a few cases, where the pressure differential was sufficient to suppress the large amplitude modes, a relatively low amplitude, high frequency type flutter was superposed, like a ripple, on the panel buckle mode shape.

<u>Pressure differential</u>.- The effect of a pressure differential on the flutter parameter of buckled panels clamped on the front and rear edges and having a width-length ratio of 0.69 is shown in figure 9. The data of figure 9(a) are for panels of several materials, those of figure 9(b) are for panels with different lengths, and those of figure 9(c) are for panels tested at Mach numbers from 1.2 to 3.0. The data were obtained by varying the pressure differential in discrete steps and the points plotted in the figures represent the lowest pressure differential at which no flutter occurred. The fact that these points are not true boundary points is not of great importance because the size of the pressure differential increments were less than the ultimate scatter of the data. Conservative boundaries are faired to include these data and represent the approximate division between the flutter region below the boundaries and the no-flutter region to the right and above. These boundaries indicate that a pressure differential is effective in eliminating flutter on these panel configurations and that the magnitude of this pressure differential

decreases as the flutter parameter increases. No flutter was obtained in these panels at a pressure differential greater than ±0.31 pound per square inch.

The flutter boundaries for panels of several materials (fig. 9(a)), for panels of different lengths (fig. 9(b)), and for panels tested at Mach numbers 1.2 to 3.0 (fig. 9(c)) are identical for values of the pressure differential less than approximately 0.10 pound per square inch. This coincidence of the boundaries indicates that, for the variables studied, the panel flutter parameter is an acceptable correlating factor at the lower values of the pressure differential. The panel flutter parameter does not appear to correlate the Mach number data satisfactorily at values of the pressure differential greater than approximately 0.10 pound per square inch. This fact is shown in figure 9(c) by the discrepancy between the Mach number 1.2 and 1.3 to 3.0 flutter boundaries at the higher values of the pressure differential. This discrepancy is caused by a relatively low-amplitude high-frequency type flutter which was superposed on the buckling mode shape and which persisted to higher values of the pressure differential than did the "oil canning" type flutter.

The boundaries of figure 9 also indicate a critical value of the flutter parameter (at zero pressure differential) of 0.44 above which no flutter was obtained for these panels having a width-length ratio of 0.69. The analysis of reference 4 indicates a critical value of the flutter parameter of 0.545 for buckled panels with an infinite width-length ratio. An attempt was therefore made to obtain experimental data on panels having width-length ratios greater than 0.69 in order to more nearly approximate the condition of infinite aerodynamic aspect ratio which was assumed in the analysis of reference 4.

Width-length ratio.- The effect on the flutter parameter of increasing the panel width-length ratio from 0.69 to 1.85 and 3.38 at $M = 1.2$ is shown in figure 10. The estimated flutter boundaries, based on the limited data available, indicate that the critical value of the flutter parameter is increased, at all values of the pressure differential tested, as the width-length ratio is increased from 0.69 to 3.38. This increase in the critical value of the flutter parameter is about 16 percent at low values of the pressure differential and results in somewhat better agreement between the experimental results and the two-dimensional theory of reference 4. The increase in the critical value of the experimental panel flutter parameter may not be entirely due to an increase in the aerodynamic aspect ratio, however, and the following observations should be of aid in evaluating the experimental results.

Observations of the tests and an inspection of the flutter results appear to indicate that the displacement of the flutter boundary caused by increasing the width-length ratio from 0.69 to 1.85 is mainly due to aerodynamic effects, since the flutter modes of these panels were predominantly of a two-dimensional nature. This result is further emphasized by tests at Mach number 1.3 on a panel of width-length ratio of 0.69 (panel no. 39, table I(b)) with fences six inches high attached to the tunnel wall along the free edges of the panel (fig. 6). Comparison of the result of this test with the flutter boundary at $M = 1.3$ (fig. 9(c)) for panels without fences ($w/l = 0.69$) at $\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3} \frac{t}{l} = 0.372$ shows that the increase in the pressure differential required to stop flutter is of the same order of magnitude as that indicated in figure 10 when the width-length ratio is increased from 0.69 to 1.85. The effect of the fences should be largely aerodynamic since the buckling mode is unaffected.

The further displacement of the flutter boundary in figure 10, as the width-length ratio was increased to 3.38, is caused by a combination of aerodynamic and buckling modifications since no two-dimensional flutter was obtained on panels with this width-length ratio.

An attempt was made to obtain an initial buckling mode of the one-half-wave type on each panel tested but this became more difficult as the width-length ratio was increased. (See appendix.) Observations of the flutter tests showed that the tendencies of the buckling mode to become more complex and irregular as the width-length ratio was increased affected the flutter characteristics by causing flutter to occur on localized areas of the panel independent from other areas.

<u>Dynamic pressure</u>.- Additional tests on buckled panels clamped at the front and rear edges were made in the modified tunnel to investigate the effect of dynamic pressure and determine whether its effect was properly accounted for by the panel flutter parameter. The results of these tests are presented in figure 11 which shows the effects of dynamic pressure on the panel flutter parameter at zero pressure differential. The results are presented in the form of flutter and no-flutter points for four panels having various stiffnesses and a constant width-length ratio of 0.69. The critical value of the flutter parameter determined in figure 9 at zero pressure differential is also indicated on figure 11. The agreement is good between this critical value of 0.44 (based on data for a limited range of dynamic pressures) and the data points for a much wider range of dynamic pressures. This agreement further substantiates the use of the panel flutter parameter as a correlating factor for this panel configuration.

The data presented in figures 9 and 11 indicate that, at zero pressure differential and for the range of variables studied, the panel flutter parameter may be adequate to describe the flutter trends of buckled panels clamped on the front and rear edges. In addition, a critical value of the panel flutter parameter, $\left[\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3} \frac{t}{l}\right]_{cr} = 0.44$, is indicated for these panels having a width-length ratio of 0.69. It is obvious from an inspection of the panel flutter parameter that increasing the Mach number (at constant dynamic pressure) or panel stiffness and decreasing the dynamic pressure or panel length are all effective in reducing the tendency to flutter since the value of the flutter parameter would be increased. In order to indicate the effect of Mach number at constant altitude or density the Mach number data of figure 9(c) have been replotted and are discussed in the following section.

Mach number.- The effect of Mach number on the flutter of buckled panels clamped at the front and rear edges at an equivalent pressure altitude of 22,500 feet is shown in figure 12 where the structural stiffness parameter, $E^{1/3} \frac{t}{l}$, is plotted against the Mach number. This value of the altitude is equal to the equivalent pressure altitude at which the Mach number 1.2 data were obtained. The experimental data at the higher Mach numbers were adjusted to this altitude with the relation

$E^{1/3} \frac{t}{l} = \left(E^{1/3} \frac{t}{l}\right)_r \left(\frac{q}{q_r}\right)^{1/3}$, where the subscript r refers to the actual experimental conditions. The flutter boundary, calculated from the critical value of the flutter parameter indicated in figure 9, is also plotted in figure 12. These experimental data indicate that there may be a slight detrimental effect due to increasing the Mach number from 1.2 to 3.0 at constant altitude or density since the value of the structural stiffness parameter required to prevent flutter is increased.

The dashed line above the experimental data was determined from the theoretical analysis of reference 4 and is included here for the sake of comparison. The theoretical curve is for a two-dimensional panel whereas the experimental results are for finite width panels having a width-length ratio of 0.69. The sharp upturn in the theoretical curve at the lower Mach numbers is caused by the use of steady-state linearized air forces which become infinite at a Mach number of 1.0.

Buckled Panels Clamped on Four Edges

Experimental studies on simplified panels clamped at the front and rear edges are useful in investigating flutter trends and providing experimental data for comparison with existing theories. However, flutter tests on panels clamped on four edges are needed to determine the extent to which the results of studies on simplified panels may be applied to the more practical panel configuration. The results of some tests on panels clamped on four edges and having width-length ratios of 0.21 to 4.0 as well as several types of buckling modes are listed in table II. These results are discussed and compared with those of simplified panels in the following sections.

Type of buckling.- The results of tests on three buckled panel configurations clamped on four edges are shown in figure 13 and these results are compared with the flutter boundary (reproduced from fig. 9(c)) for panels of the same length clamped on the front and rear edges. The one- and two-half-wave and diagonal types of buckling (figs. 8(b), 8(c), and 8(d), respectively) were easily obtained on panels clamped on four edges which had width-length ratios of 0.83. (See appendix.) The flutter parameter is again plotted against the pressure differential and the boundary and data points indicate the pressure differential required to stop flutter at a Mach number of 1.3. Boundaries are not drawn for panels clamped on four edges because of the scatter in the limited data available. The data for panels clamped on four edges show, however, that a pressure differential was effective in suppressing flutter and the value required did not exceed 0.87 pound per square inch for the panels tested. Panels with diagonal and two-half-wave types of buckling require a greater pressure differential to stop flutter than do panels buckled in one half wave. In addition, panels buckled in two half waves may encounter flutter at higher values of the flutter parameter. In fact, flutter was obtained on each panel which could be buckled in two half waves and no upper stiffness boundary for these panels was obtained within the limits of the tests.

The erratic variation in the pressure differential required to prevent flutter, even on panels of comparable stiffness, is thought to be the result of unavoidable and undetected imperfections in the symmetry of the buckling mode and variations in the amount of buckling. Tests involving measurable variations in these conditions indicated that, increasing the amount of buckling or destroying the symmetry of the two-half-wave type of buckling appeared to have a stabilizing effect on the stiffer panels clamped on four edges. The influence of the type and amount of buckling on the flutter results of the thinner panels appeared to be less critical. This is probably due to the fact that the stiffness of these thin panels is relatively insignificant in comparison with the effect of the tension induced in the panel by the pressure differential. The data of figure 13 offer some evidence that, due to the probable beneficial effect of tension, these panels with low values of the flutter parameter may be flutter-free at lower values of the pressure differential than is the case for some of the stiffer panels.

The results of figure 13 also indicate that at the higher values of the flutter parameter the buckled panels clamped on four edges and having width-length ratios of 0.83 may be considerably more susceptible to flutter than buckled panels clamped on the front and rear edges.

Panel width-length ratio.- The effect of panel width-length ratio on the flutter of buckled panels clamped on four edges is shown in figure 14. The data were obtained at a Mach number of 1.3 and at zero pressure differential for panels with width-length ratios of 0.21, 0.25, 0.50, 0.83, 2.0, and 4.0. Panels having width-length ratios of 0.21, 0.25, 0.50, and 0.83 were 11.62 inches long and those having width-length ratios of 2.0 and 4.0 were 5.81 and 2.91 inches in length, respectively. In order to indicate the type of panel buckling mode, the symbols n and m are introduced. (n is the number of half waves in the direction of the stream flow and m is the number of half waves perpendicular to the stream flow.) Approximate values of n and m are listed at the top of the figure and indicate that the buckling modes usually consisted of a number of half waves running in the direction of the greater panel dimension. The buckling modes were usually obtained by heating the panel but in a few cases the type of buckling mode was changed by applying edge forces. Additional discussion on the types of buckling modes obtained and factors affecting their formation is included in the appendix.

The abscissa of figure 14 is the same as the ordinate except that the panel length has been replaced by the panel width. The straight lines radiating from the origin are lines of constant width-length ratios and moving away from the origin on these lines represents an increase in panel stiffness since the Mach number and dynamic pressure were constant for these tests. Although additional data are needed to establish the estimated flutter boundary more definitely, it is apparent that the panel width is significant when the panel width-length ratio is reduced sufficiently. For example, for panels with width-length ratios greater than approximately 0.8, decreasing the length would be effective in eliminating flutter. However, for panels with width-length ratios less than approximately 0.5, decreasing the width would appear to be a more effective method of reducing the possibility of flutter.

Panel flutter can occur throughout the unstable region as indicated by the data points in figure 14. However, its occurrence may be of a somewhat statistical nature on actual aircraft panels since such factors as variations in the type and amount of buckling and a pressure differential may reduce or eliminate the unstable region. For instance, the data plotted in figure 14 for panels with $w/l = 0.83$ show that these panels are flutter-free at lower values of the flutter parameter when they are buckled in one half wave (round symbols) than when they are buckled in two half waves (square symbols). The beneficial effect of a pressure differential on panel flutter has been discussed in previous sections.

<u>Damping</u>.- The effect of viscous damping forces applied at discrete points on a panel (fig. 7) was investigated for panel no. 81. This 0.025-inch-thick steel panel was initially buckled in two half waves and was flutter tested at Mach number 1.3 with values of the damping coefficient (for each damper) of zero, 15.6, and 33.0 pounds per foot per second. These damping coefficients are for low relative velocities between the damper rod and cylinder. At the relative velocities present during flutter of the panel the damping coefficient is reduced to the order of 1 to 2 pounds per foot per second. The results of the tests,

listed in table II, show that for $c = 0$ (panel no. 8a) flutter was obtained over a pressure differential range of ±0.26 pound per square inch and that increasing the damping coefficient to $c = 15.6$ pounds per foot per second (panel no. 81b) essentially only reduced the flutter frequency somewhat. However, when the damping coefficient was increased still further to 33.0 pounds per foot per second (panel no. 81c), the flutter on the panel was eliminated.

The results of tests on a steel panel ($t = 0.025$ inch) with 1/4-inch-thick hard rubber bonded to the panel surface offer no evidence that the overall effect of this material was beneficial. (Compare the pressure differential required to stop flutter for panels number 79 and 82, table II.) The hard rubber increased the damping by a factor of $2\frac{1}{2}$ for first mode vibrations with amplitudes of the same order as the panel thickness.

These results suggest that a considerable amount of damping is required to eliminate flutter on these panel configurations which are well within the unstable region.

Curvature.- Steel panels with thicknesses of 0.0085, 0.018, and 0.030 inch and having radii of curvature of 12 and 48 inches were flutter tested with the curvature both perpendicular and parallel to the stream flow. The results of these tests are listed in table III and were obtained at a Mach number of 2.0 with the dynamic pressure equal to an average of 9.67 pounds per square inch. These results include the range of pressure differential over which flutter occurred, the range of pressure differential over which tests were made, and the flutter frequencies. The remarks on the panel buckle indicate that the thinnest panel was buckled in a complex manner but that the two thicker panels were not noticeably buckled. Although the limited data do not warrant a detailed discussion of the results, the following general observations may be of interest.

Increasing the curvature perpendicular to the stream flow appeared to be beneficial since the panels became less likely to buckle and flutter, and the flutter which did occur was relatively mild and tended to involve only localized portions of the buckled panel. Most of the flutter was obtained on these panels at negative values of the pressure differential. This is probably due to the fact that a negative pressure differential tends to cause the panel to buckle whereas a positive pressure differential acting on the concave surface tends to put the panel in tension. No flutter was obtained on the 0.018 and 0.030-inch-thick steel panels with a radius of curvature of 12 inches and on the 0.030-inch-thick panel with a radius of curvature of 48 inches.

When the above panels were rotated 90° and tested with the curvature parallel to the stream, flutter was encountered on the two thinner panels having either a 12-inch or a 48-inch radius of curvature. This flutter was extremely violent and caused a permanent set in the panels. It appeared that the flutter occurred when the combined effects of the pressure differential and static air forces acting on the panel were sufficient to overcome the structural stiffness and cause the front portion of the panel to buckle away from the stream and the rear portion to buckle somewhat towards the stream. (It might be pointed out that this type of buckling is similar to the two-half-wave type of buckle in a panel with no curvature which was also particularly susceptible to flutter.) The 0.030-inch-thick steel panel did not buckle during the tests and no flutter was obtained on panels of this thickness having either radius of curvature.

Effect of Lengthwise Stiffeners on the Flutter of a Buckled Panel

The results of tests on a panel with lengthwise stiffeners (see figure 5) are listed in table IV. This panel configuration was tested over a wide range of pressure differential for each of several buckling modes involving both the individual panels and the stiffeners. It was noted that the stiffeners had the effect of causing the buckling forces to be applied eccentrically. Stiffener heights of 0.40 and 0.27 inch were used for tests with the panel-stiffener configuration clamped on four edges and stiffener heights of 0.27 and 0.12 inch for the tests with the panel clamped front and rear. A mild localized flutter was encountered on a section of one of the panels when the stiffener height was 0.40 inch but no other flutter was obtained on this panel configuration. These results indicate that the addition of stiffeners to a 0.0165-inch-thick Dural panel had a beneficial effect since panels with the same dimensions ($l = 11.62$ inches, $w/l = 0.83$) without stiffeners would be well within the flutter region and would flutter readily.

Panels number 58 and 59, table IIa, are similar to the individual panels between the stiffeners of the panel-stiffener combination (i.e., $l = 11.62$ inches, $w/l = 0.21$) except that all four edges are rigidly clamped. The results of tests on these panels show that no flutter was obtained on panel no. 59 which had the same thickness (0.165 inch) as the stiffened panels. However, when the thickness was reduced to 0.0115 inch (panel no. 58), mild localized flutter was encountered. These limited results indicate that the individual panels between stiffeners may have flutter characteristics very much like those of similar panels clamped on four edges.

Panel Flutter Stresses

Several failures occurred on the thinner panels during the flutter tests. These failures were usually at the trailing edge of the panel and appeared to be the result of accelerated fatigue of the material since the panels fluttered for only a few seconds. However, the fact that most of the panels were not permanently deformed by the flutter stresses indicates that panel flutter is not necessarily immediately destructive and may be of concern mainly from a fatigue standpoint.

The flutter stresses measured 3/16 of an inch from the trailing edge of panel number 39 showed that the magnitude of the stress was dependent on the initial amount of buckling in the panel. When the value of d/l was approximately 0.009, the measured stresses were of the order of ±10,000 to ±15,000 pounds per square inch and for $d/l \approx 0.003$ the stresses were about ±6,000 pounds per square inch.

CONCLUSIONS

The present report gives results of experimental flutter tests on buckled rectangular panels. In the case of panels clamped on four edges, for which case the buckle depth was found to be significant, results were based mainly on the most critical buckle depth, that is the least value that could be maintained. The following conclusions appear to be justified on the basis of these results:

1. A pressure differential was effective in eliminating flutter and for the panels tested the required value did not exceed 0.87 pound per square inch.

2. At low values of the pressure differential, the panel flutter parameter, $\left(\sqrt{M^2 - 1}\,\frac{E}{q}\right)^{1/3}\frac{t}{l}$, (where M is the Mach number, q is the dynamic pressure, E is Young's modulus, and t and l are the panel thickness and length) is probably adequate to describe the flutter trends of panels clamped on the front and rear edges and buckled predominantly in the one-half-wave type of buckle. A critical value of the flutter parameter of 0.44 is indicated at zero pressure differential for these panels which have a width-length ratio of 0.69.

3. Increasing the panel width-length ratio from 0.69 to 3.38 increases the critical value of the flutter parameter by about 16 percent at low values of the pressure differential.

4. Calculations based on the panel flutter parameter show that increasing the Mach number from 1.2 to 3.0 at constant altitude or density has a slight adverse effect (at zero pressure differential) on the flutter of buckled panels clamped on the front and rear edges.

5. The flutter data of buckled panels clamped on four edges exhibit considerable scatter because of the variation in the type and amount of buckling.

6. Panels clamped on four edges and buckled in two half waves in the direction of the stream flow appear to be particularly susceptible to flutter and increasing the stiffness of these panels was not effective in eliminating flutter at zero pressure differential within the limits of the tests.

7. The panel width becomes significant when the width-length ratio of buckled panels clamped on four edges is reduced sufficiently. For panels with width-length ratios greater than approximately 0.8, decreasing the length is effective in eliminating flutter. However, for panels with width-length ratios less than approximately 0.5, decreasing the width would appear to be a more effective method of reducing the possibility of flutter.

8. Panel flutter is not usually immediately destructive and will probably be of concern mainly from a fatigue standpoint.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 16, 1955.

APPENDIX

PANEL BUCKLE MODE SHAPES

The following discussion is based on observations of the panel buckling behavior during the present tests and indicates the types of buckling modes obtained as well as factors affecting their formation. Further insight into the rather complicated panel buckling phenomenon may be gained from standard textbooks on the subject such as reference 5.

The testing procedure required that the temperature of each panel be increased by 20° to 100° F before each run. This heating of the panel usually caused it to buckle and was a factor in determining the types and amounts of buckling tested. The heat was applied as uniformly as possible (with a heat lamp) but the conduction of heat away from the panel to the relatively cool clamps resulted in sharp thermal gradients near the edges of the panel. These thermal gradients undoubtedly influenced the type of buckling mode formed particularly on short or narrow panels where a relatively large portion of the panel was affected by the gradient.

Panels clamped on the front and rear edges were buckled predominantly in the one-half-wave type of buckle shown in figure 8(a). This type of buckling mode was easily induced in these panels when the width-length ratio was 0.69 since this mode occurred when the panel was heated as required by the testing procedure. The amount of buckling could then be easily adjusted (by moving the panel clamps) without altering the type of buckling mode significantly. However, it became increasingly difficult to obtain the one-half-wave buckle as the panel width-length ratio was increased to 1.85 and 3.38. This difficulty was partly due to the tendency of the thermal stresses to buckle the panel in a number of half waves running in the direction of the greater panel dimension. Imperfections in the panels and their edge conditions also affected the type of buckling mode for these wide panels. In order to maintain the desired half-wave type of buckle on these panels, it was often necessary to increase the amount of buckling by applying compression forces with the panel clamps.

Panels clamped on four edges with width-length ratios of 0.83 were buckled in one-half-wave, two-half-wave, and diagonal types of buckling as shown in figure 8(b), 8(c), and 8(d), respectively. The one-half-wave type of buckle was induced in the panels when they were heated and the two-half-wave type of buckling mode was obtained by applying compressive forces to the panel in the direction parallel to the stream flow and tensile forces in the perpendicular direction. The mode shape in which the buckles ran diagonally across the panel was obtained by shearing two opposite panel clamps with respect to each other. As the width-length ratio of panels clamped on four edges was reduced to 0.50, 0.25, and 0.21 or increased to 2.0 and 4.0 there was an increase in the number of half waves formed when the panel was buckled by heating. These panels tended to buckle in several half waves which ran in the direction of the longer panel dimension and which had a half wave length roughly equal to the shorter panel dimension (fig. 8(e)). These higher order buckling modes were sensitive to unavoidable irregularities in the panel and its edge conditions, were often without symmetry of shape, and were difficult to maintain at a given number of buckles during a series of tests. Attempts to adjust the amount of buckling usually resulted in a change in the number of half waves also.

The previous discussion applies to the type of buckling modes obtained with no airflow over the panel and zero pressure differential between the two panel surfaces. These two factors, of course, modified the buckling mode shapes during the flutter runs but no attempt was made to determine these modified buckling configurations.

REFERENCES

1. Sylvester, Maurice A., and Baker, John E.: Some Experimental Studies of Panel Flutter at Mach Number 1.3. NACA RM L52I16, 1952.

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3. Tuovila, W. J., Baker, John E., and Regier, Arthur A.: Initial Experiments on Flutter of Unswept Cantilever Wings at Mach Number 1.3. NACA TN 3312, 1954. (Supersedes NACA RM L8J11.)

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5. Timoshenko, S.: Theory of Elastic Stability, McGraw-Hill Book Co., Inc., 1936, pp. 324-367.

TABLE I.- EXPERIMENTAL PANEL FLUTTER DATA FOR BUCKLED PANELS CLAMPED FRONT AND REAR

Panel	Material	t, in.	l, in.	w/l	$\left(\sqrt{M^2-1}\,\frac{E}{q}\right)^{1/3}\frac{t}{l}$	d/t (approx.)	Pressure differential (t) required to stop flutter, lb/sq in.	Range of flutter frequencies, cps
(a) M = 1.2; q = 6.12 lb/sq in.; ρ = 0.00102 slug/cu ft								
1a		0.026			0.200	0.009	0.18	112-128
1b		.026			.200	.009	.15	108-120
2	Magnesium	.033	11.62	0.69	.252	.009	.14	100-109
3		.039			.298	.007	.11	92-94
4		.064			.490	.005	0	No flutter
5		.019			.167	.007	.12	100-125
6		.031			.276	.009	.14	82-260
7a	Aluminum alloy	.039	11.62	.69	.347	.009	.11	72-97
7b		.039			.347	.004	.10	72-75
8a		.051			.454	.005	0	No flutter
8b		.051			.454	.003	0	No flutter
9		.021			.215	.007	.13	60-156
10		.024			.244	.005	>.16	55-170
11	Brass	.033	11.62	.69	.333	.009	.14	48-146
12a		.040			.404	.009	.03	28-56
12b		.040			.404	.007	.05	28
13	Monel	.025	11.62	.69	.303	.007	.08	52-53
14		.031			.376	.007	.09	40-65
15a		.016			.228	.007	>.16	40-130
15b		.018			.228	.007	.17	65-148
16		.025			.315	.004	.17	56-74
17a	Steel	.032	11.62	.69	.407	.007	.02	42-65
17b		.032			.407	.007	.08	44-80
18a		.034			.432	.005	.04	32
18b		.034			.432	.003	.02	30-40
19	Magnesium	.026			.251	.005	.18	92-133
20	Aluminum alloy	.029			.325	.005	.13	90-92
21	Aluminum alloy	.041	9.25	.69	.458	.005	0	No flutter
22	Steel	.018			.288	.008	.17	76-96
23	Steel	.025			.399	.005	.06	42-50
24	Magnesium	.0080			.220	.012	.13	240-280
25	Aluminum alloy	.0115			.366	.012	.04	112-168
26	Brass	.0125	3.25	.69	.452	.009	0	No flutter
27	Steel	.0065			.296	.012	.12	122-180
28a	Steel	.0085			.386	.012	.05	121-126
28b	Steel	.0085			.386	.006	.05	118-120
29	Aluminum alloy	.0115	3.25	1.85	.366	.012	.23	96-230
30	Brass	.0125			.452	.012	.10	78-120
31	Steel	.0065	3.25	1.85	.296	.022	.26	158-240
32	Aluminum alloy	.0115			.366		.36	132-200
33	Aluminum alloy	.0160	3.25	3.38	.510	.018	0	No flutter
34	Brass	.0125			.452		.29	92-134
35	Aluminum	.0165	11.62	.21	.145	.007	.12	84-244
(b) M = 1.3; q = 6.32 lb/sq in.; ρ = 0.00092 slug/cu ft								
36	Magnesium	.026	11.62	.69	.215	.009	.31	104-355
37		.037			.295	.007	.22	95-264
38	Aluminum alloy	.039	11.62	.69	372	.009	.10	65-66
[a]39		.039			.372	.005	.25	62-220
40	Brass	.040			.432	.009	.04	21
41		.025			.336	.009	.13	188-196
42a		.030			.408	.007	.06	38
42b	Steel	.034	11.62	.69	.408	.015	.07	30
43a		.034			.462	.007	0	No flutter
43b		.034			.462	.003	0	No flutter
(c) M = 1.6; q = 6.20 lb/sq in.; ρ = 0.0067 slug/cu ft								
44		.026			.246	.007	.23	112-330
45	Magnesium	.033	11.62	.69	.310	.009	.11	106-290
46		.039			.364	.007	.07	92
47		.029			.318	.009	.18	70-270
48	Aluminum alloy	.031	11.62	.69	.341	.010	.16	64-92
49a		.039			.426	.007	.06	45-210
49b		.039			.426	.009	.05	----------
50	Brass	.040			.496	.007	0	No flutter
51	Monel	.025	11.62	.69	.374	.009	.08	30-100
52	Steel	.025			.388	.007	.10	42-156
53	Steel	.030			.468	.007	0	No flutter
(d) M = 3.0; q ≈ 7.04 lb/sq in.; ρ ≈ 0.00046 slug/cu ft								
54	Magnesium	.016	11.62	.69	.189	.015	.28	----------
55		.008			.158	.017	>.23	156
56	Steel	.019	11.62	.69	.374	.009	.14	40-145
57		.025			.493	.013	0	No flutter

[a]"Fences" attached to tunnel along free edges of panel, see figure 6.

TABLE II.- EXPERIMENTAL PANEL FLUTTER DATA FOR

BUCKLED PANELS CLAMPED ON FOUR EDGES

$[M = 1.3;\ q \approx 6.32\ \text{lb/sq in.}]$

Panel	Material	t, in.	$\left(\sqrt{M^2 - 1}\ \frac{E}{q}\right)^{1/3} \frac{t}{l}$	$\left(\sqrt{M^2 - 1}\ \frac{E}{q}\right)^{1/3} \frac{t}{w}$	n	m	Pressure differential (±) required to stop flutter, lb/sq in.	Range of flutter frequencies, cps
(a) $w/l = 0.21$; $l = 11.62$ in.; $\rho = 0.00092$ slug/cu ft								
58	Aluminum alloy	0.0115	0.109	0.518	2-7	1	0.01	105-120
59		.0165	.156	.743	2-7	1	0	No flutter
(b) $w/l = 0.25$; $l = 11.62$ in.; $\rho \approx 0.00107$ slug/cu ft								
60	Aluminum alloy	0.0115	0.109	0.436	4-6	1	0.30	295-310
61		.016	.152	.608	4-6	1	.30	320-356
62		.020	.191	.764	5-6	1	0	No flutter
(c) $w/l = 0.50$; $l = 11.62$ in.; $\rho \approx 0.00107$ slug/cu ft								
63	Aluminum alloy	0.0115	0.109	0.218	2-3	1	0.10	184
64		.020	.191	.382			.14	185-205
65		.033	.314	.628			.29	209-228
66		.040	.380	.760			.10	212-250
67	Steel	.0065	.088	.176	4-6	1	----	248
(d) $w/l = 0.83$; $l = 11.62$ in.; $\rho = 0.00092$ slug/cu ft								
68	Aluminum alloy	0.029	0.278	0.335	1	1	0.03	63-77
69	Brass	.040	.432	.520	1	1	0	No flutter
70	Steel	.025	.336	.405	1	1	.11	63-124
71	Aluminum alloy	.019	.180	.217	2	1	.38	110-132
72		.029	.278	.335			.74	48-178
73		.041	.394	.474			.16	178-187
74	Brass	.040	.432	.520	2	1	.87	102-160
75		.046	.502	.605			.60	117-128
76	Monel	.025	.326	.393	2	1	.31	41-114
77		.031	.405	.488			>.23	108-119
78	Steel	.0085	.114	.137	2	1	.31	150-220
79		.025	.336	.405			.26	61-113
80		.043	.575	.693			.05	165-167
[a]81a		.025	.336	.405			.26	55-324
81b		.025	.336	.405			.21	22-245
81c		.025	.336	.405			0	No flutter
[b]82		.025	.336	.405			.42	40-77
[c]83		.025	.336	.405	---	---	.29	122-126
(e) $w/l = 2.0$; $l = 5.81$ in.; $\rho \approx 0.00107$ slug/cu ft								
84	Aluminum alloy	0.0115	0.218	0.109	1	2-3	0.32	230-315
85		.020	.382	.191			.05	115-122
86		.033	.628	.314			0	No flutter
87		.040	.760	.380			0	No flutter
88	Steel	.0065	.176	.088	1	4-6	.04	125
(f) $w/l = 4.0$; $l = 2.91$ in.; $\rho \approx 0.00107$ slug/cu ft								
89	Aluminum alloy	0.0115	0.436	0.109	1	4-6	0.13	240
90		016	.608	.152	1	4-6	0	No flutter
91		.020	.764	.191	1	5-6	0	No flutter

[a]Dampers installed on panels 81a, 81b, and 81c as shown in figure 7. Damping coefficients are indicated in section entitled "Damping."

[b]1/4 in.-thick hard rubber backing cemented to panel, damping of small amplitude vibrations in first mode increased by a factor of $2\frac{1}{2}$, $\frac{\text{Mass rubber}}{\text{Mass panel}} = 1.78$.

[c]Buckling mode consisted of approximately three half-waves running diagonally across panel, see figure 8(d).

TABLE III.- EXPERIMENTAL PANEL FLUTTER DATA FOR

CURVED PANELS CLAMPED ON FOUR EDGES

[M = 2.0; q ≈ 9.67 lb/sq in.; ρ ≈ 0.00093 slug/cu ft]

Panel	Material	t, in.	Radius of curvature - 12 inches: [a]Range of pressure differential, lb/sq in.	Radius of curvature - 12 inches: Range of flutter frequencies, cps	Radius of curvature - 12 inches: Remarks on panel buckle	Radius of curvature - 48 inches: [a]Range of pressure differential, lb/sq in.	Radius of curvature - 48 inches: Range of flutter frequencies, cps	Radius of curvature - 48 inches: Remarks on panel buckle
(a) Curvature perpendicular to stream flow; l = 11.62 in.; w/l = 0.83								
92,93	Steel	0.0085	(-0.57 to -0.30) -.62 to +1.76	100-140	Complex and irregular	(-0.26 to +0.09) -1.09 to +1.09	142	Complex and irregular
94,95	Steel	.018	-1.06 to +.53	No flutter	Section of panel buckled easily	(-.56 to -.51) -1.11 to +.40	54	Not buckled
96,97	Steel	.030	-.94 to -.13	No flutter	Not buckled	-1.51 to -.48	No flutter	Not buckled
(b) Curvature parallel to stream flow; l = 9.62 in.; w/l = 1.21								
92,93	Steel	.0085	(--- to > +1.66) +1.66	----------	Complex and irregular	(<-1.05 to +1.10) -1.05 to +1.84	278	Complex and irregular
94,95	Steel	.018	(<-1.10 to > +1.67) -1.10 to +1.67	198	Section of panel buckled easily	(<-1.08 to +1.26) -1.08 to +1.57	154-284	Not buckled
96,97	Steel	.030	-1.03 to -.10	No flutter	Not buckled	-.92 to +.94	No flutter	Not buckled

[a]Values in parentheses indicate range of pressure differential where flutter occurred; values not in parentheses indicate range of pressure differential for which tests were made.

TABLE IV.- EXPERIMENTAL FLUTTER DATA FOR ALUMINUM ALLOY PANEL WITH LENGTHWISE STIFFENERS l = 11.62 INCHES; w = 9.62 INCHES; t = 0.0165 INCH

Panel	M	q, lb/sq in.	ρ, slug/cu ft	Stiffener height, in.	Number edges clamped	Range of flutter frequencies, cps
98	1.2	6.12	0.00102	0.40	4	[a]130-340
99	1.2	6.12	.00102	.27	4	No flutter
100	1.2	6.12	.00102	.27	2	No flutter
101	1.3	6.32	.00092	.12	2	No flutter

[a]Localized flutter.

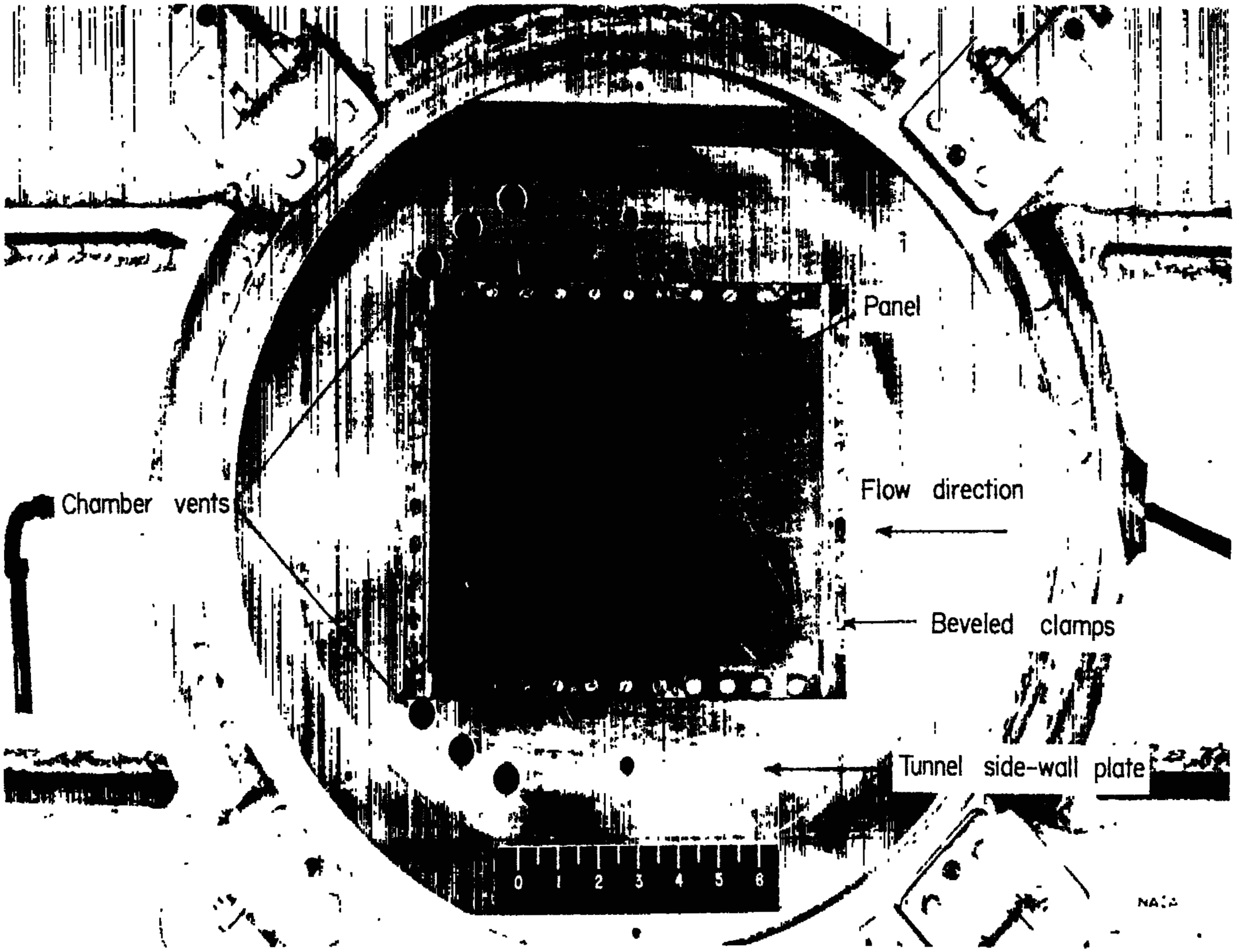


Figure 1.- Tunnel test section showing panel installed in the side-wall plate as seen through an opening in the opposite side wall.

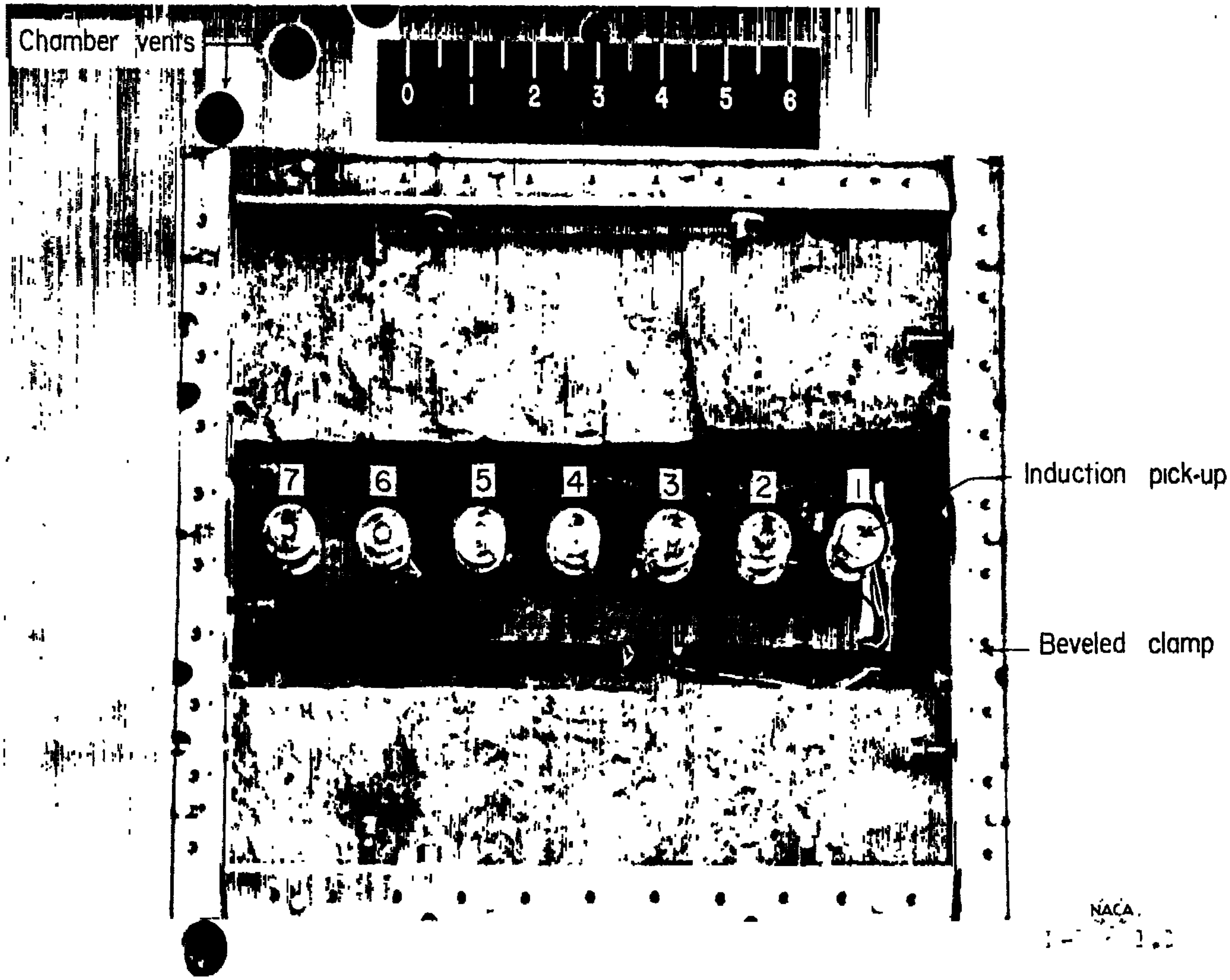
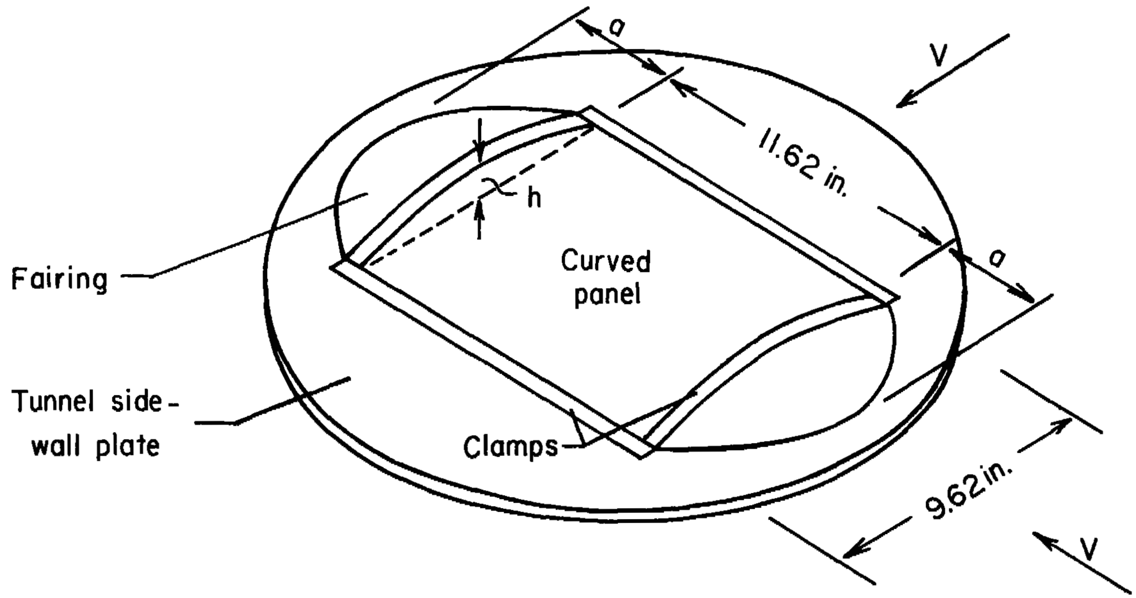


Figure 2.- Close-up view of the side-wall plate with panel removed showing location of induction pickups and beveled clamps.

[redacted]



Radius of curvature	h	a
12 in.	1.01 in.	3.5 in.
48 in.	.22 in.	2.3 in.

Figure 3.- Schematic drawing of curved panel installation.

[redacted]

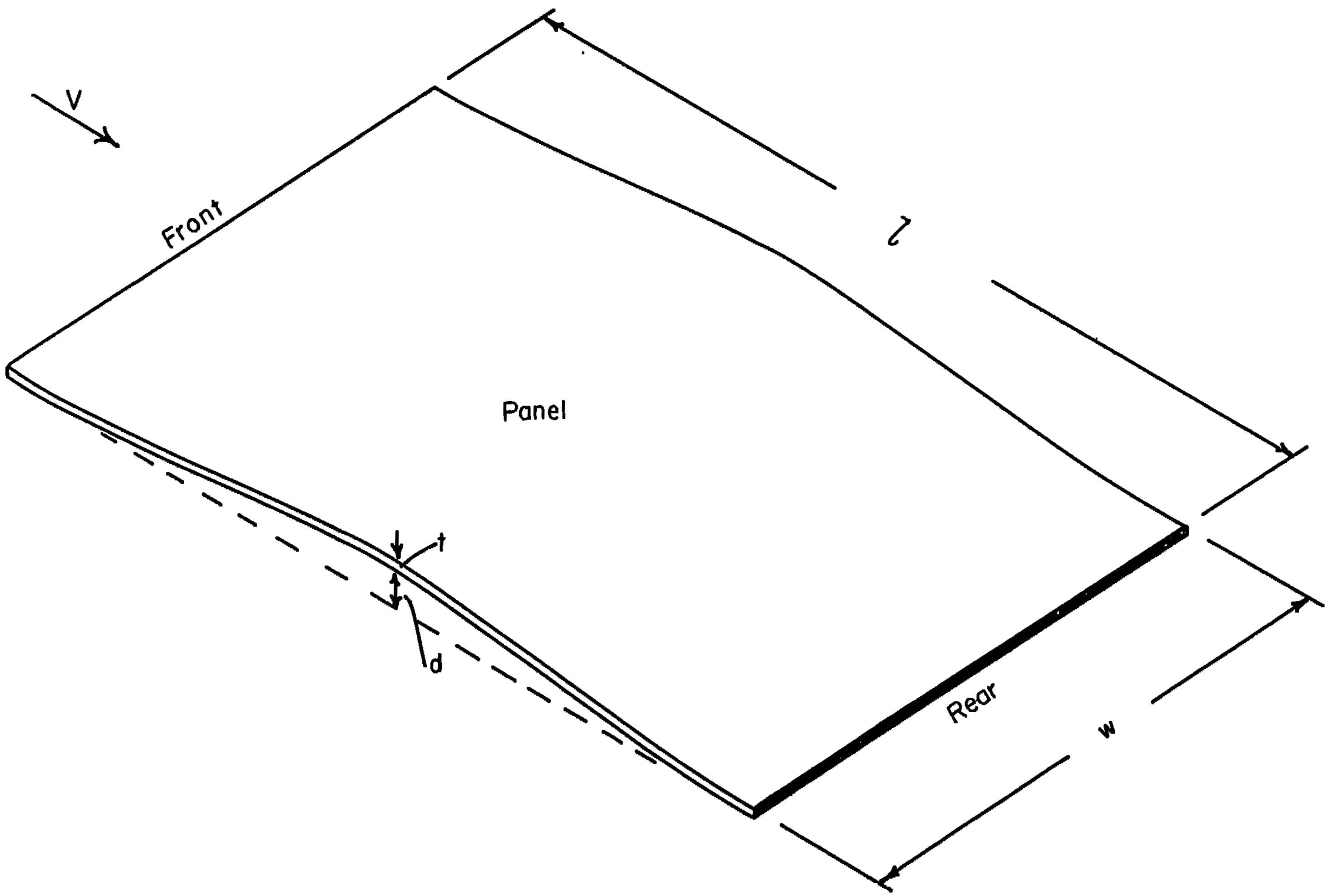


Figure 4.- Notation used in describing panels.

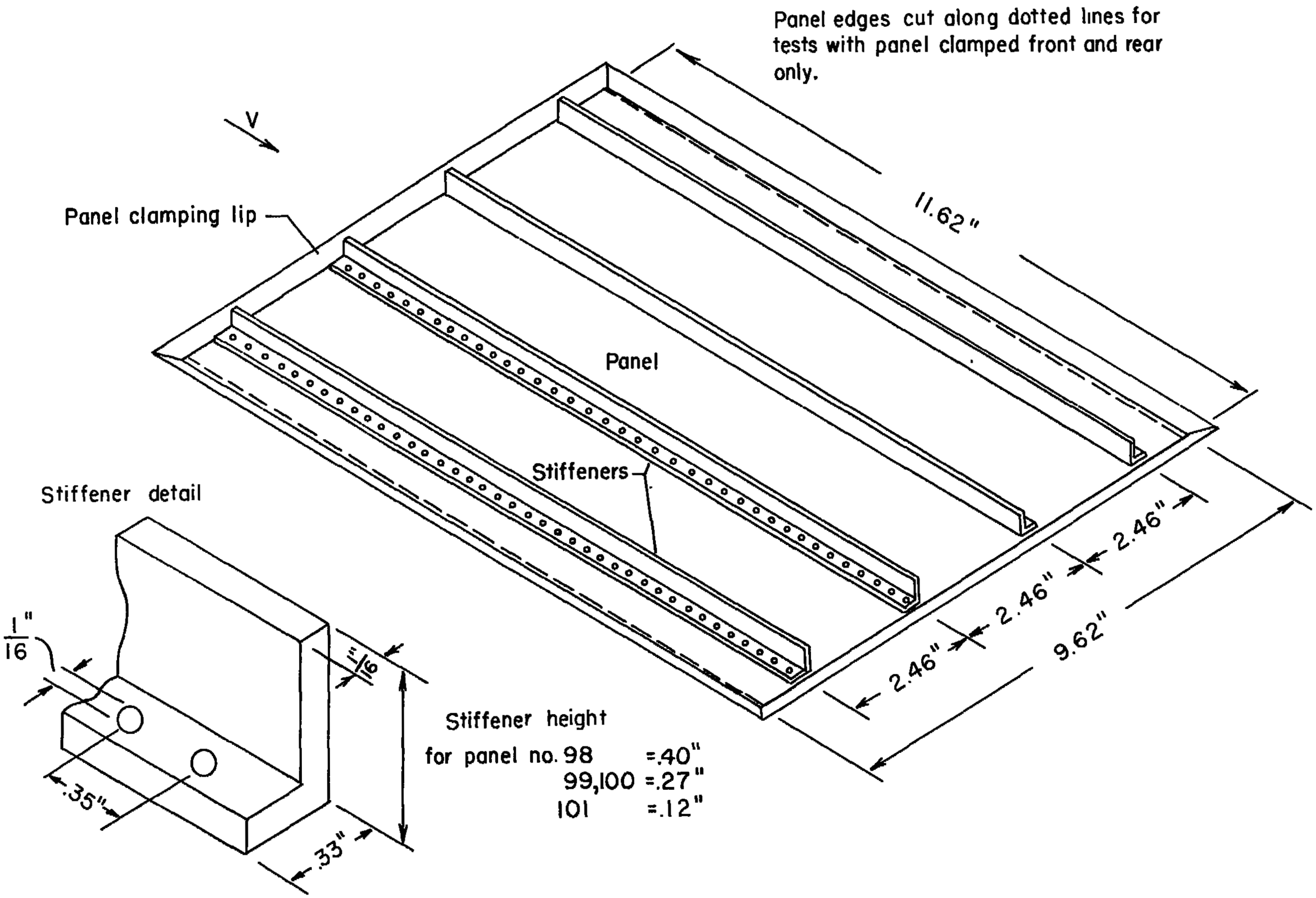


Figure 5.- Sketch of panel with lengthwise stiffeners.

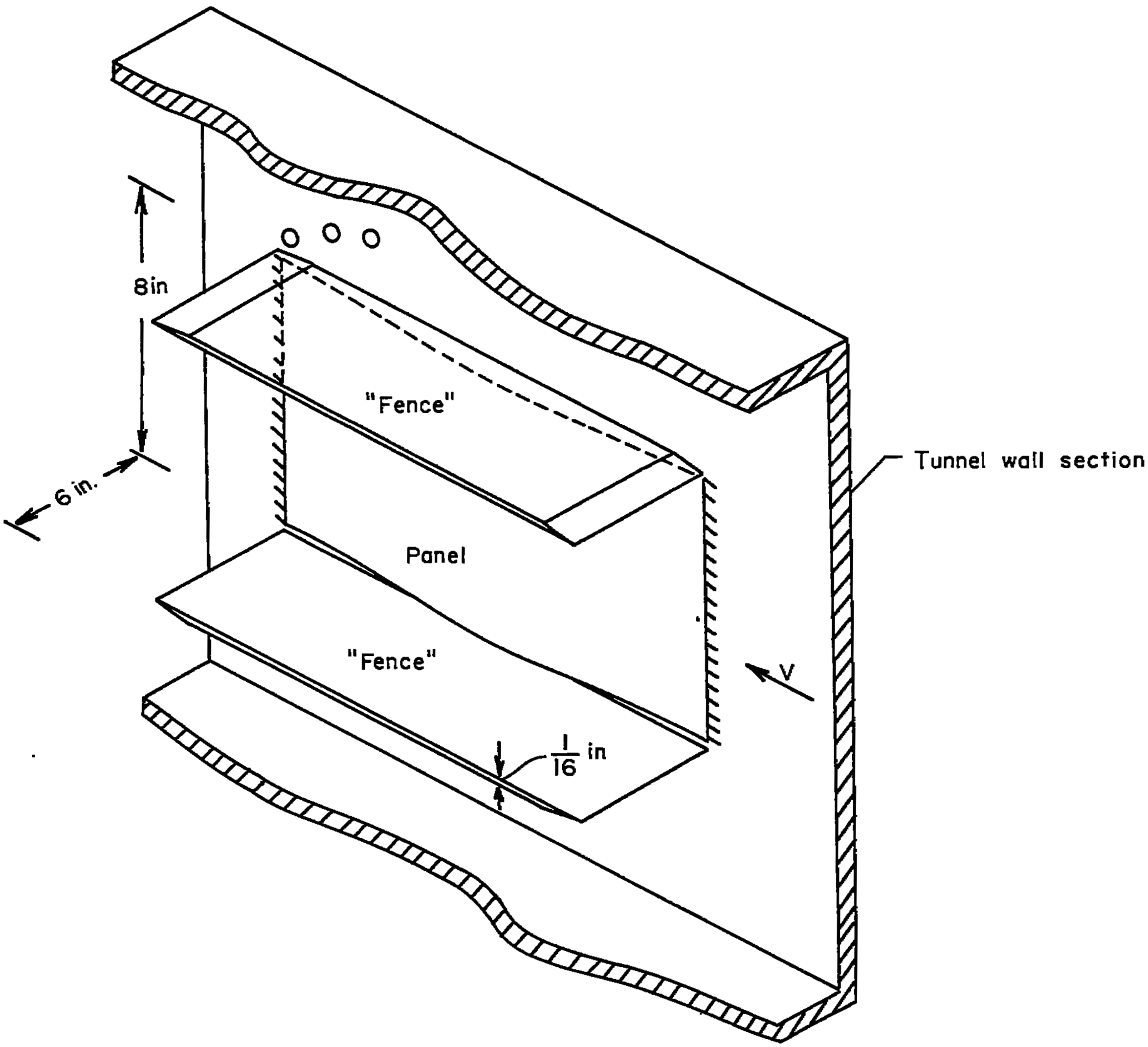


Figure 6.- Schematic drawing showing "fence" installation.

[redacted]

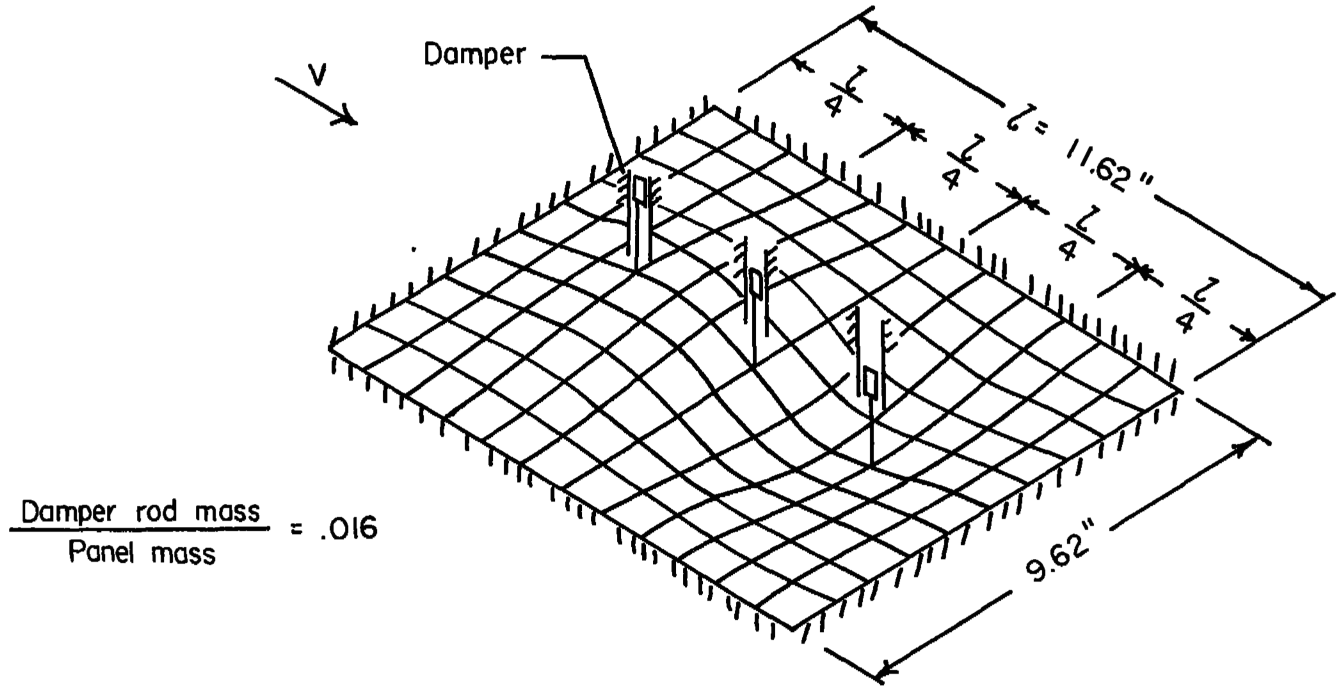
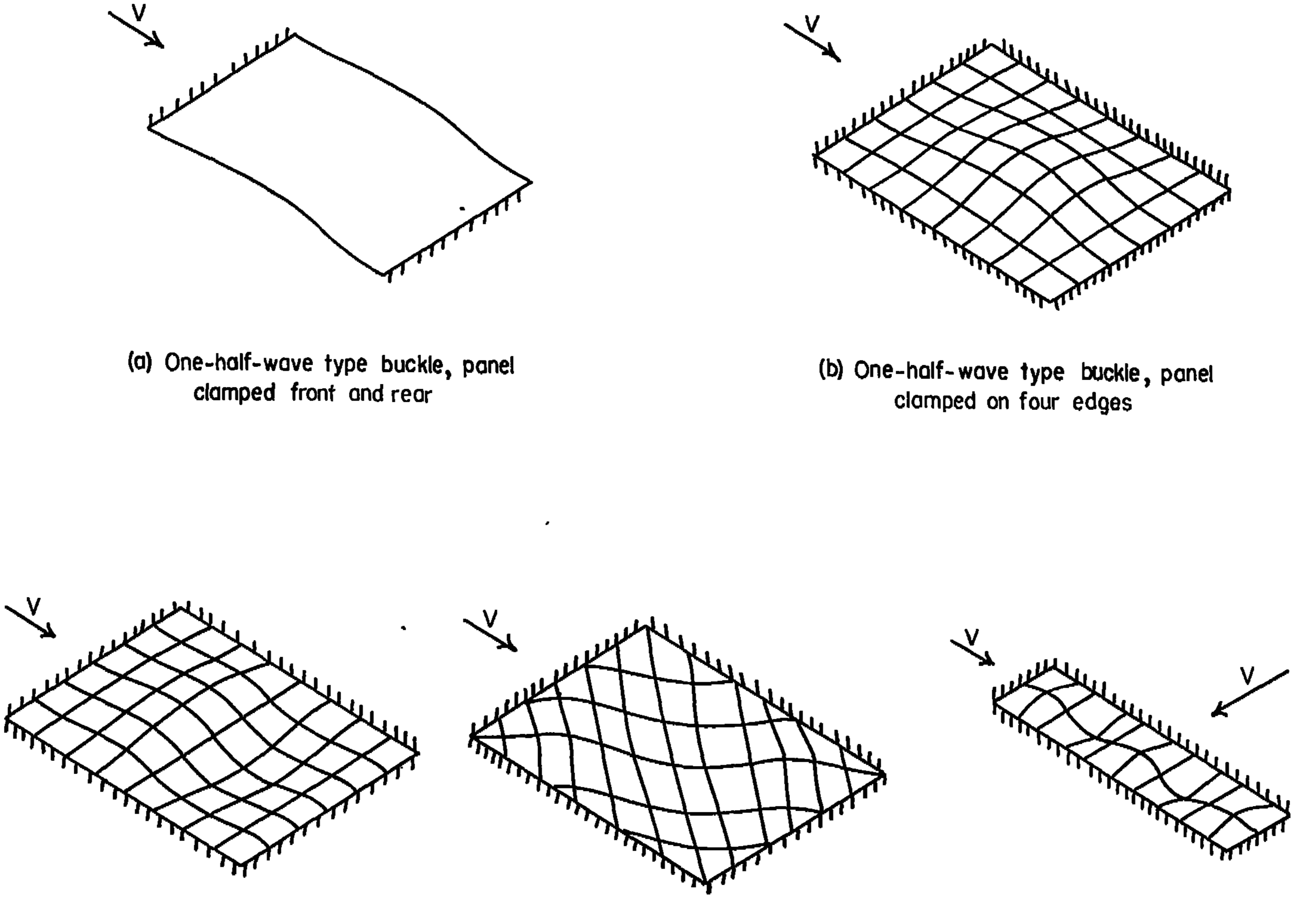


Figure 7.- Schematic drawing of buckled panel with viscous dampers.



(a) One-half-wave type buckle, panel clamped front and rear

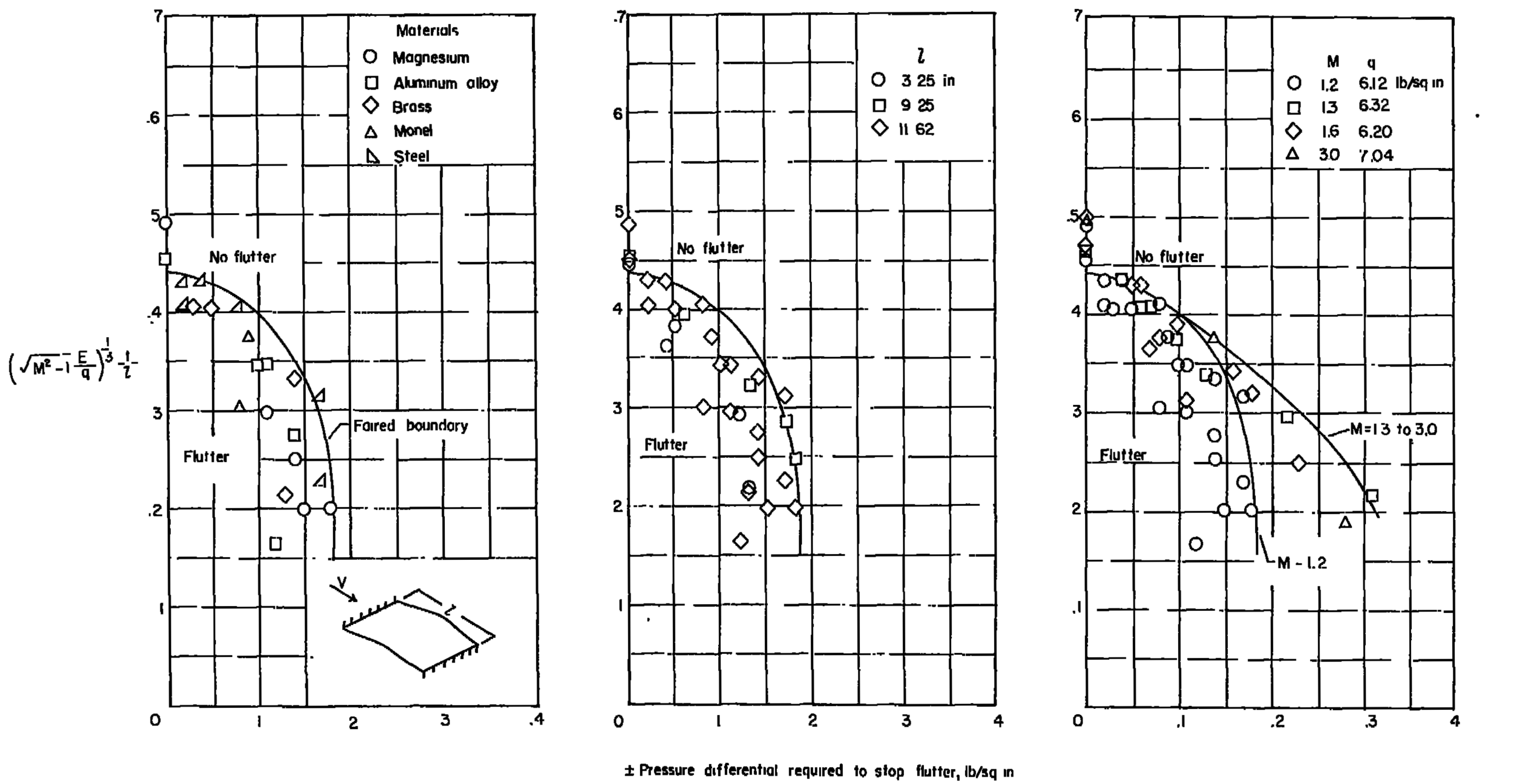
(b) One-half-wave type buckle, panel clamped on four edges

(c) Two-half-wave type buckle, panel clamped on four edges

(d) Diagonal type buckle, panel clamped on four edges

(e) Several-half-wave type buckle, panel clamped on four edges

Figure 8.- Panel static buckling-mode shapes.



(a) Panels of various materials. M = 1.2; l = 11.62; q = 6.12 lb/sq in.

(b) Panels of various lengths. M = 1.2; q = 6.12 lb/sq in.

(c) Panels at several Mach numbers. l = 11.62 in.

Figure 9.- Effect of a pressure differential on the flutter parameter of buckled panels clamped on the front and rear edges. $w/l = 0.69$.

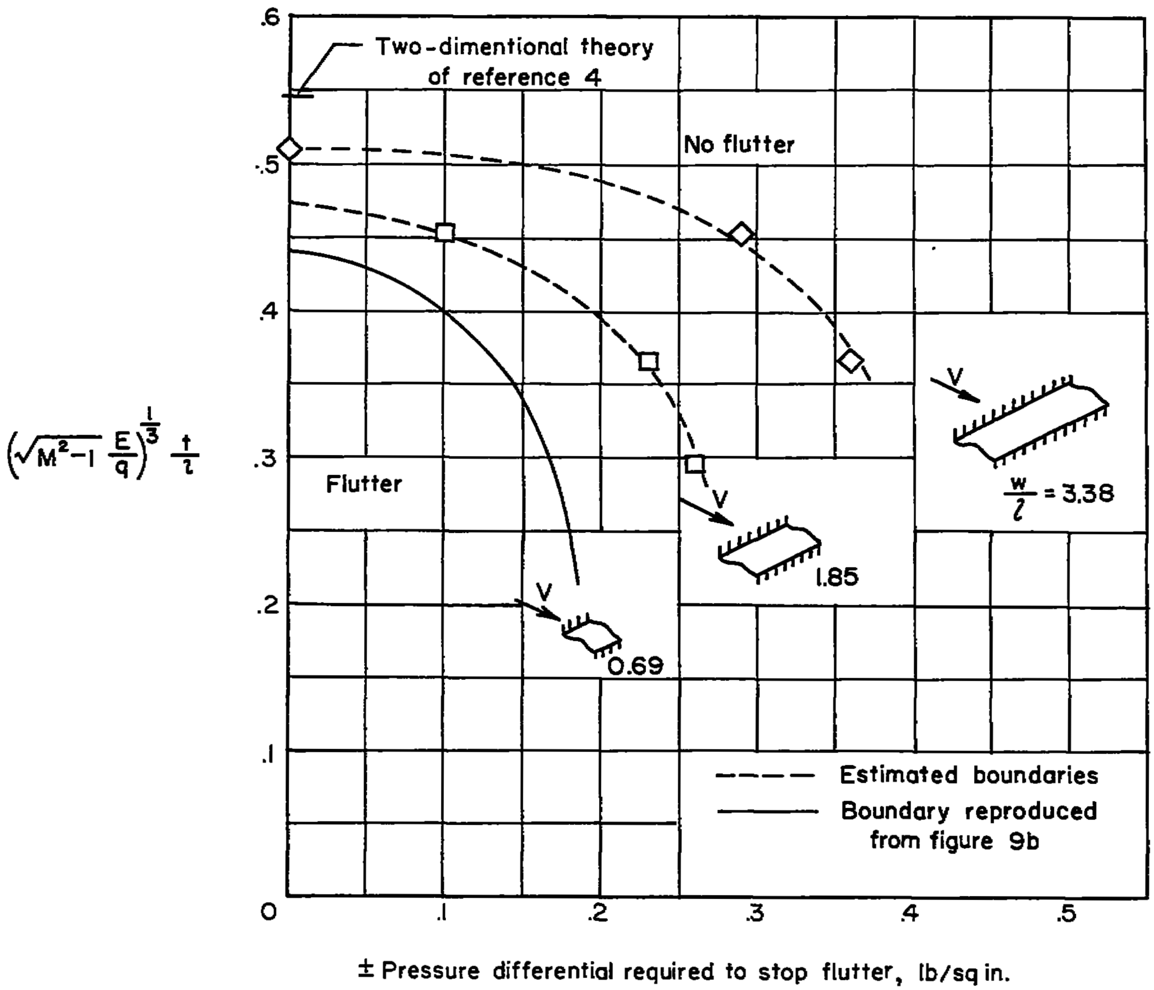


Figure 10.- Effect of width-length ratio on the flutter parameter for buckled panels clamped on the front and rear edges. $M = 1.2$; $q = 6.12$ lb/sq in.; $l = 3.25$ in.

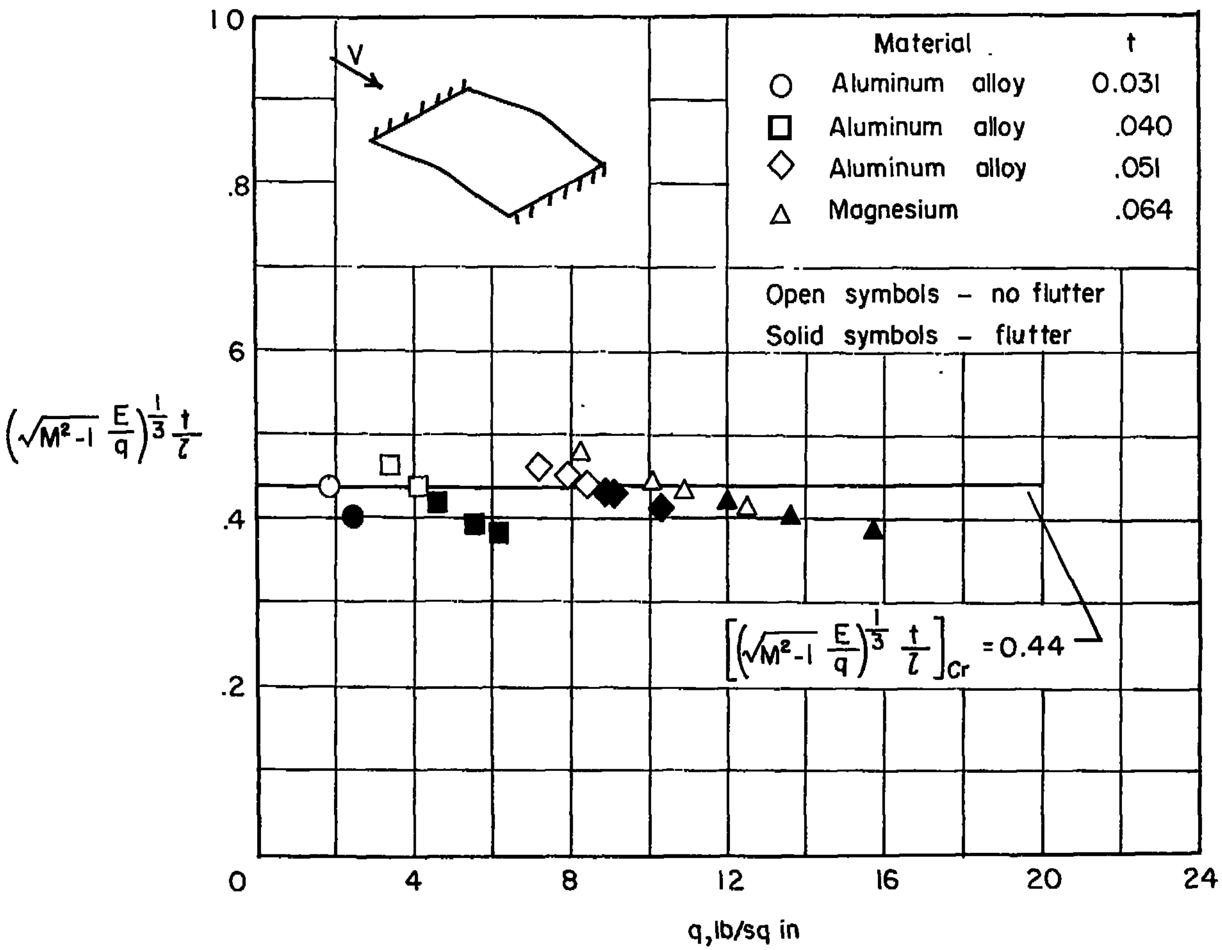


Figure 11.- Effect of dynamic pressure on the panel flutter parameter at zero pressure differential for buckled panels clamped on the front and rear edges. $w/l = 0.69$; $l = 11.62$ in.; $M = 1.3$; $\rho \approx 0.00017q$ slug/cu ft.

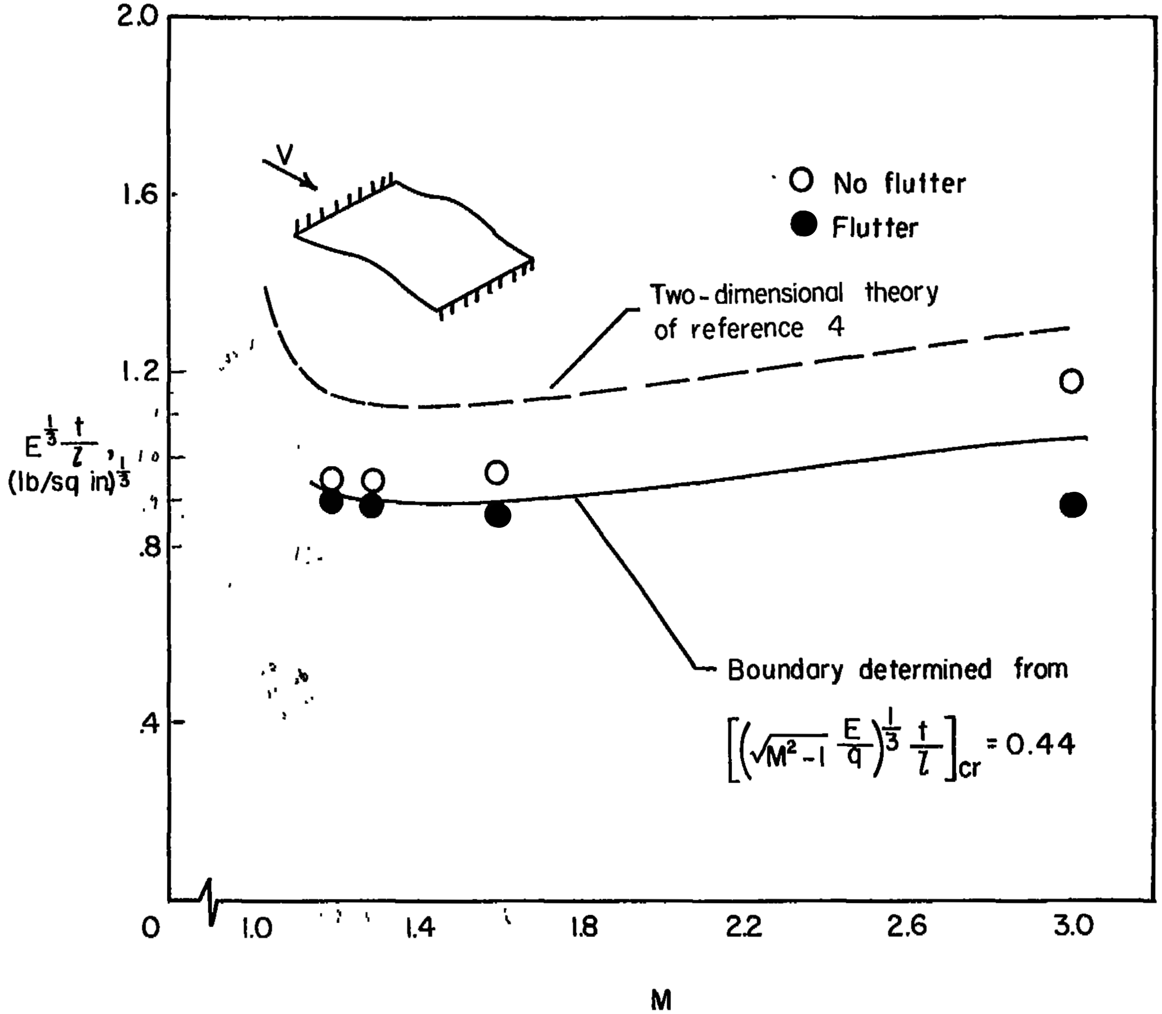


Figure 12.- Effect of Mach number on panel flutter at zero pressure differential. Buckled panels clamped on the front and rear edges. $w/l = 0.69$; $l = 11.62$ in.; equivalent pressure altitude = 22,500 ft.

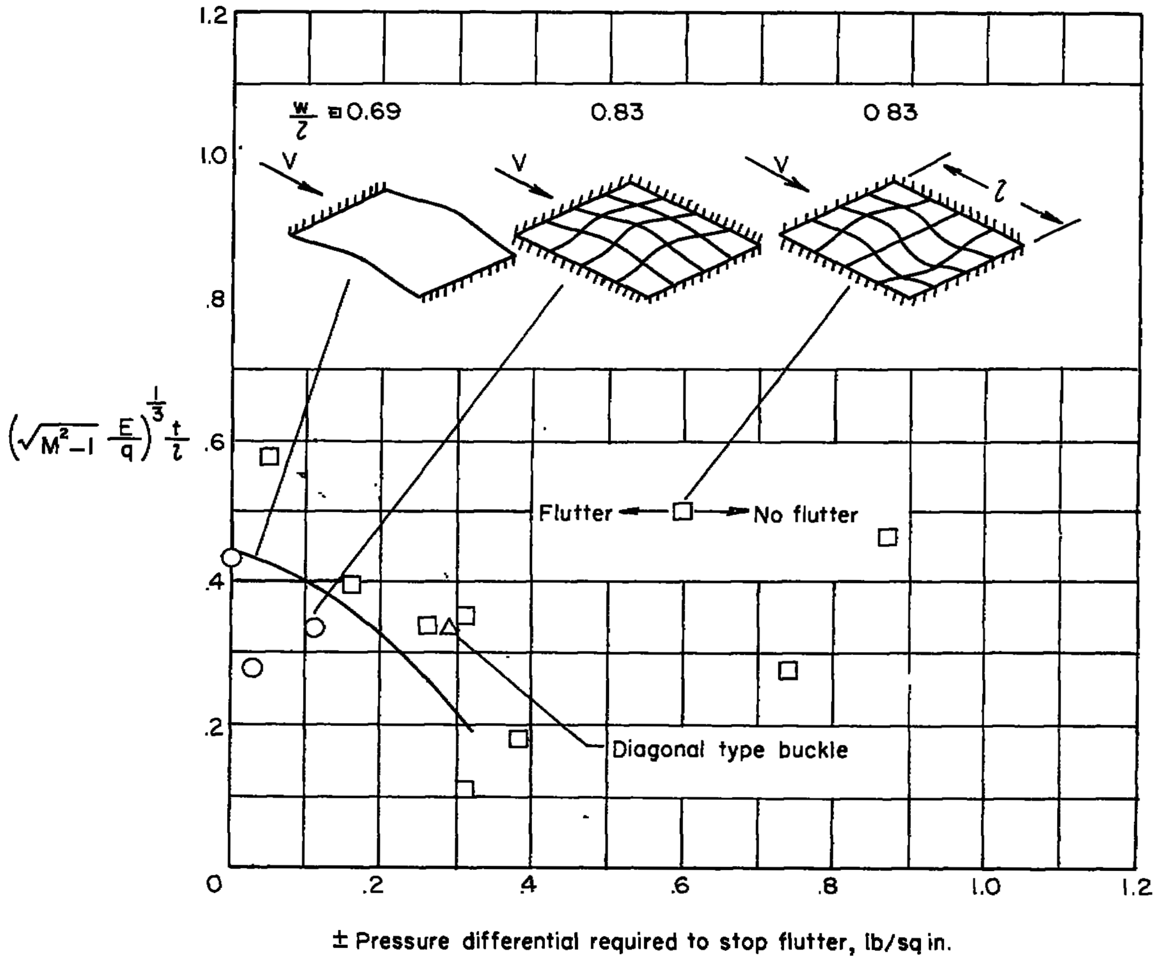


Figure 13.- Comparison of the effect of a pressure differential on several panel configurations. $M = 1.3$; $q = 6.32$ lb/sq in.; $l = 11.62$ in.

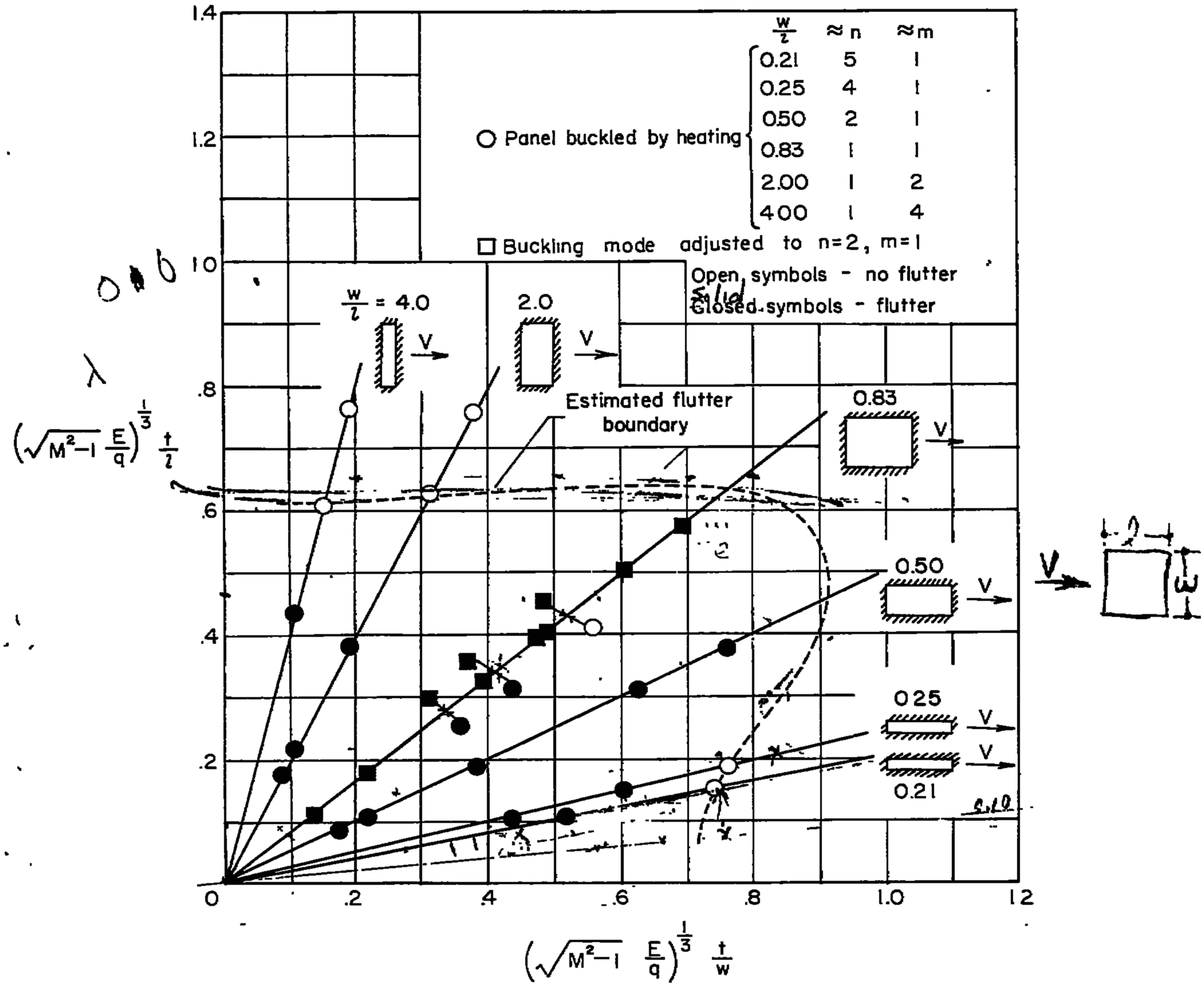


Figure 14.- Effect of panel width-length ratio at zero pressure differential. Buckled panels clamped on four edges. $M = 1.3$; $q = 6.32$ lb/sq in.

[redacted]