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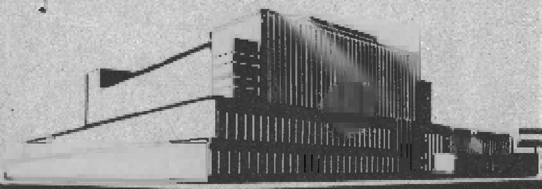

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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
In Cooperation with the University of Wisconsin

WRINKLING OF THE FACINGS OF ALUMINUM AND STAINLESS STEEL SANDWICH SUBJECTED TO EDGEWISE COMPRESSION[1]

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Summary

This report describes the fabrication, measurement, and testing of 28 sandwich constructions, consisting of facings of clad 2024-T3, 7075-T6 aluminum alloy, and 17-7PH(TH1050) stainless steel, on cores of 3003-H19 aluminum foil. The results are analyzed to relate the edgewise compressive stress that causes wrinkling of the facings to the mechanical properties and measurements of the specimens.

A method of measuring initial facing irregularities is described. Test data and measurements are analyzed in an attempt to correlate experimental results with theory. Definite correlation is obtained by several methods of analysis, but excessive scatter in the data makes these methods unsuitable for design purposes.

A design method is presented that relates edgewise compressive strength of the facings to the lateral support provided by the core. This relation is determined graphically for each facing material. Minimum lateral support values necessary to develop the yield strength of the facings in edgewise compression are determined for the facing materials evaluated.

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[2] Maintained at Madison Wis., in cooperation with the University of Wisconsin.

Introduction

Sandwich constructions, because of their rigidity and high strength-to-weight ratio, are used extensively in high-speed flight vehicles. Panels are often subjected to edgewise compressive loads at high stress levels. The facings of a sandwich construction subjected to edgewise compression act as axially loaded columns laterally supported by the core material. The amount of lateral support required for a given facing load depends on the thickness and elastic modulus of the facing material. Failure of the sandwich may occur by a localized wrinkling of the facing into the core, causing core compression failure, or by a wrinkling away from the core, causing tensile failure of the bond between the facing and core or tensile failure of the core. Since the facings of fabricated sandwich panels are never perfectly plane, these localized wrinkling failures can develop by enlargement of the initial surface irregularities as edgewise load is increased. Existing theories for determining stresses at which facings wrinkle include parameters involving the initial lack of flatness of sandwich facing materials. This report describes a method of measuring initial facing irregularities. Analyses of edgewise compression test results are correlated with theory by several methods.

Design methods have been developed for most modes of edgewise compression failure. Satisfactory design methods for elastic instability of the facings, resulting in a wrinkling of the facings into or away from the core, have not been developed. This report presents a design method based on an experimental study of face wrinkling phenomena. A graphical relationship is developed between edgewise compressive strength of sandwich facings and the lateral support provided by the core material. Minimum values of lateral support necessary to develop the yield strength of the facings in edgewise compression are determined for the clad aluminum and stainless steel facing materials evaluated.

Materials and Preparation of Specimens

The construction of each of the 28 sandwich panels tested is given in table 1.

Facings

Facings for the sandwich constructions tested were of clad 2024-T3 aluminum alloy, clad 7075-T6 aluminum alloy, and 17-7PH (TH1050) stainless steel. Clad 2024-T3 aluminum facings were 0.012, 0.018, and 0.020 inch thick. Clad 7075-T6 aluminum facings were 0.012, 0.016, 0.020, and 0.032 inch thick. Stainless steel facings were used in thicknesses of 0.015 and 0.031 inch.

Sandwich panels with aluminum alloy facings were fabricated in a 12-inch-square size.

The aluminum facings were wiped with acetone to remove code markings and surface contamination. Each facing was etched for 10 minutes at 150° F. in an etching solution containing 10 parts of concentrated sulfuric acid (specific gravity 1.84), 1 part of sodium dichromate, and 20 parts of distilled water. Following the etch bath, the facings were rinsed in distilled water (80° F.) and then dried in a stream of air for 30 minutes at 110° F.

Sandwich panels with stainless steel facings were fabricated in a 14-inch-square size. The panel facings were cleaned with acetone and etched in a solution of 10 percent of nitric acid, 2 percent of hydrofluoric acid, and 88 percent of distilled water at 150° F. until all scale was removed. The panel facings were then removed from the acid, rinsed with distilled water, and dried in a stream of air at 110° F.

Cores

Core material was of 3003-H19 aluminum alloy foil in thicknesses of 0.001, 0.002, 0.003, and 0.005 inch, expanded to 1/8-inch cells or corrugated to 1/4- and 3/8-inch cells. Core thicknesses of 1/2 and 2 inches were used. The core material was not etched.

Adhesives

Adhesives used to bond facings to core were a nitrile-phenolic tape adhesive, a vinyl-phenolic tape adhesive, and an epoxy-resin adhesive. These adhesives were selected so that core-to-facing bonds would have a range of flatwise tensile strengths.

Nitrile-phenolic tape.--After etching and drying, a double thickness of nitrile-phenolic tape was placed on each facing. The panel was assembled and put into a press for 1 hour at 325° F. at a pressure of 15 pounds per square inch. Three layers of blotting paper were placed between the top facing and the upper platen of the press. The panels were removed hot.

Vinyl-phenolic tape.--The facings were sprayed with a thin coat of adhesive primer. After spraying, the primer coat was left to set overnight. The core was placed on edge and a small amount of unthinned vinyl-phenolic liquid was applied with a paint roller. The next morning the vinyl-phenolic tape was tacked to the facings in several places with a solder gun. The adhesive on the facings and on the core was precured in an oven at 220° F. for 1 hour. The panel was then assembled, and three pieces of blotter were placed between the top facing and the upper platen of the press, so that pressure would be more uniformly distributed. The assembled panel was then put into a press heated to 325° F. for 7 minutes with no pressure and for 35 minutes with a pressure of 15 pounds per square inch. The panels were then cooled in the press and removed.

Epoxy-resin.--Epoxy adhesive with 6 percent of catalyst A was used to bond the facings to the core. The bonding adhesive was spread on the facings with a trowel that had notches 1/8 inch deep. The honeycomb core was placed on edge and a small amount of adhesive was applied with a paint roller. Panels were bonded in a hot press for 90 minutes at 220° F. under a pressure of 15 pounds per square inch. The panels were pressed with three layers of blotting paper placed between the top facing and the upper platen of the press. Panels were removed from the press while they were still hot.

Preparation of Specimens

After fabrication, each panel was cut into six edgewise compression specimens 3 inches wide and 4 inches long with the core ribbon direction parallel to the 4-inch side; 10 flatwise tension specimens 1 or 2 inches square; and 4 flatwise compression specimens 2 inches square. The edgewise compression specimens were ground so that the ends were smooth and parallel.

Some of the ends of edgewise compression specimens with cores 2 inches thick were then dipped in cast epoxy-resin adhesive about 1/2 inch thick to confine failure to the central portion of the specimen.

The procedure used to cast the ends of the specimens was as follows: A glass plate was covered with a sheet of cellophane. Small cardboard molds were made for each specimen end. The adhesive was mixed and poured into the molds. The specimen ends were then forced down in the adhesive-filled molds so that the ground specimen ends were bearing against the cellophane-covered glass plate. A weight was then placed on the specimen to hold it down until the adhesive set. Heating the specimens for 1 hour at 180° F. improved the strength of the cast adhesive considerably. A completed specimen with ends dipped is shown in figure 1.

Aluminum cubes were bonded to the facings of flatwise tension specimens. The aluminum cubes were cleaned by first wiping with acetone, then etching for 10 minutes at 150° F. in a solution containing 10 parts of concentrated sulfuric acid (specific gravity 1.84), 1 part of sodium dichromate, and 30 parts of distilled water Following the etch bath, the cubes were rinsed in distilled water, then dried in a stream of air at 110° F. The aluminum facings were first wiped off with acetone; then an abrasive cloth, which was free of iron particles, and emery cloth were used to remove the surface gloss, and the facings were wiped with a clean cloth. The stainless steel facings were first wiped with acetone and then sanded with emery cloth and wiped again with a clean cloth soaked with acetone.

Epoxy-resin adhesive with 6 percent of catalyst was used to bond the cubes to the facings. The bonding adhesive was spread on the facings and the cubes with a spatula.

Cubes and specimens were assembled in special wood jigs that held the cubes and the specimens from sliding and turning. Thus assembled (with cellophane wrapped around each specimen), the jigs were placed in a small, electrically heated press for 90 minutes at 220° F. under a pressure of 15 pounds per square inch.

Test Methods

Six edgewise compression tests, 10 flatwise tension tests, and four flatwise compression tests were made of each construction. All tests were conducted at 70° to 85° F.

Measurement of Specimens

Length and width of specimens were measured to 0.01 inch and sandwich thickness to 0.001 inch. Core thickness was calculated by deducting twice the nominal facing thickness from the sandwich thickness (table 1, col. 4).

Edgewise Compression Tests

Edgewise compression tests were made by loading the specimens parallel to the plane of the facings. Load was applied through a spherical head to the ground specimen ends. The loading direction was parallel to the core ribbon direction.

Specimens which were not end dipped in adhesive had the ends stabilized by papreg restrainers, as shown in figure 1. Marten's mirror compressometers with a 1- or 2-inch gage length were attached to the specimen facings, as shown in figure 1.

The specimens were positioned between the heads of the testing machine and adjusted until the deformation of each facing (as measured by the Marten's mirror compressometer) was the same under a load of 500 to 1,000 pounds. The load was then dropped to 50 or 100 pounds and specimens were tested to failure, readings of load and deformation being taken at intervals until the proportional limit was passed. Load was applied at a uniform rate, such that failure occurred in 3 to 6 minutes. The Marten's mirror compressometers were removed before failure to avoid damaging them.

Tension Tests

Flatwise tension tests were conducted to determine maximum load only. The cubes bonded to the tension specimens were held in universal-joint fixtures, assuring a fairly uniform stress across the specimens. A specimen and the loading apparatus are shown in figure 2. Load was applied at a uniform rate, such that failure occurred in 3 to 6 minutes.

Flatwise Compression Tests

Flatwise compression specimens were tested between a spherical head and a fixed platen of the testing machine. Marten's mirror compressometers with a 1-inch gage length were attached to the core on opposite sides of the specimens. Specimens were positioned between the heads, so that deformations (as indicated by the Marten's mirror compressometers) on both sides were equal at some arbitrary load below the proportional limit. The load was dropped to a level of 25 or 50 pounds. The specimens were then tested to failure at a uniform load rate such that failure occurred in 3 to 6 minutes. Readings of load and deformation were taken at intervals until the proportional limit was passed. The Marten's mirror compressometers were removed before failure. Specimens with 1/2-inch-thick cores were tested for maximum load only.

Calculation of Data and Presentation of Results

Data for the mechanical tests and measurements of the 28 sandwich panels are summarized in table 1.

Edgewise Compression Tests

The edgewise compressive strength (facing stress) was computed by dividing the maximum load by the cross-sectional area of the facings (table 1, col. 13).

The edgewise compressive strength was averaged for all specimens in each panel that failed by face wrinkling. The effective modulus of elasticity of the facings given in column 9 is the tangent modulus [3] at the average compressive strength given in column 13 of table 1. Values for compressive yield strength of the facing material (col. 10) were taken from tables in Military Handbook 5 for the facing materials used.[3]

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[3] Tangent modulus values were obtained from tables in MIL-Handbook 5, Strength of Metal Aircraft Elements. Office of the Assistant Secretary of Defense. (Supply and Logistics) 30 December 1958.

Flatwise Tension Tests

The flatwise tensile strength for each specimen was computed by dividing the maximum load by the cross-sectional area (table 1, col. 12). An average strength for each panel was computed.

Flatwise Compressive Tests

The flatwise compressive strength was computed by dividing the maximum load by the cross-sectional area (table 1, col. 6). An average compressive strength was computed for each panel. The core modulus of elasticity in the direction parallel to the flutes and perpendicular to the facings was computed and is given in column 5 of table 1.

Since the flatwise tensile strength of some of the panels was greater than the proportional limit stress in flatwise compression, it was necessary to determine an effective elastic modulus. For such panels, the effective modulus was taken to be the tangent modulus and was obtained from previous test data.[4] Values were obtained at the stress level corresponding to flatwise tensile or compressive strength, whichever was the lower.

Surface Profile Measurements

In order to analyze edgewise compression test data on the basis of existing theory, it was necessary to measure the initial irregularities in the facings of the edgewise compression specimens. Accordingly, apparatus was devised to measure both the amplitude and wave length of the irregularities in the facings of the edgewise compression specimens prior to test.

The device consisted of a simple two-plate capacitor mounted on a supporting frame, as shown in figure 3. The lower capacitor plate was attached to the frame through a hinged connection, permitting

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[4] Kuenzi, E. W. Mechanical Properties of Aluminum Honeycomb Cores. Forest Products Laboratory Report No. 1849, September 1955, (original data).

movement of the plate in a vertical plane. A probe point with a sapphire ball tip was attached to the lower plate of the capacitor. The upper plate was connected to the supporting frame through a micrometer. The arrangement permitted measured vertical movements of the upper plate. This assembly was mounted on a horizontal track as shown in figure 4. The specimen to be measured was placed under the track so that the track bases fitted flat against the upper facing. As the capacitor assembly slid along the track, the probe point traversed the long dimension of the specimen, its sapphire ball tip riding up and down, following the profile of the facing.

Electronic and photographic equipment was used to obtain a photograph of the surface profile as the facing was traced by the probe tip. Vertical movements of the probe tip changed the capacitance of the capacitor, which controlled the frequency-determining circuit of an oscillator. The output of the oscillator was amplified, and applied to a frequency discriminator that generated a DC voltage proportional to the frequency. This DC voltage was the vertical input to an oscilloscope. Thus, vertical movements of the probe point produced vertical movements of the oscilloscope trace. Horizontal movements of the probe assembly along the track were transmitted through a wire and pulley arrangement that turned the control shaft on a potentiometer. A constant DC voltage was applied across the potentiometer, so that rotation of the control shaft varied the output voltage of the potentiometer. The varying voltage provided the horizontal input to the oscilloscope. As a result, horizontal movements of the probe point produced horizontal movements of the oscilloscope trace. Consequently, as the probe point traced the surface profile across a specimen facing, a similar profile was traced across the oscilloscope screen and photographed by a camera mounted on the oscilloscope. Typical surface-profile photographs for the specimens from one panel are shown in figure 5.

Vertical calibration factors for the photographs were obtained by two methods. One procedure involved setting the oscilloscope for a horizontal sweep. The vertical distance between capacitor plates was varied in 0.001-inch steps by means of the micrometer, which produced a series of horizontal lines spaced vertically at a distance proportional to 0.001 inch. These lines were then photographed using a time exposure. The other procedure required the use of a gage block whose surface was ground in a series of 0.001-inch steps (see fig. 4). This gage block was profiled in the same manner as an edgewise compression specimen. A picture of the stepped oscilloscope trace was made on the same film frame as the surface profile photograph for each specimen, providing a calibration for each photograph (see fig. 5). In order to obtain a sufficient number of calibration steps on the photograph, the gage block was photographed with half the sensitivity used on the sandwich specimen, thus giving steps proportional to 0.0005 inch.

Horizontal calibration factors were obtained as ratios of travel length on the specimen (3.75 in.) to trace length on the photograph.

The photographs were measured for amplitude and wavelength of each half wave in the surface profile. (See sketch of typical profile in fig. 6.) The points of inflection for each half wave were located by eye and connected by a straight line. The horizontal component of this line multiplied by the horizontal calibration factor gave the half wavelength. The maximum vertical distance between this line and the profile curve multiplied by the vertical calibration factor gave the amplitude. The ratio (K_O) of amplitude to half wavelength was calculated for each half wave. Finally, the average half wavelength (L), average amplitude (α), and the average ratio (K_O) were computed for each specimen. Panel averages of these values are presented in table 2 for five panels with aluminum facings and five panels with stainless steel facings.

Three surface profile measurements were made for each facing of each edgewise compression specimen. The first profile was 1/2 inch from one edge, the second down the center of the facing, and the third 1/2 inch from the other edge. The profiles on one facing of each specimen were detected as being consistently rougher than the profiles on the other facing. The rough facing was found to be that on which the blotters were placed during the hot press operation. This variation in facing roughness is illustrated in figure 5.

Analysis of Results

Modified Method of Report 1810-A

Edgewise compressive strength can be related to specimen measurements, mechanical properties, and facing waviness by:[5]

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[5] Equation 9, of Forest Products Laboratory Report No. 1810-A, "Wrinkling of the Facings of Sandwich Construction Subjected to Edgewise Compression."

$$f = \frac{\pi^2 t^2 E'}{12L^2\lambda} \; \frac{1 + \dfrac{24E'_c\lambda L^4}{\pi^4 E' t^3 t_c}}{1 + \dfrac{2E'_c L K_o}{\pi F_c t_c}} \qquad (1)$$

where:

f is edgewise compressive strength (facing stress at wrinkling)

t is facing thickness

E' is effective facing compression elastic modulus at stress f

L is half wavelength of facing waves

E'_c is effective core compression elastic modulus (at core stress equal to flatwise compressive or flatwise tensile strength, whichever is the lower)

λ is 1 minus the square of Poisson's ratio of the facings (0.91)

t_c is core thickness

F_c is sandwich flatwise tensile or compressive strength, whichever is less.

K_o is ratio of the amplitude (α) to the half wavelength L of the facing waves.

It should be pointed out that the amplitude α and the half wavelength L be in this formula pertain to the Fourier component of the irregularity that is critical, rather than to the irregularity itself. This is described in section 12, part I, of report 1810.[6] The traces of the irregularities were not sufficiently accurate to allow the determination of the Fourier components. The wavelengths and amplitudes of the parts of the traces of the irregularities that resembled sinesoidal curves were used instead.

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[6] Norris, C. B.; Ericksen, W. S.; March, H. W. and others. Wrinkling of the Facings of Sandwich Construction Subjected to Edgewise Compression. Forest Products Laboratory Report No. 1810, March 1956.

This equation can be written as:

$$f = \frac{A}{1 + B} \tag{2}$$

where:

$$A = \frac{\pi^2 t^2 E'}{12L^2 \lambda} \left(1 + \frac{24E'_c \lambda L^4}{\pi^4 E' t^3 t_c}\right)$$

$$B = \frac{2E'_c L K_o}{\pi F_c t_c}$$

Edgewise compressive strengths computed from formula (2) were found to be much higher than test strengths, and so a factor M was introduced in the numerator, and a factor N was introduced in the second term of the denominator, resulting in the equation:

$$f = \frac{MA}{1 + NB} \tag{3}$$

The factors M and N were determined by using the test stress for f and calculating M and N from least squares using equations (4) and (5).

$$M = \frac{\Sigma \frac{f}{A} B \; \Sigma \frac{f^2}{A^2} B - \Sigma \frac{f}{A} \; \Sigma \left(\frac{f}{A} B\right)^2}{\left(\Sigma \frac{f}{A} B\right)^2 - n \, \Sigma \left(\frac{f}{A} B\right)^2} \tag{4}$$

$$N = \frac{n \, \Sigma \frac{f^2}{A^2} B - \Sigma \frac{f}{A} B \; \Sigma \frac{f}{A}}{\left(\Sigma \frac{f}{A} B\right)^2 - n \, \Sigma \left(\frac{f}{A} B\right)^2} \tag{5}$$

where n = number of specimens or panels.

The least squares analysis was based on specimens from five panels with aluminum facings and five panels with steel facings that were selected to fit the following criteria: Specimens failed by face wrinkling in the center portion of the facings, and facing stress at failure was below the proportional limit stress of the facings. Preliminary calculations revealed that the best results were obtained by separately treating specimens with aluminum and steel facings, and by using average data for each panel.

The calculation of M and N by least squares is summarized in table 2. Average data for specimens selected by the above criteria are presented in columns 2 through 8. Face-waviness properties as measured from surface profile photographs are entered in columns 9, 10, and 11. Parameters A and B (cols. 12 and 13) were calculated from the average specimen measurements, mechanical properties, and face-waviness data in accordance with equation (2). $\frac{f_{Test}}{A}$ and $\frac{f_{Test}}{A}B$ (cols. 14 and 15) were obtained by dividing column 7 by column 12, and by multiplying column 14 by column 13, respectively. M and N were then obtained from the values in columns 14 and 15 by use of equations (4) and (5).

Once M and N had been computed, equation (3) was used to compute the stress f for each panel (col. 16). Finally, the calculated stresses were compared to the test stresses as a ratio (col. 17). This information is also presented graphically in figure 7, a plot of calculated stresses versus test stresses. Figure 7 shows that the scatter in the data is so great that the behavior of any one specimen cannot be predicted confidently. Therefore, this method does not provide a basis for a design method to determine facing stress at wrinkling in edgewise compression.

Maximum Deflection Method

Equation (1) may be approximated by letting the half wavelength L be equal to the honeycomb cell size s, and disregarding the first term in the numerator:

$$f = \frac{2E_c' s^2}{\pi^2 t t_c \left(1 + \frac{2 E_c' \alpha}{\pi F_c t_c}\right)} \qquad (6)$$

where α is the amplitude of a half wave.

This equation produced an error in f of about 10 percent as compared to equation (1) for the sandwich tested.

It was assumed that the maximum amplitude α in any profile across a facing would cause the failing buckle, the half wavelength of which would be the cell size. The maximum amplitude for each specimen was measured and panel averages were computed for a series of 13 panels. The facing strength f was calculated for each panel using equation (6). Calculated facing stresses are compared with test stresses in figure 8.

These data show excessive scatter that precludes the use of formula (6) for accurate prediction of facing stresses at wrinkling.

Theoretical Amplitude Method

Equation (1) can be used to compute a theoretical amplitude α if the failing stress f is known. L was set equal to the cell size, and α was computed for four panels.

Computed values of α and average measured values of amplitude α are given in the following tabulation:

Panel	Calculated α In.	Measured α In.
2	0.00300	0.000311
3	.00580	.000312
7	.00601	.000221
10	.01332	.000328

Examination of the values in the table shows that theoretical values of amplitude α bear no constant relationahip to actual values, and therefor, this method of analysis is of little use in determining facing stresses at wrinkling.

Ideal Wavelength Method

This method consisted of determining the half wavelength L, which produced the minimum edgewise compressive strength f. Equation (1) was differentiated with respect to L and set equal to zero, noting that LK_o in the denominator is equal to α. Solving the differentiated expression for L gave:

$$L = \pi \left(\frac{t}{2}\right)^{1/2} \left(\frac{E'tt_c}{6E_c'\lambda}\right)^{1/4} \qquad (7)$$

and substituting this value of L in equation (1) gave:

$$f = \frac{1/3 \left(\frac{6E'E_c't}{\lambda t_c}\right)^{1/2}}{1 + K_o \left[\frac{2E'(E_c')^3}{3\lambda F_c{}^4} \left(\frac{t}{t_c}\right)^3\right]^{1/4}} \qquad (8)$$

Six specimens that satisfied the following criteria were chosen for calculation: Maximum facing stresses were below the proportional limit, failure occurred by face wrinkling at or near the center of the specimen, flatwise tensile data for the panels involved varied through a small range of strengths, and photographs of facing profiles were sharp and clear, showing waves whose half wavelength and amplitude could be readily measured.

The ideal half wavelength was computed from equation (7) for each specimen. A half wavelength of this size was found on the facing profile photograph, and the amplitude was measured. K_o was then calculated and the failing stresses f were computed using equation (8). The computed stresses were all much higher than the test stresses, so f was calculated by applying the factors M and N previously found by least squares. This gave stress values which were uniformly too low.

The results are given in the following tabulation:

Panel No.	Core cell size	L (Equation 7)	α	f Test	Equation 8	Equation 8, M and N
	In.	In.	In.	P. s. i.	P. s. i.	P. s. i.
4	1/4	0.175	0.00015	19,500	74,000	6,960
14	1/4	.1414	.00010	38,500	91,000	3,880
26	3/8	.228	.00025	31,800	174,000	20,700
26	3/8	.228	.00046	31,600	142,000	11,920
26	3/8	.228	.00035	40,500	157,500	15,400
26	3/8	.228	.00062	37,500	124,800	9,070

This analysis clearly showed that a critical half wavelength could be calculated and an actual half wave of this length could be located on the surface-profile photographs, and the amplitude measured. Values of the ideal half wavelengths given in the table are less than the core cell size. Correct facing stresses cannot be obtained, however, even by using the correction factors M and N previously determined.

Analysis of Two Sandwich Panels Differing in Construction Only by Core Thickness

Equation (1) may be written:[7]

$$f = \frac{K_1}{L^2} \frac{t_c + K_2 L^4}{t_c + K_3 L} \qquad (9)$$

where:

f is edgewise compressive strength

$$K_1 = \frac{\pi^2 E' t^2}{12\lambda}$$

$$K_2 = \frac{24 E_c' \lambda}{\pi^4 E' t^3}$$

$$K_3 = \frac{2 E_c' K_o}{\pi F_c}$$

t_c is core thickness.

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[7] Equation 10 of Forest Products Laboratory Report No. 1810-A, "Wrinkling of the Facings of Sandwich Construction Subjected to Edgewise Compression."

L is half wavelength of initial surface waves in facings

If K_3 and L are considered to be unknown, then data from two specimens whose construction differs only in core thickness can be used in the following equations.

$$K_1K_2\left[\frac{1}{f_1}-\frac{1}{f_2}\right]L^4+\left[tc_2-tc_1\right]L^2+K_1\left[\frac{tc_1}{f_1}-\frac{tc_2}{f_2}\right]=0 \quad (10)$$

$$K_3=\frac{K_1tc_1}{L^3f_1}+\frac{K_1K_2L}{f_1}-\frac{tc_1}{L}=\frac{K_1tc_2}{L^3f_2}+\frac{K_1K_2L}{f_2}-\frac{tc_2}{L} \quad (11)$$

If K_3 and L are thus determined, K_o is also known. Any other construc- with the same cell size and panel bonding technique may be considered as having the same L and K_o. If the other mechanical properties and measurements are known, the edgewise compressive strength f may be computed

Panels 10 and 12 were selected for this study. Equation (10) was solved to yield L = 0.1260 inch. Equation (11) gave K_3 = 65.9. Then K_o was found to be 0.0526 from the equation defining K_3; but $\alpha = K_oL$, so α = 0.00664 inch. These values are compared with the results of surface profile measurements on panel 10 for which: L = 0.436 inch, α = 0.000328 inch, and K_o = 0.000772.

If factors M = 0.1093 and N = 1,881 are introduced into equation (9), equations (10) and (11) are altered by the substitution of MK_1 and NK_3 for K_1 and K_3, respectively. Then computed values were determined to be L = 0.0600 inch, α = 0.001351 inch, and K_o = 0.0225.

These values are compared in the following tabulation:

Factors	Measured	Calculated equations (10) and (11)	Calculated equations (10) and (11) using MK, and NK3
L (in.)	0.436	0.1260	0.0600
α (in.)	.000328	.00664	.001351
K_o	.000772	.0526	.0225

Panels 5 and 11 were selected to test the prediction qualities of this analysis. The value, L, was taken as 0.1260 inch and K_o as 0.0526. Computed from equation (9) was f. The results are presented below:

Panel No.	f calculated Equation (9) P.s.i.	f test P.s.i.
5	2,700	51,160
11	16,300	58,500

This method obviously does not yield the expected correlation between wavelengths, amplitude, and failing stresses. The lack of correlation can be partially explained by the fact that two actual panels are never exactly alike. The properties likely to show the most variation are the lateral support strength F_c and the facing waviness.

Face Dimpling Analysis

The test results in table 1 present edgewise compression data for those specimens that failed by face wrinkling only. Dimpling of the facings into the core cells, however, may occur at stresses lower than those required to cause failure of a specimen by face wrinkling. In this case, the sandwich design stress would be limited by the critical stress at which face dimpling occurs.

Forest Products Laboratory report No. 1817[8] presents the following equation for determining face dimpling stresses:

$$f = \frac{E'}{3}\left(\frac{2t}{s}\right)^{3/2} \tag{12}$$

where:

f is facing stress at which face dimpling takes place

t is facing thickness

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[8] Norris, C. B.; Kommers, W. J. Short Column Compressive Strength of Sandwich Constructions as Affected by the Size of the Cells of Honeycomb-Core Materials. Forest Products Laboratory Report No. 1817, March 1956.

s is cell size

E' is effective facing modulus of elasticity at stress f

Equation (12) cannot be solved for f directly, because E' is unknown. Therefore, the equation is solved for f as follows: If both sides of the equation are divided by the modulus of elasticity E of the facing material, then

$$\frac{f}{E} = 0.943 \left(\frac{t}{s}\right)^{3/2} \frac{E'}{E}$$

Then equating the reciprocals of both sides

$$\frac{E}{f} = \frac{1}{0.943 \left(\frac{t}{s}\right)^{3/2}} \; \frac{E}{E'}$$

If a graph is plotted with $\frac{E}{f}$ as the ordinate and $\frac{E}{E'}$ as the abscissa, this last equation represents a straight line passing through the origin with slope

$$\frac{1}{0.943 \left(\frac{t}{s}\right)^{3/2}}$$

This is illustrated in figure 9. A curve of $\frac{E}{f}$ versus $\frac{E}{E'}$ may be plotted using tangent modulus data for the facing material. The point at which this curve intersects the straight line gives the values of $\frac{E}{f}$ and $\frac{E}{E'}$, which are compatible with equation (12) for the facing thickness and cell size used. The stress f is readily computed once $\frac{E}{f}$ is known.

Equation (12) was used to compute face dimpling stresses for all 28 sandwich constructions. Of these, seven constructions showed edgewise compressive strengths greater than computed face dimpling stresses. Specimens from these panels were examined for evidence of face dimpling. Two panels exhibited marked face dimpling, while the other five showed only slight evidence once load had been removed. Data on the constructions that face dimpled are tabulated as follows:

Panel No.	Edgewise compressive strength P. s. i.	Computed face dimpling stress P. s. i.	Extent of face dimpling observed
5	51,160	38,200	Slight
8	73,740	44,500	Slight
9	71,450	44,500	Marked
13	66,600	62,500	Slight
15	60,300	57,100	Slight
16	79,400	57,100	Marked
18	69,570	66,600	Slight

As the edgewise compression specimens for these constructions were tested, face dimples were probably present at a very low load. The magnitude of the dimples increased as load was applied, until the dimples were quite noticeable at 50 to 75 percent of maximum load. The face-dimpling stresses as calculated represent some arbitrary amount of face dimpling, rather than a stress at which the facings suddenly buckle into the core cells. As loading continued, the face dimples became more and more pronounced. Finally a face wrinkle began to form, usually beginning as a wrinkle or dimple at one edge of the specimen, and slowly growing across the width of the specimen until a sudden failure occurred. Specimens from panels 9 and 16 were so severely face dimpled at the time of failure that the dimples took a permanent set. These dimples were still quite marked after all load had been released. The severely dimpled specimens exhibited multiple face wrinkles extending in horizontal lines across the specimen. As the specimens neared failure, one face wrinkle suddenly began to grow faster than the others, and spread across the facing, producing the final failure.

Correlation of Edgewise Compressive Strength and Flatwise Tensile Strength

An analysis can be made of equation (2) to determine which terms probably introduce the greatest variation in edgewise compressive strength. The term

$$A = \frac{\pi^2 t^2 E'}{12 L^2 \lambda} \left(1 + \frac{24 E_c' \lambda L^4}{\pi^4 E' t^3 t_c} \right)$$

can be approximated by eliminating the 1. The term then becomes

$$A = \frac{2E_c'L^2}{\pi^2 t t_c}$$

and is in error less than 10 percent for most specimens. The term

$$B = \frac{2E_c'LK_o}{\pi F_c t_c}$$

can be rewritten

$$B = \frac{2E_c'\alpha}{\pi F_c t_c}$$

since

$$K_o = \frac{\alpha}{L}$$

The face-waviness parameters $\underline{\alpha}$ and $\underline{L}$ have a great effect on $\underline{f}$. Methods dealing with these parameters have been discussed in the previous sections. Values of $\underline{t_c}$, $\underline{t}$, and E_c' can be measured accurately, and do not vary much in any one construction. The parameter F_c, the flatwise tensile or flatwise compressive strength, whichever is less, is the other source of variation in $\underline{f}$. The flatwise compressive strength is fairly uniform throughout a panel, since the properties of aluminum honeycomb cores are fairly uniform. The flatwise tensile strength of the bond between facings and core, however, often varies widely in bonded panels. Variables such as surface cleaning and preparation, press pressure, initial adhesive proportions, and curing time and temperature have a profound effect on a panel's flatwise tensile strength. As a result, it is difficult to obtain two otherwise identical panels with the same flatwise tensile strength.

The flatwise strength, F_c, can be correlated with edgewise compressive strength by graphical methods. The sandwich facing is considered to be a laterally supported column of thickness $\underline{t}$ and elastic modulus $\underline{E'}$. Failure is caused by collapse of the lateral supports (compressive core failure), or detachment of the column from the lateral supports (tensile core or core-to-facing-bond failure). The stress $\underline{f}$ producing lateral support failure is related to the strength of the lateral support system F_c by the stiffness of the column. Therefore, edgewise compressive strength $\underline{f}$ was plotted versus lateral support strength $\underline{F_c}$ for each facing material and facing thickness.

Graphs of edgewise compressive strength versus flatwise tensile (or compressive) strength are represented in figures 10, 11, and 12.

Figure 10 was drawn for sandwich with clad 2024-T3 aluminum facings, figure 11 expresses values for 7075-T6 clad aluminum facings, and figure 12 shows curves for sandwich with 17-7PH (TH1050) stainless steel facings. The curve for brazed sandwich in figure 12 was plotted using Convair data.[9] For each material, a family of curves was drawn representing several facing thicknesses. The curves were plotted through the data by eye. Experience showed that a curve with a knee in it fitted the plotted points best. For each facing material, more flatwise strength was needed to support the thin facings than to support the stiffer thicker facings. For a given flatwise strength, the thicker facings were able to carry more edgewise compressive load than the thinner facings. The edgewise compressive strength at zero flatwise strength was taken to be the Euler stress for an unsupported facing. A horizontal line, representing the yield strength of the facing material in edgewise compression, was drawn on each graph. The intersection of the curves with this line furnished the flatwise strength necessary to develop the yield strength of the facings in edgewise compression. These values are presented in table 3.

Design Method

Table 3 provides the information necessary for a method of design for face wrinkling. Once the facing material and thickness have been selected, a core is chosen with a flatwise compressive strength slightly greater than that designated in the table. A core-to-facing bond is selected that is at least as strong as the flatwise compressive strength.

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[9] Stainless Steel Sandwich Specimens 17-7PH Condition TH1050 Column Compression Skin-Buckle Failures. Convair Report. September 9, 1958.

In this way, the sandwich is designed to resist face wrinkling until facing stresses have passed the yield point. The completed design, of course, would consider all other possible modes of failure.

Edgewise Compressive Strength as a Function of Elastic Moduli

Edgewise compressive strength f has been related to the sandwich elastic moduli by the equation[10]

$$f = K\,(EE_cG_c)^{1/3}$$

where:

f is edgewise compressive strength

E is facing modulus of elasticity

E_c is flatwise compressive core modulus of elasticity

G_c is core shear modulus[11]

K is a constant

Calculation of experimental values of the constant K is summarized in table 4. Figure 13 is a graph of edgewise compressive strength plotted against $(E\,E_cG_c)^{1/3}$. Points were plotted for specimens for which core and facing stresses were in the elastic range at edgewise compression failure. In this graph, K is the slope of a line passing through the origin and any data point. Values of K varied from 0.0244 to 0.0576 for the nine panels calculated. A straight line representing a value of K of 0.044 was calculated by least squares and drawn through the data. Table 4 shows that experimental values of K increased as

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[10] Hoff, N. J. and Mautner, S. E. The Buckling of Sandwich-Type Panels. Institute of the Aeronautical Sciences, February 1945.

[11] Values of G_c were taken from Forest Products Laboratory Report No. 1849, September 1955.

facing thickness increased. All the points plotted represented sandwich with low core-to-facing bond strengths (see table 1), which meant that edgewise compressive strength increased with increasing facing thickness, if flatwise tensile strength remained constant. This conclusion was also derived from the curves of edgewise compressive strength versus flatwise tensile strength in the previous section.

Conclusions

Several theoretical approaches revealed some correlation between computed and experimental values of stress at which sandwich facings wrinkled. Excessive scatter in the data showed that the theoretical approaches have not led to satisfactory design methods.

Test data on sandwich with a range of core or core-to-facing bond strength can be used to determine core or bond strengths necessary to support facings, so that they will not wrinkle at any arbitrary stress level.

Table 1.--Mechanical properties of sandwich panels

Panel	Core properties					Facing properties				Sandwich properties		
	Cell size	Foil thickness	Core thickness	Compression: modulus of elasticity	Flatwise compressive strength	Material	Facing thickness	Compression: modulus of elasticity	Yield strength in compression	Core to facing bond adhesive	Flatwise tensile strength	Edgewise compressive strength
1	2	3	4	5	6	7	8	9	10	11	12	13
	In.	In.	In.	10³ P.s.i.	P.s.i.		In.	10⁶ P.s.i.	P.s.i.		P.s.i.	P.s.i.
											190	
											220	44,050
						Alclad					230	38,380
					530	2024-T3				Nitrile	230	36,580
1	1/8	.001	.507	250	480	Aluminum	.012	[1]5.80	39,000	Phenolic	220	33,050
					460	Alloy					110	36,250
					500						190	24,360
Ave.					490						200	35,450
											190	
											200	
											160	
										Nitrile	120	28,100
2	1/8	.001	.506	250		2024-T3	.018	[1]10.40	39,000	Phenolic	30	23,300
											50	35,200
					570						40	30,400
					600						80	23,400
					520						70	32,200
Ave.					560						110	28,800
											50	
											50	
											60	
											70	
										Nitrile	70	
3	1/4	.002	.505	201		2024-T3	.012	10.65	39,000	Phenolic	50	18,200
											50	18,500
					460						60	19,700
					420						70	10,630
					320						40	13,830
Ave.					400						60	16,170
												14,340
					180							20,090
					170					Nitrile		13,250
4	1/4	.002	2.016	177	170	2024-T3	.012	10.65	39,000	Phenolic	50	13,820
					190						30	19,530
Ave.					180						40	16,210
											220	
											140	
											190	
										Vinyl	130	48,480
										Phenolic	260	46,950
5	1/4	.002	2.018	216	440	2024-T3	.012	[1]1.15	39,000		190	52,800
					360						160	53,950
					380						160	52,450
					460						170	52,350
Ave.					410						180	51,160
											120	
											110	
											150	
											120	
										Epoxy	80	19,400
6	1/4	.003	2.014	373		2024-T3	.012	10.65	39,000	Resin	160	21,100
					800						170	27,000
					780						140	21,800
					760						160	24,600
					750						90	24,000
Ave.					770						130	23,000
											190	
											140	
											160	
										Nitrile	100	
7	1/4	.002	1.993	201		2024-T3	.020	10.65	39,000	Phenolic	40	25,500

Table 1.--Mechanical properties of sandwich panels (continued)

Panel	Core properties					Facing properties				Sandwich properties		
	Cell size	Foil thickness	Core thickness	Compression modulus of elasticity	Flatwise compressive strength	Material	Facing thickness	Compression modulus of elasticity	Yield strength in compression	Core to facing bond adhesive	Flatwise tensile strength	Edgewise compressive strength
1	2	3	4	5	6	7	8	9	10	11	12	13
	In.	In.	In.	10^3 P.s.i.	P.s.i.		In.	10^6 P.s.i.	P.s.i.		P.s.i.	P.s.i.
											30	16,200
					370						100	21,100
					350						70	31,400
					360						80	22,600
					350						20	31,000
Ave.					360						90	24,600
					450							75,250
8	1/4	.002	2.003	[1]0	470	2024-T3	.020	[1]0.025	39,000	Phenolic	480	71,280
					460						490	74,150
					480					Vinyl	440	74,250
Ave.					470						470	73,740
											580	70,400
											520	65,050
					400					Epoxy	630	80,650
9	1/4	.002	1.999	[1]108	410	2024-T3	.020	[1].050	39,000	Resin	560	74,700
					410						440	75,850
					430						520	62,050
Ave.					410						540	71,450
											170	
											160	
						Alclad				Nitrile	200	
10	1/4	.002	.509	201		7075-T6	.012	10.45	65,000	Phenolic	120	13,930
						Aluminum					100	8,700
						Alloy					30	12,800
											60	9,340
											30	9,170
					450						10	14,380
Ave.					450						100	11,400
											90	62,700
					410						110	57,600
					450						130	65,800
					440					Nitrile	140	66,650
11	1/4	.002	.504	201	450	7075-T6	.020	[1]7.20	65,000	Phenolic	160	39,750
Ave.					440						130	58,500
												17,500
											60	26,500
					340					Nitrile	130	12,400
12	1/4	.002	2.003	211	530	7075-T6	.012	10.45	65,000	Phenolic	160	25,000
					380						140	22,000
					430						110	24,800
Ave.					420						120	21,400
					430							
					510							
					490					Vinyl		69,500
13	1/4	.002	2.004	[1]0	480	7075-T6	.016	[1]2.20	65,000	Phenolic	430	63,800
Ave.					480						430	66,600
												38,600
										Epoxy		52,500
14	1/4	.003	2.009	400		7075-T6	.012	[1]9.30	65,000	Resin	420	35,500
					770						320	59,500
					790						380	38,500
					760						330	70,000
Ave.					770						360	49,100
												59,700
					240							61,300
					220					Vinyl		54,600
15	3/8	.002	2.001	[1]82	220	7075-T6	.016	[1]4.60	65,000	Phenolic		59,000
					230						230	66,800
Ave.					230						230	60,300
												73,950
					410					Epoxy	530	83,850
16	3/8	.003	2.002	[1]0	410	7075-T6	.016	[1]1.00	65,000	Resin	440	84,650

Table 1.--Mechanical properties of sandwich panels (continued)

Panel	Core properties					Facing properties				Sandwich properties		
	Cell size	Foil thickness	Core thickness	Compression modulus of elasticity	Flatwise compressive strength	Material	Facing thickness	Compression modulus of elasticity	Yield strength in compression	Core to facing bond adhesive	Flatwise tensile strength	Edgewise compressive strength
1	2	3	4	5	6	7	8	9	10	11	12	13
	In.	In.	In.	10^3 P.s.i.	P.s.i.		In.	10^6 P.s.i.	P.s.i.		P.s.i.	P.s.i.
					430						430	74,750
					430						350	80,200
Ave.					420						440	79,490
											90	
											170	
											150	
											130	
										Nitrile	160	54,100
17	1/4	.002	2.009	215		7075-T6	.032	[1]3.40	65,000	Phenolic	170	55,200
					430						150	67,100
					340						140	64,400
					420						180	61,000
					450						210	70,600
Ave.					410						160	62,100
											310	
					220					Vinyl	300	
18	3/8	.002	2.011	[1]0	180	7075-T6	.032	[1]1.40	65,000	Phenolic	340	73,300
					180						340	66,200
					190						300	69,200
Ave.					190						320	69,570
											160	
											180	
										Epoxy	180	
19	3/8	.002	2.009	136		7075-T6	.032	[1]7.40	65,000	Resin	180	
					280						200	58,000
					260						180	66,900
					290						240	65,500
					270						220	66,400
Ave.					280						190	64,200
											90	34,000
						17-7PH				Nitrile	120	32,600
											140	
20	3/8	.002	2.018	229	230	TH1050	.015	30.0	162,000	Phenolic	100	34,300
											100	
					230	Stainless					60	27,600
					240	Steel					50	37,300
					230						20	36,400
											100	
Ave.					230						90	33,700
											250	
											410	
										Vinyl	340	
											310	93,900
21	3/8	.002	2.016	[1]0		17-7PH	.015	[1]27.8	162,000	Phenolic	330	
					250						320	96,300
					230						340	87,400
					240						350	83,400
					240						290	90,900
Ave.					240						330	90,400
											360	
											350	133,000
											360	126,000
					260					Epoxy	350	132,000
22	3/8	.002	2.010	[1]0	260	17-7PH	.015	[1]27.3	162,000	Resin	370	95,500
					290						370	79,100
					290						330	71,500
Ave.					280						360	106,200
											210	
											160	
											130	
											160	
										Nitrile	150	145,000
23	3/8	.003	2.014	194		17-7PH	.031	[1]27.6	162,000	Phenolic	130	119,000
					380						150	55,200
					420						140	73,600
					360						160	76,900
					340						180	134,000
Ave.					380						160	100,600

Table 1.--Mechanical properties of sandwich panels (continued)

Panel	Core properties					Facing properties				Sandwich properties		
	Cell size	Foil thickness	Core thickness	Compression modulus of elasticity	Flatwise compressive strength	Material	Facing thickness	Compression modulus of elasticity	Yield strength in compression	Core to facing bond adhesive	Flatwise tensile strength	Edgewise compressive strength
1	2	3	4	5	6	7	8	9	10	11	12	13
	In.	In.	In.	10^3 P.s.i.	P.s.i.		In.	10^6 P.s.i.	P.s.i.		P.s.i.	P.s.i.
											450	
											480	
											480	
											460	
										Vinyl	450	152,500
24	3/8	.003	2.020	[1]0		17-7PH	.031	[1]20.0	162,000	Phenolic	480	130,000
					440						450	151,000
					440						460	164,000
					450						440	174,600
					330						480	154,300
Ave.					420						460	154,400
											510	
											500	
											540	
										Epoxy	590	
25	3/8	.003	2.018	[1]0		17-7PH	.031	[1]14.3	162,000	Resin	520	183,000
											520	182,000
					410						580	176,000
					400						580	185,000
					450						560	184,800
					400						520	198,000
Ave.					420						540	185,000
											110	
											160	
											160	
										Nitrile	160	
26	3/8	.005	2.023	340		17-7PH	.015	30.0	162,000	Phenolic	150	
											150	31,800
					580						120	31,600
					570						70	40,500
					510						110	37,500
Ave.					550						130	35,400
											600	
											600	
											570	
											560	124,000
										Vinyl	300	103,000
27	3/8	.005	2.025	[1]274		17-7PH	.015	[1]27.6	162,000	Phenolic	410	114,500
					810						410	83,700
					870						370	107,700
					860						370	49,500
Ave.					850						470	97,100
											420	
											600	
											540	
										Epoxy	590	
28	3/8	.005	2.019	[1]222		17-7PH	.015	[1]26.4	162,000	Resin	560	
											650	109,600
					660						680	118,700
					720						640	131,400
					730						680	117,800
					680						690	128,000
Ave.					700						600	121,100

---

[1] Effective elastic modulus.

(Sheet 4 of 4)

Table 2.--Properties and calculation of edgewise compressive strength for ten sandwich panels

Panel No.	Specimen properties							Face waviness properties			Stress calculations					Stress comparison P calc/P test
	Core			Facings		Sandwich										
	Cell size	Thickness	Compression modulus of elasticity	Facings thickness	Compression modulus of elasticity	Edgewise compressive strength	Flatwise tensile strength	Half wavelength L	Amplitude α	K_o	A	B	$\frac{f\ test}{A}$	$\frac{f\ test_B}{A}$	Calculated edgewise compressive strength $\frac{MA}{1 + NB}$	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	In.	In.	10^3 P.s.i.	In.	10^6 P.s.i.	P.s.i.	P.s.i.	In.	In.	In.	10^6 P.s.i.				P.s.i.	
SANDWICH WITH ALUMINUM FACINGS: M = 0.1093, N = 1.881																
2	1/8	0.510	250	.018	10.65	24,900	110	0.438	.000311	.000723	1.007	0.938	0.0232	0.0218	42,700	1.715
3	1/4	.505	201	.012	10.65	16,170	60	.340	.000312	.000923	.792	1.430	.0204	.0292	23,500	1.453
7	1/4	1.997	201	.020	10.65	24,600	90	.388	.000221	.000570	.179	.1514	.1373	.0208	15,280	.621
10	1/4	.509	201	.012	10.45	11,420	90	.436	.000328	.000772	1.273	.951	.00895	.00850	50,000	4.370
14	1/4	2.016	400	.012	10.45	38,500	360	.238	.000207	.000895	.214	.0747	.180	.01348	20,500	.532
SANDWICH WITH STAINLESS STEEL FACINGS: M = 0.612, N = 16.80																
20	3/8	2.017	229	.015	30.0	30,100	90	.540	.000478	.001079	.471	.485	.0643	.0312	31,600	1.050
22	3/8	2.010	[1]0	.015	30.0	82,000	350	.332	.000407	.001274	.0548	0	.478	0	33,500	.409
26	3/8	2.024	340	.015	30.0	36,500	130	.379	.000576	.001593	.368	.485	.0996	.0485	24,600	.674
27	3/8	2.026	[1]274	.015	30.0	80,300	470	.346	.000258	.000737	.270	.0469	.1742	.01408	92,400	1.150
28	3/8	2.017	[1]222	.015	30.0	109,600	600	.359	.000555	.001539	.238	.0643	.1693	.0297	70,400	.642

[1] Effective elastic modulus.

Table 3.--Flatwise tensile strengths necessary to develop yield strength of facings in edgewise compression

Facing material	Edgewise compressive yield strength	Facing thickness	Required flatwise tensile strength
	P.s.i.	In.	P.s.i.
Clad Aluminum 2024-T3	39,000	.020	160
		.012	200
Clad Aluminum 7075-T6	65,000	.032	225
		.020	250
		.016	300
		.012	540
Stainless Steel 17-7PH (TH1050)	162,000	.031	400
		.015	800

Table 4.--Comparison of elastic properties and edgewise compressive strength for sandwich

Panel No.	Facing modulus of elasticity E	Core modulus of elasticity E_c	Core shear modulus G_c	$(EE_cG_c)^{1/3}$	Edgewise compressive strength f	K	Facing thickness t
	10^6 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	1,000 P.s.i.	P.s.i.		In.
10	10.45	201	47.9	466	11,400	0.0244	.012
6	10.65	373	87.8	702	23,000	.0328	.012
3	10.65	201	47.9	468	16,170	.0346	.012
4	10.65	177	47.9	450	16,210	.0362	.012
26	30.0	340	75.2	920	35,400	.0385	.015
12	10.45	211	47.9	474	21,400	.0452	.012
7	10.65	201	47.9	469	24,600	.0525	.020
2	10.40	250	59.4	535	28,800	.0538	.018
20	30.0	229	29.1	585	33,700	.0576	.015

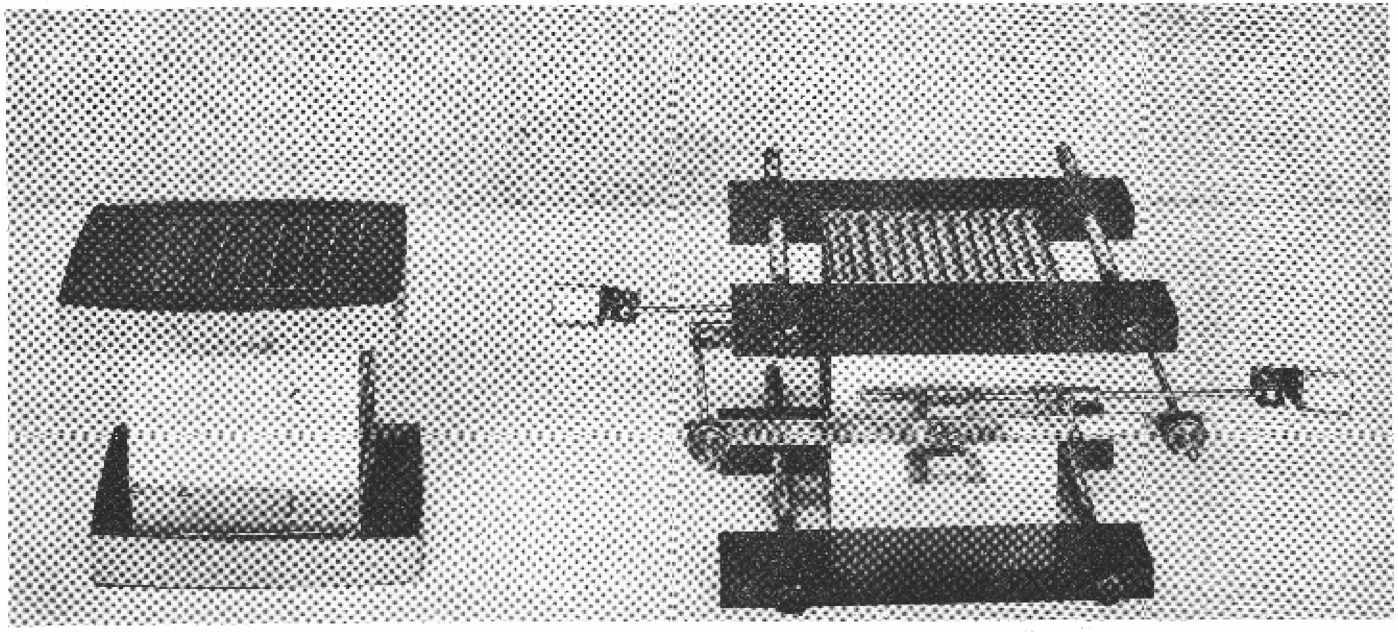

Figure 1. --Edgewise compression specimens showing end restraints and marten's mirror compressometer.

ZM 116 172

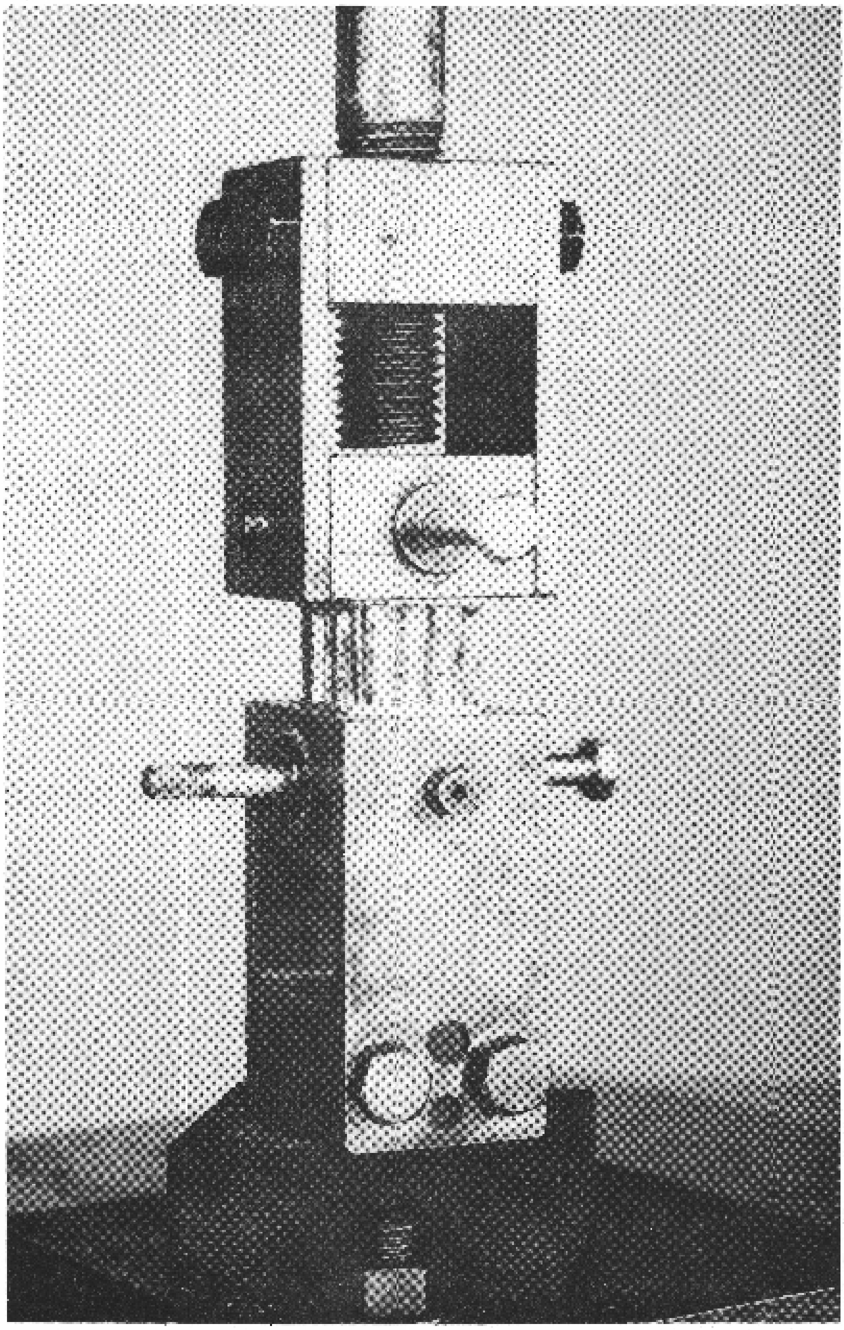

Figure 2. --Flatwise tension specimen and loading apparatus.

ZM 116 171

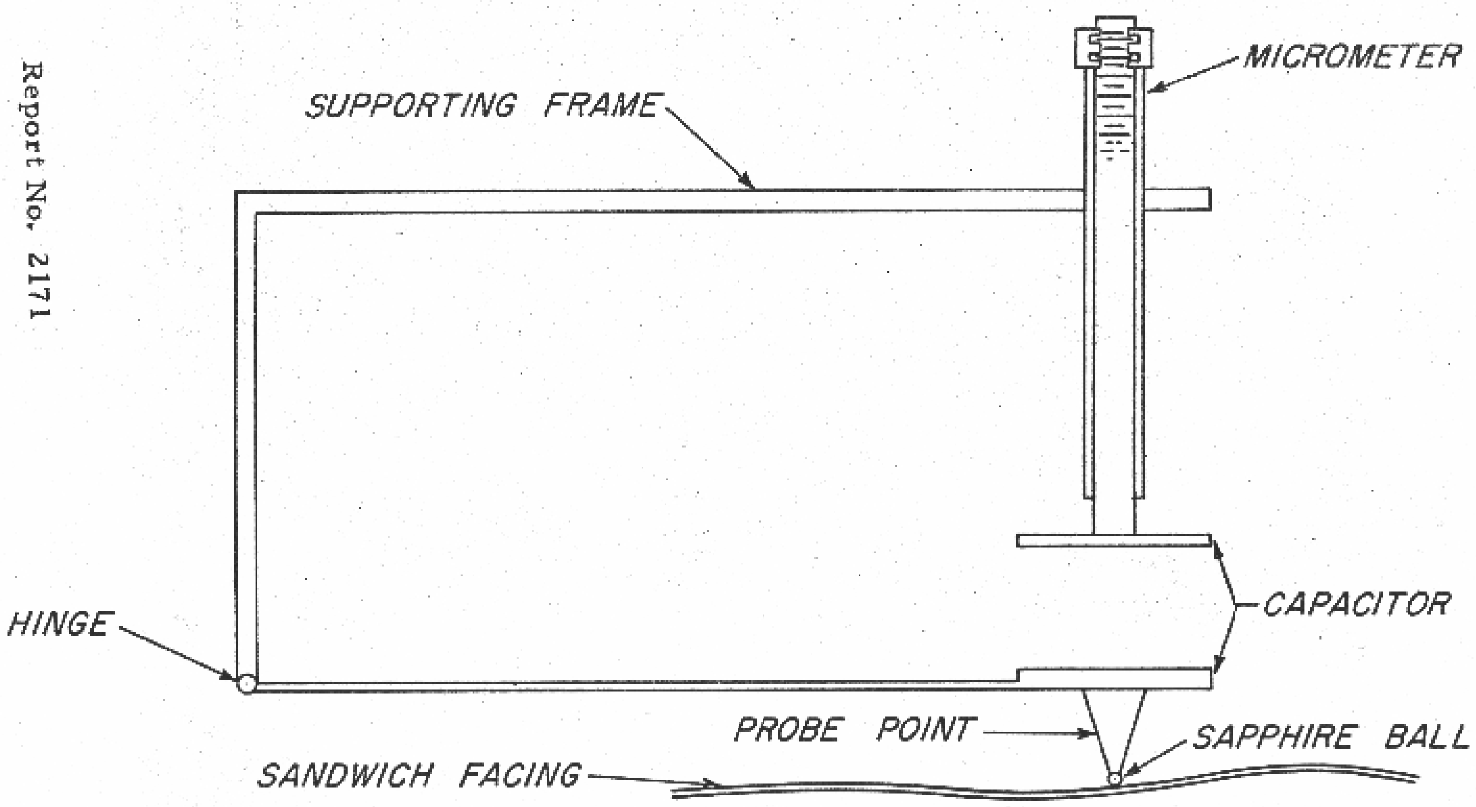

Figure 3. --Sketch of capacitor assembly and surface profile probe.

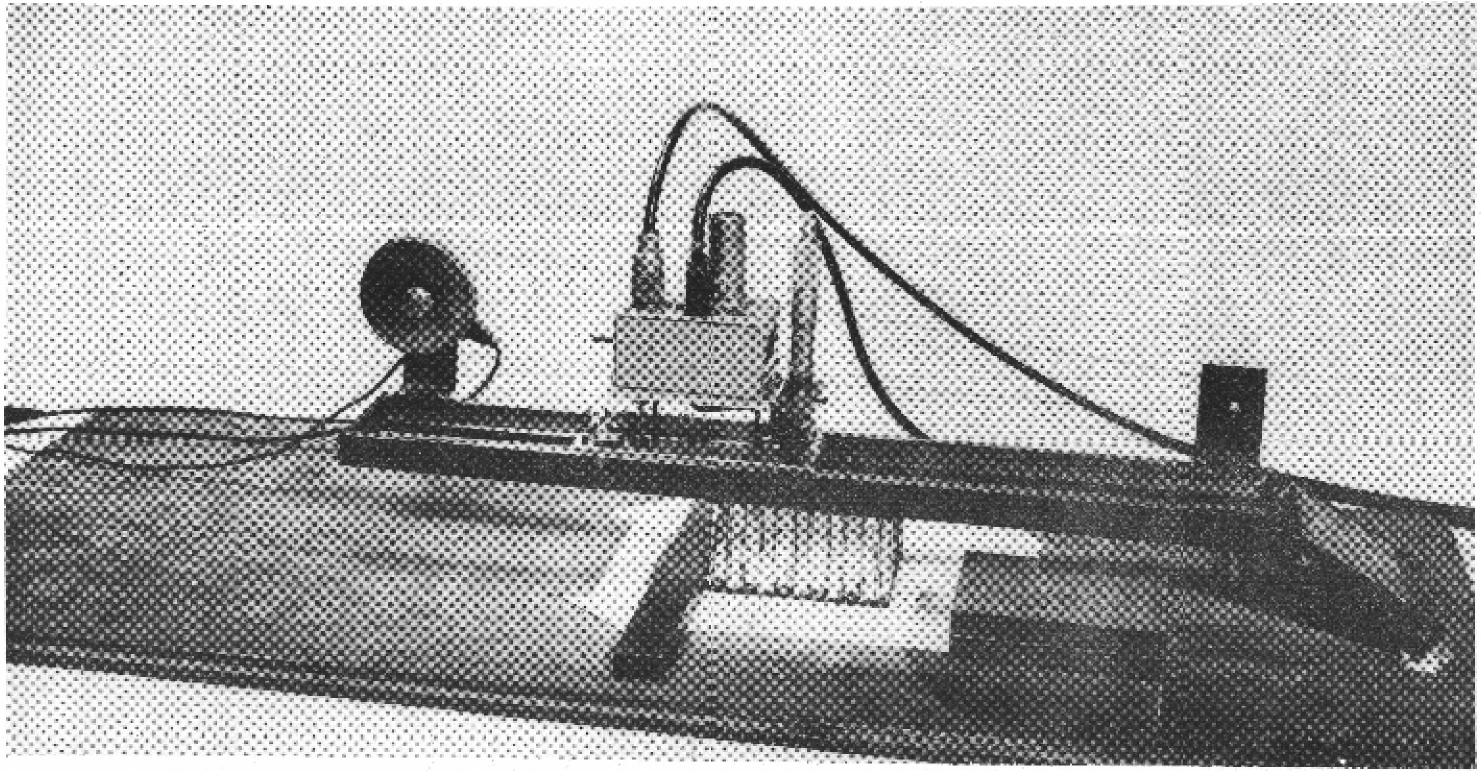

Figure 4. --Apparatus for determining initial facing irregularities of sandwich edgewise compression specimens. Gage block in foreground.

ZM 116 340

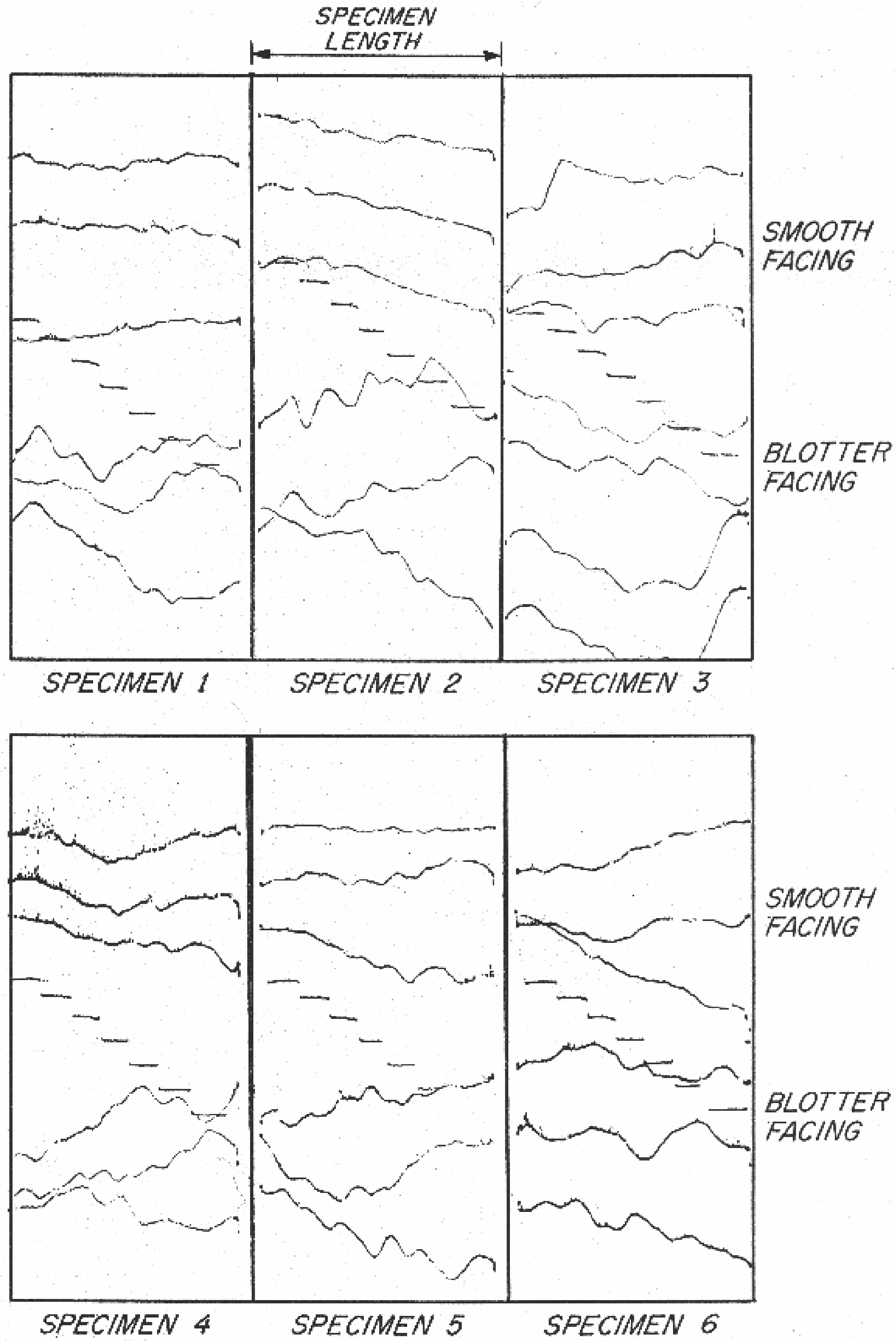

Figure 5.--Facing profiles for specimens of sandwich panel 13 showing calibration steps of .0005 inch.

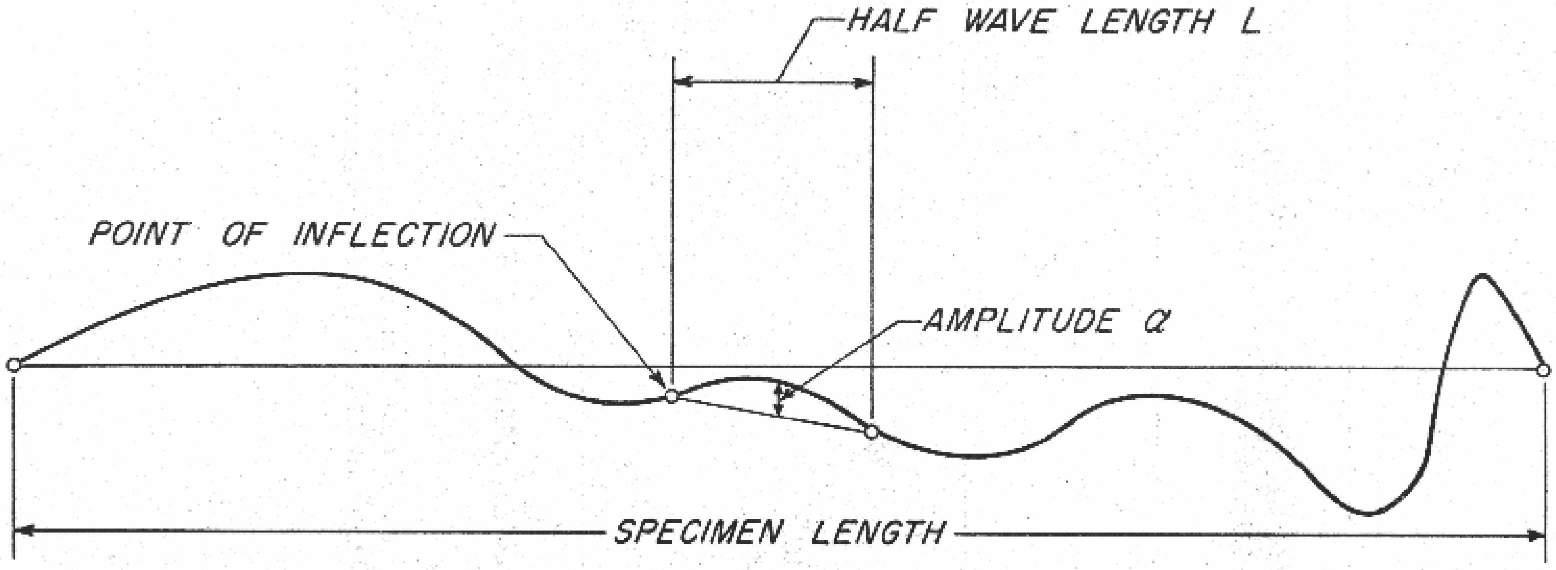

Figure 6. --Typical surface profile of a facing of an edgewise compression specimen-expanded vertical scale.

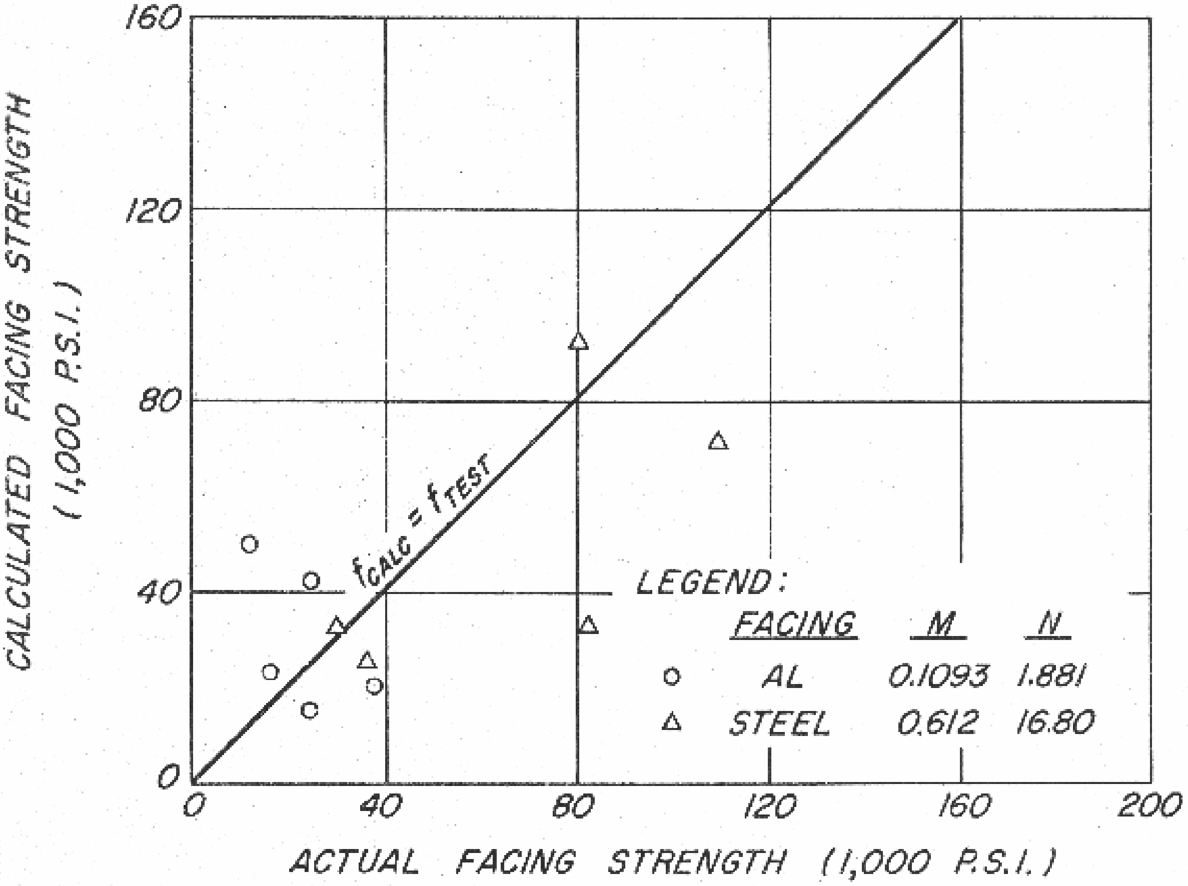

Figure 7. --Comparison of test facing stress with stress calculated by equation 3 using values of M and N determined by least squares.

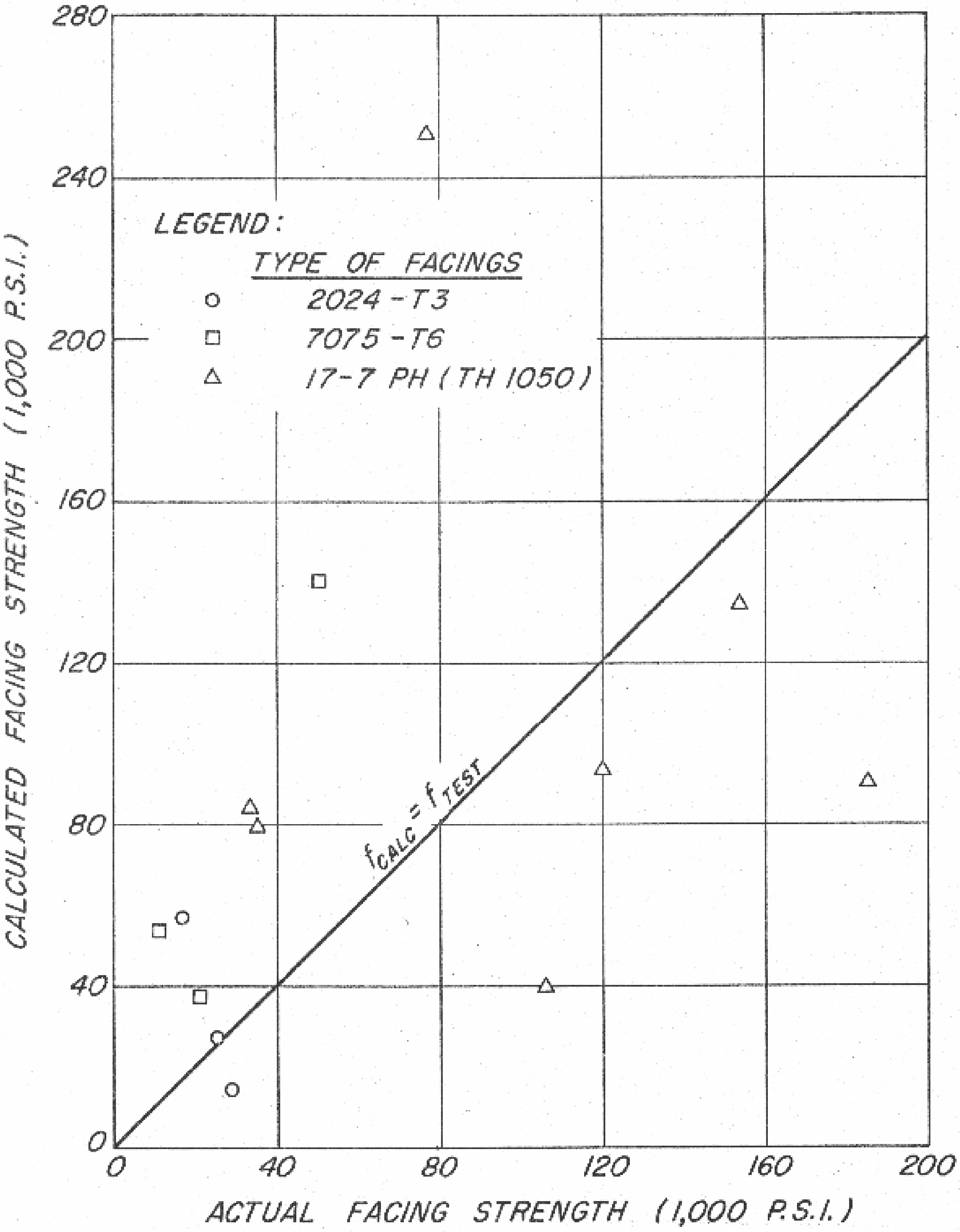

Figure 8. --Comparison of test facing stress with stress calculated from equation 6.

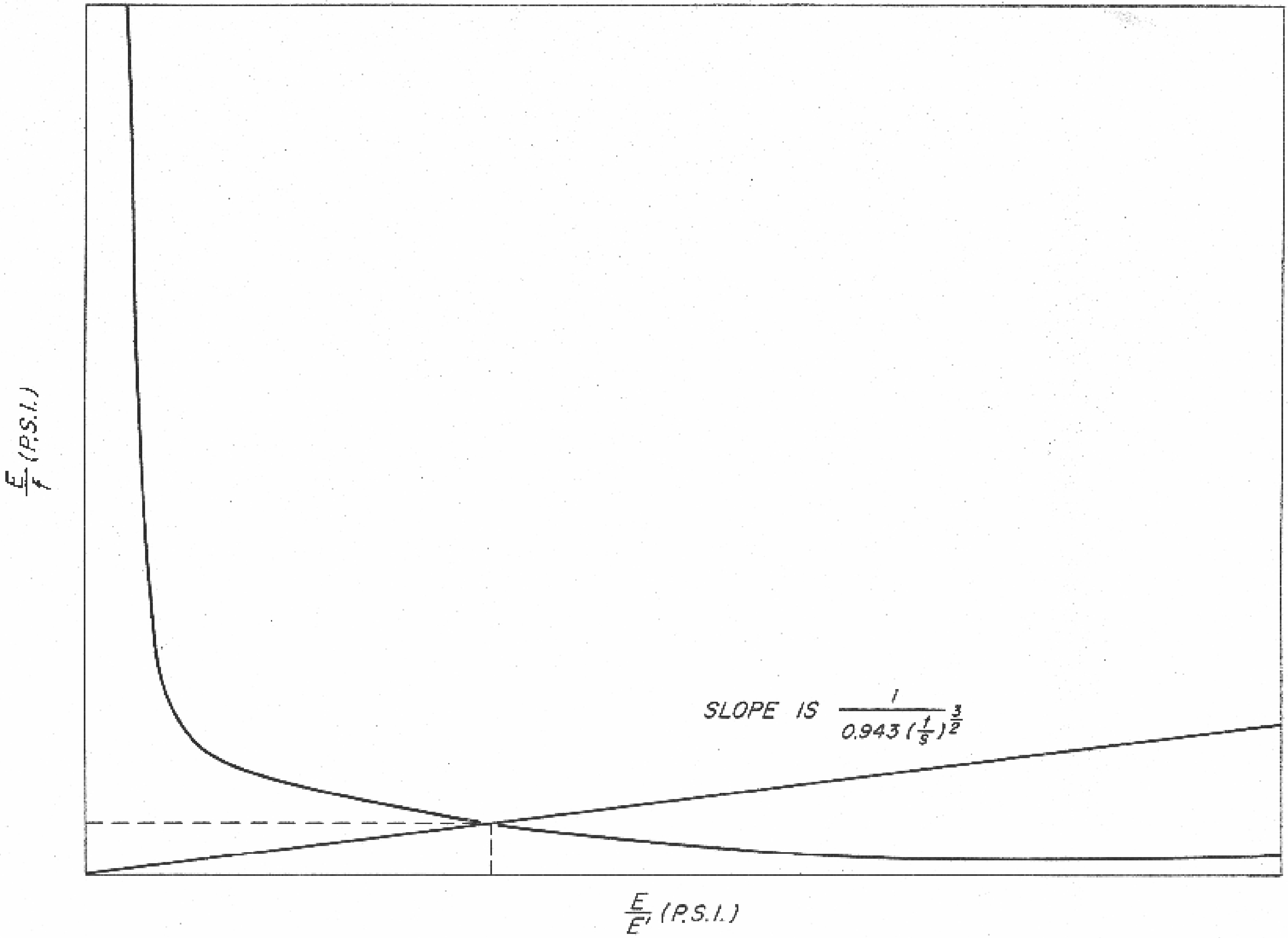

Figure 9. --Sketch illustrating method of determining face dimpling stresses for sandwich subjected to edgewise compression.

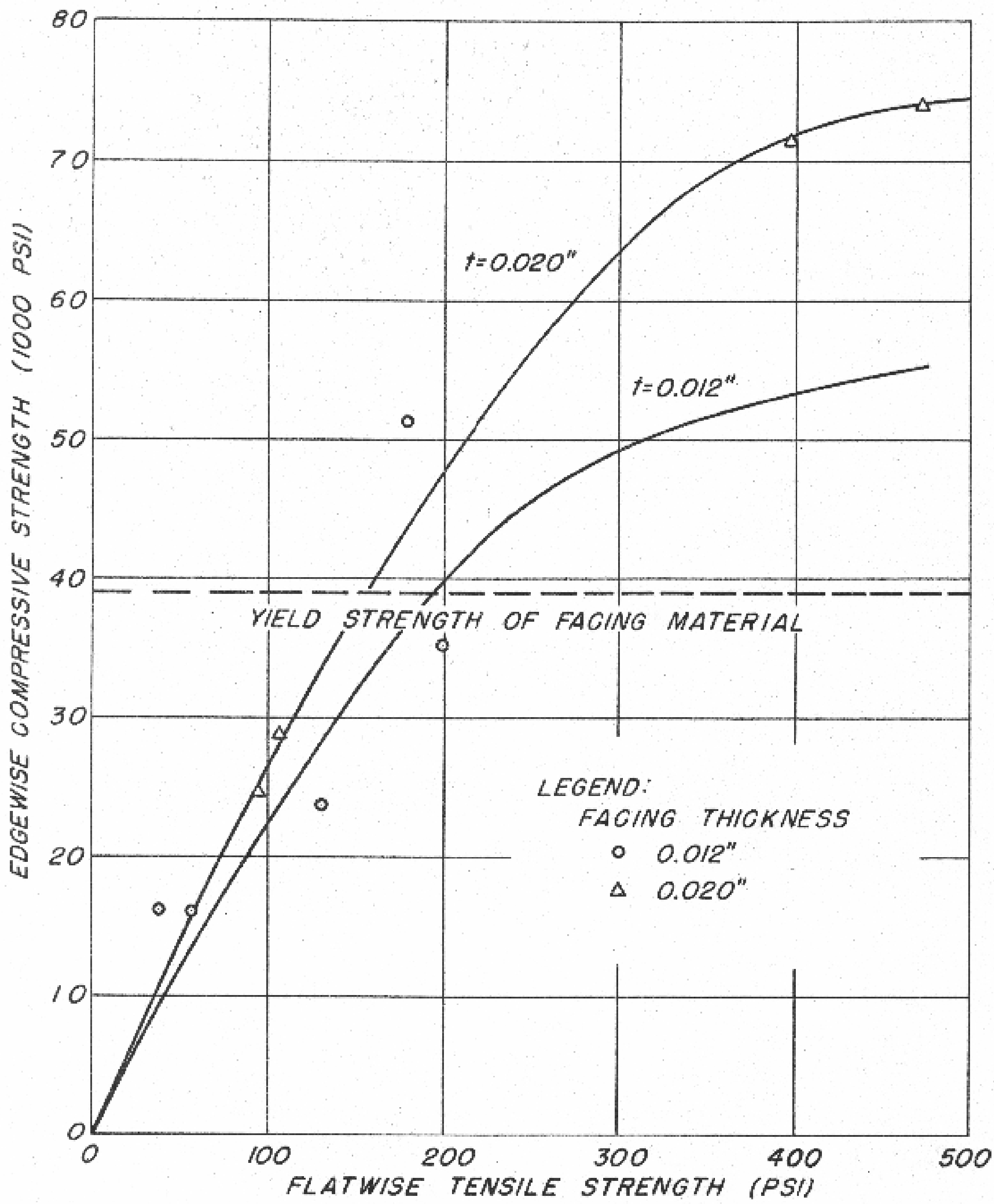

Figure 10. --Variation of edgewise compressive strength of sandwich with clad 2024-T3 aluminum facings with changes in flatwise tensile strength and facing thickness

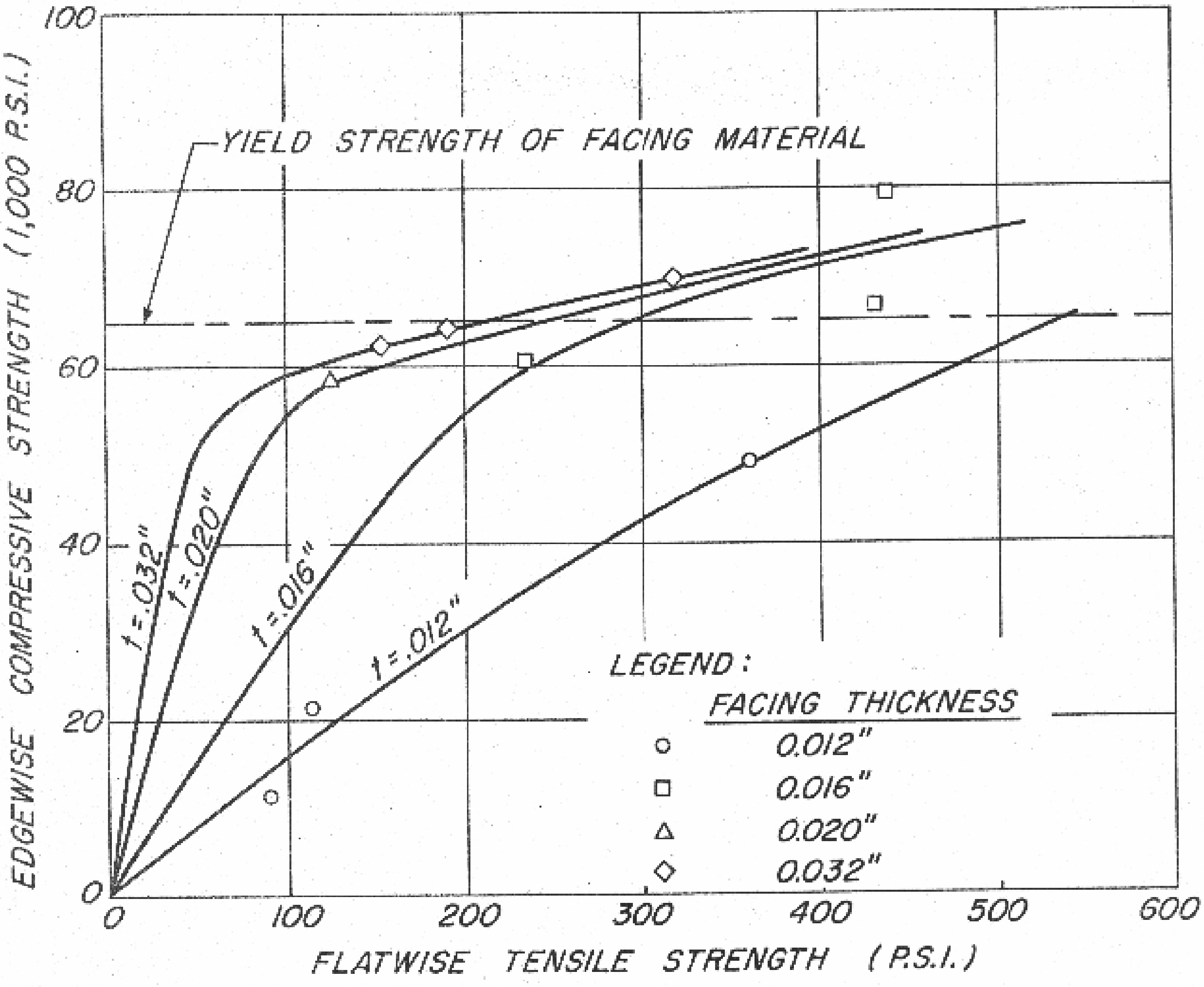

Figure 11. --Variation of edgewise compressive strength of sandwich with clad 7075-T6 aluminum facings with changes in flatwise tensile strength and facing thickness.

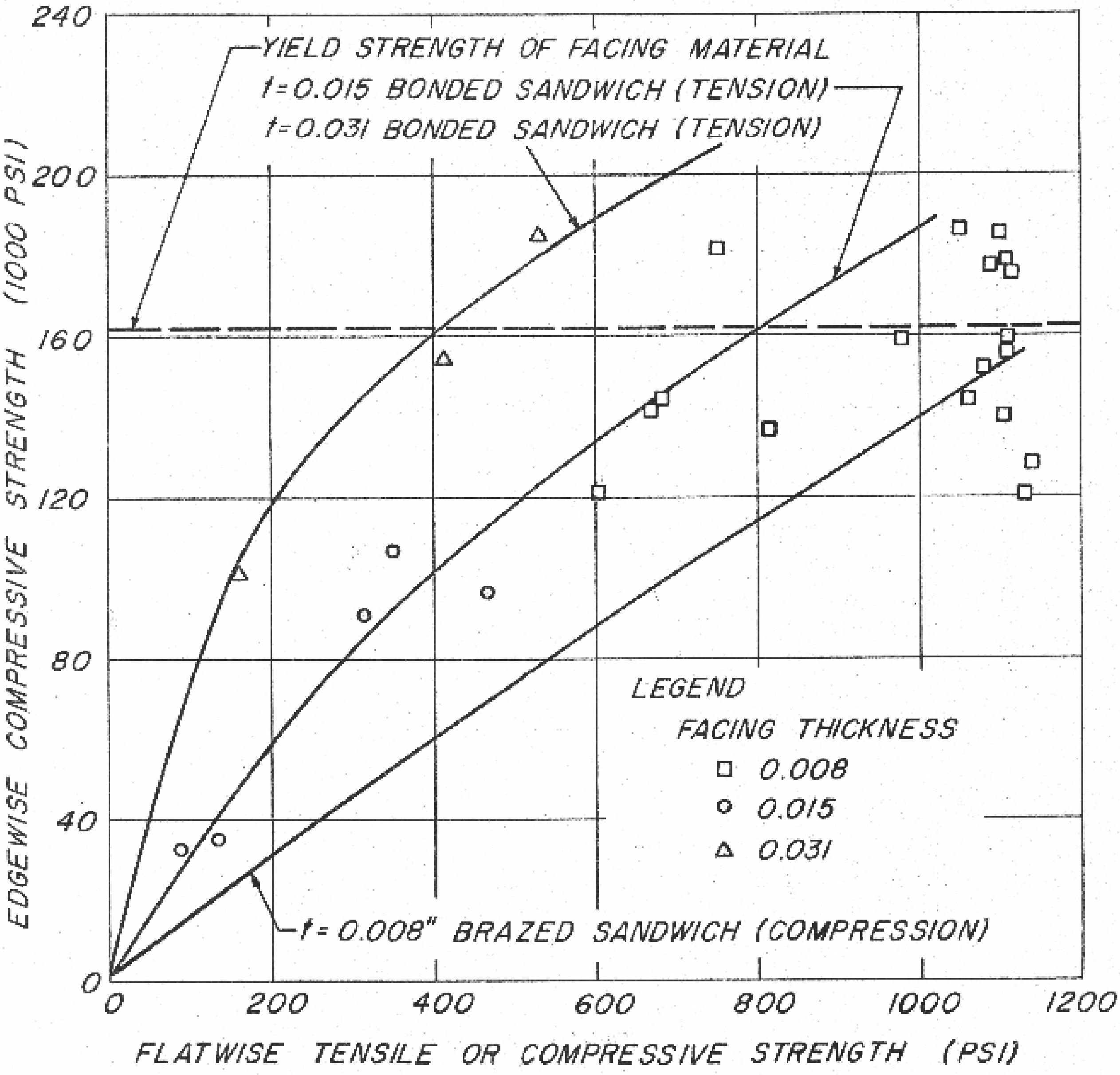

Figure 12. --Variation of edgewise compressive strength of sandwich with 17-7PH (TH1050) stainless steel facings with changes in flatwise strength and facing thickness.

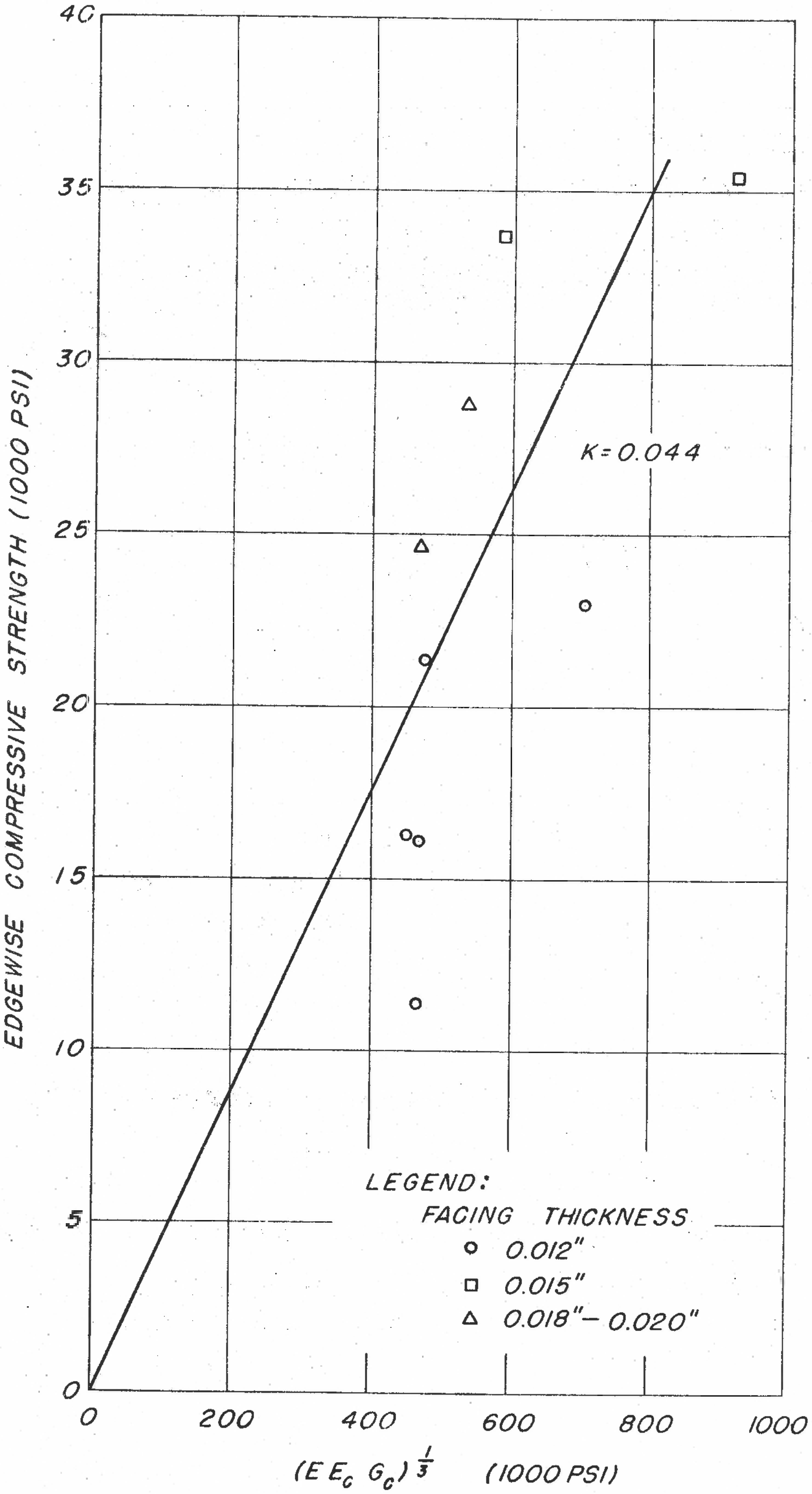

Figure 13. --Edgewise compressive strength plotted as a function of elastic moduli.