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TECHNICAL NOTE 4348

EFFECT OF TEMPERATURE ON DYNAMIC MODULUS OF
ELASTICITY OF SOME STRUCTURAL ALLOYS

By Louis F. Vosteen

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Langley Field, Va.



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ELASTICITY OF SOME STRUCTURAL ALLOYS

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SUMMARY

The effect of temperature on Young's modulus of elasticity was determined for 2024-T3 and 7075-T6 aluminum alloys, AZ31A-0 magnesium alloy, RS-120 titanium alloy, and type 303 stainless steel by flexural vibration tests of beam specimens at temperatures from room temperature to 900° F. The test frequencies were varied from 40 to 550 cycles per second. The results are compared with values of moduli obtained from conventional stress-strain tests. The data show that the dynamic modulus decreases with temperature but does not decrease as rapidly as the static modulus. It is shown that the difference between the static modulus and dynamic modulus is due to internal friction and cannot be attributed to creep.

INTRODUCTION

The effect of temperature on the properties of aircraft structural materials has become increasingly important in aircraft design. A property which is temperature dependent is Young's modulus of elasticity. The decrease in modulus with increasing temperature, as indicated by conventional stress-strain tests, is well established. As has been noted by previous investigators (for example, refs. 1 and 2), values of modulus determined by dynamic testing techniques also decrease with temperature but do not show so great a decrease as those indicated by stress-strain tests.

The purpose of the present investigation was to determine values of dynamic modulus at elevated temperatures for some aircraft structural materials by means of flexural beam vibration tests. Although dynamic-modulus values have been obtained by previous investigators for numerous materials, the frequencies employed in the tests generally ranged upward from about 900 cycles per second, well above those usually encountered in aircraft structural vibrations. Inasmuch as Young's modulus is of importance in aeroelastic analyses, it was thought advisable to obtain

information at frequencies more representative of aircraft vibrations. In the present investigation the beams were proportioned so that the frequencies of the tests were considerably closer to the usual airframe frequencies. The tests were conducted over a range of frequencies by resonant vibration of several natural modes.

Specimens of 2024-T3 and 7075-T6 aluminum alloys, AZ31A-0 magnesium alloy, RS-120 titanium alloy, and type 303 stainless steel were tested at temperatures ranging from room temperature to 900° F. The results of these tests are compared with moduli determined from conventional tensile and compressive stress-strain tests and with previously obtained dynamic moduli. The data are analyzed in detail in an effort to identify the source of the discrepancy between static and dynamic moduli. In addition, the question of which value of modulus is appropriate for vibration and flutter analyses is discussed.

SYMBOLS

A	area of beam cross section, sq in.
E	Young's modulus of elasticity, psi
E ₀	room-temperature value of modulus, psi
f _i	frequency of ith mode of vibration, cycles/sec
g	acceleration due to gravity, in./sec ²
λ _i	beam frequency function
l	beam length, in.
T	temperature, °F
ΔT	temperature difference, °F
α	coefficient of thermal expansion, $\frac{\text{in.}}{(\text{in.})(\text{°F})}$
γ	specific weight, lb/cu in.
I	cross-sectional moment of inertia, in. ⁴

TEST PROCEDURE

Test Specimens and Instrumentation

The test specimens were beams of rectangular cross section. The 2024-T3 and 7075-T6 aluminum-alloy and AZ31A-0 magnesium-alloy beams were machined from 3/8-inch-thick plate material and were $1\frac{1}{2}$ inches wide and 36 inches long. The type 303 stainless-steel and RS-120 titanium-alloy beams were taken from 1/4-inch-thick plate and were 1 inch wide and 30 inches long. The longitudinal axes of the beams were parallel to the rolling direction of the material.

The beams were instrumented with two Nichrome foil strain gages for detecting the vibratory motion of the beam and three thermocouples for measuring specimen temperature. The thermocouples were placed symmetrically about the center of the beam. The strain gages were positioned so as to be near the points of maximum strain for the higher modes of vibration. The location of the instrumentation is shown in figure 1.

Method of Test

Two beam specimens (designated A and B) of each material were tested. The beams were suspended in an oven by two lightweight flexible wires at points 0.167 from each end. Suspension at these points appeared to have the least overall effect on all the modes tested. The specimens were heated uniformly by raising the oven temperature to the desired level. A beam was considered to be at test temperature when the three thermocouples on the beam indicated a stable temperature condition and the temperatures agreed within 5° F.

The beams were vibrated in the horizontal direction about the smallest inertial axis by means of pulsating air jets which impinged alternately on opposite sides of the beams near one end. The cooling effect of the jets was found to be negligible during the short time required to establish resonance. The response of the beam was indicated by the output of the two foil gages which were connected to adjacent arms of a Wheatstone bridge circuit. The resonant frequency was taken as the frequency at which maximum strain amplitude was detected. Calculations indicate that outer-fiber strains were less than 30 $\mu\text{in./in.}$

At each temperature level, the frequencies of the first four natural modes of the beam were determined. The temperature was then increased to the next higher value and the frequencies were again measured. The time required to complete one test over the entire temperature range (80° to 900° F) was about 6 hours.

Inasmuch as none of the tests were repeated on the same specimen, it is difficult to make an accurate evaluation of the accuracy of the data. At the higher temperatures, the sensitivity of the foil strain gages decreased markedly and a high amplification of the strain signal was necessary. Also, in some cases, the electrical insulating qualities of the bonding agent used to bond the gages to the beam appeared to deteriorate with increasing temperature. The combination of these two effects made the strain amplitude signal indistinct and, consequently, the measured frequencies may have been as much as 2 percent off resonance. By consideration of the accuracy of the equipment and the consistency of the data it is concluded that, over most of the frequency range, the measured frequencies were within 1 percent of the resonant frequencies. Some tests were terminated before the 900° F temperature level was reached because of strain-gage failures.

RESULTS AND DISCUSSION

Calculation of Dynamic Modulus

The dynamic modulus was calculated from the measured frequencies by use of the following equation, which was derived from the frequency equation of a free-free beam:

$$E = \frac{4\pi^2 l^4 \gamma A f_1^2}{\lambda_1^2 I g (1 + \alpha \Delta T)}$$

where f_1 is the frequency of the i th mode of vibration and λ_1 is the eigenvalue appropriate for the i th mode of a free-free beam. Values of l , I , γ , and A were determined from the measurements of each beam. The beam frequency functions λ_1 , which are given in table 1, were determined from the frequency equation given in reference 3 and include the effects of transverse shear and rotary inertia. The term $1 + \alpha \Delta T$, where α is the coefficient of thermal expansion and ΔT is the difference between test temperature and room temperature, corrects for changes in beam dimensions caused by thermal expansion. The value of α appropriate at a given temperature was obtained from reference 4.

The measured frequency values for each of the first four modes of vibration and the corresponding calculated values of the modulus are given in table 2. Where no values are listed in the table, resonance could not be established because of instrumentation difficulties, as noted in the previous section.

Discussion of Results

The values of modulus indicated for each of the four modes at each temperature level have been averaged for comparison with modulus values obtained from stress-strain tests. The averaged values are given in table 2. The ratio of modulus at test temperatures to that obtained at room temperature is shown in figure 2 as a function of temperature. Data also have been shown for values obtained in stress-strain tests and from dynamic tests performed by other investigators. In figure 3 the actual modulus values obtained in this investigation are shown for several of the materials and again are compared with static and other dynamic values.

Figures 2 and 3 show that the dynamic-modulus values obtained in these tests decrease with increasing temperature and agree fairly well with those given in references 2 and 5. There is a significant difference, however, between the dynamic and the static values. The static tests show a greater decrease in modulus than do the dynamic tests.

Creep effects.- It is conceivable that the decrease in modulus with temperature indicated by stress-strain tests could be due to creep effects resulting from the combined influence of load and temperature. In order to determine an upper limit on the creep strain that might be involved in a stress-strain test, the assumption was made that a specimen was loaded to a certain stress level instantaneously and then was allowed to creep in the manner indicated by the primary portion of a creep curve for the length of time that would be required to reach the same stress level during a stress-strain test at a nominal strain rate of 0.002 per minute. The creep strain determined in this manner is certainly greater than the creep strain that would result from the conventional stress-strain test wherein the load increases steadily. Calculations made for 7075-T6 aluminum alloy at 400° F in the manner just described yielded values of creep strains which were scarcely perceptible at stresses less than one-half the proportional limit stress.

It is apparent, therefore, that creep cannot account for the difference between the static and dynamic moduli. A better possibility is the effect of various internal-friction mechanisms on the moduli. The sources of internal friction and their influence on modulus measurements are discussed in reference 6. From that discussion it is deduced that the mechanisms of primary concern in these tests are anelastic effects and static hysteresis. The manner in which these effects influence the modulus is discussed briefly.

Anelastic effects.- Anelasticity (the dependence of stress on time as well as strain in the nonplastic, noncreep range) can arise from

several sources which are discussed in references 7 to 9. The one which appears to be involved for the frequencies and temperatures considered herein is the stress relaxation in the disordered boundaries between grains. This relaxation of stress requires a finite time to occur. If loads are applied very rapidly, there is not sufficient time for relaxation to occur. On the other hand, if loads are applied very slowly, as is the case in a conventional stress-strain test, there is sufficient time for relaxation to occur and the observed strains are larger than for a dynamic loading. At very low frequencies there is one ratio of stress to strain (relaxed modulus) and at high frequencies there is another ratio (unrelaxed modulus). Obviously, over some intermediate frequency range, transition from relaxed to unrelaxed modulus takes place. The ratio of unrelaxed to relaxed modulus increases and the frequency range in which transition takes place becomes higher with increasing temperature. The difference between the relaxed and unrelaxed moduli can be large. Calculations by Zener, which are supported by tests by Kê, indicate that for pure aluminum at 400° F the relaxed modulus is only about 68 percent of the unrelaxed modulus (ref. 7, p. 157).

A close inspection of the data given in table 2 shows that the values of modulus indicated by each of the four modes agree very well up to a certain temperature. Above this temperature (which varies depending on material) the aluminum and magnesium alloys show a slight but definite upward trend in modulus with increasing frequency. This trend becomes more pronounced as the temperature is increased further. The modulus becomes frequency dependent (over the frequency range of these tests) at about 500° F for the aluminum alloys and at about 300° F for the magnesium alloy. The moduli of the stainless-steel and titanium-alloy beams do not show any frequency dependence over the temperature and the frequency ranges of these tests. The appearance of a frequency-dependent modulus tends to show that the discrepancy between static and dynamic moduli is partly due to anelastic effects.

Static hysteresis.- Static hysteresis, as discussed in reference 6 (pp. 22 to 25), is a phenomenon separate from anelasticity. Hysteresis may arise in nonviscous materials for which there is a definite value of strain associated with each value of increasing stress and a different, but definite, value of strain for each value of decreasing stress. If the value of strain corresponding to a particular value of stress is attained instantaneously, the hysteresis loop will be independent of the rate of traverse. As indicated in reference 6, static hysteresis can occur at very low strain amplitudes. These effects are, however, quite small compared with anelastic effects and, therefore, may be considered negligible with respect to the accuracy of the data obtained in the present investigation.

Application of Results to Aircraft Analyses

From the results obtained in the present tests, it appears that there is sufficient difference between the static- and dynamic-modulus values to warrant some consideration as to which modulus applies in a particular design. When applied loads vary slowly, the static modulus is the obvious choice. In the case of dynamic loadings, such as flutter, cognizance must be taken of the frequency of the loading. For frequencies within the range of these tests and higher, the dynamic modulus would probably be the more suitable. If the frequencies are lower, as is often the case for full-scale aircraft, the frequency dependence of the modulus may become important, but flutter calculations based on the static modulus probably would be conservative inasmuch as calculated flutter speeds would be lower.

CONCLUDING REMARKS

The change in Young's modulus of elasticity with temperature was determined for 2024-T3 and 7075-T6 aluminum alloys, AZ31A-0 magnesium alloy, RS-120 titanium alloy, and type 303 stainless steel by flexural vibration tests of beam specimens. The test results indicate a general reduction in modulus with increasing temperature for the materials tested. This decrease was substantially less than that given by conventional stress-strain tests.

An analysis of the results show that the difference between the dynamic and the static moduli is due to several internal-friction mechanisms, of which anelastic effects appear to be predominant, and cannot be attributed to the influence of creep on static stress-strain measurements.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., June 5, 1958.

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TABLE 1.- VALUES OF FREQUENCY FUNCTION λ_1 FOR
 A FREE-FREE BEAM, INCLUDING EFFECTS OF
 SHEAR AND ROTARY INERTIA

Mode	λ_1 for beam sizes of -	
	$\frac{3}{8}$ " \times $1\frac{1}{2}$ " \times 36"	$\frac{1}{4}$ " \times 1" \times 30"
1	22.3643	22.3677
2	61.6006	61.6260
3	120.6300	120.7286
4	199.1998	199.3900

TABLE 2.- MEASURED FREQUENCIES AND CALCULATED MODULI FOR EACH OF FOUR MODES TESTED

(a) 2024-T3 aluminum alloy

T, °F	Frequency, cps, of mode -				Modulus, psi, from mode -				Average modulus, psi
	1	2	3	4	1	2	3	4	
Specimen A									
80	60.32	166.44	325.38	541.08	10.65×10^6	10.68×10^6	10.65×10^6	10.80×10^6	10.70×10^6
200	59.32	163.86	320.24	-----	10.28	10.33	10.30	-----	10.30
340	58.14	160.40	313.83	-----	9.87	9.89	9.87	-----	9.88
450	57.10	157.55	308.80	510.71	9.50	9.52	9.54	9.57	9.53
610	55.16	152.63	299.66	494.45	8.85	8.93	8.96	8.95	8.92
730	53.28	147.85	289.96	480.66	8.23	8.35	8.38	8.45	8.35
850	51.14	141.34	277.18	462.14	7.58	7.62	7.63	7.79	7.65
Specimen B									
105	60.19	165.67	323.96	533.32	10.62×10^6	10.60×10^6	10.57×10^6	10.51×10^6	10.58×10^6
205	59.32	163.68	319.32	526.28	10.30	10.32	10.25	10.21	10.27
350	58.14	159.66	312.93	515.75	9.88	9.81	9.83	9.79	9.83
500	56.45	156.01	305.08	502.52	9.29	9.35	9.32	9.28	9.31
670	54.24	150.35	294.68	487.08	8.55	8.66	8.68	8.70	8.65
800	51.85	144.31	283.17	468.05	7.80	7.96	8.00	8.01	7.94
850	50.29	140.28	276.86	456.83	7.34	7.52	7.63	7.62	7.53

TABLE 2.- MEASURED FREQUENCIES AND CALCULATED MODULI FOR EACH OF FOUR MODES TESTED - Continued

(b) 7075-T6 aluminum alloy

T, °F	Frequency, cps, of mode -				Modulus, psi, from mode -				Average modulus, psi
	1	2	3	4	1	2	3	4	
Specimen A									
87	60.85	167.60	328.57	542.96	10.55 × 10 ⁶	10.54 × 10 ⁶	10.57 × 10 ⁶	10.59 × 10 ⁶	10.56 × 10 ⁶
205	59.96	165.00	322.66	534.25	10.22	10.20	10.18	10.23	10.21
300	59.02	162.50	318.03	526.59	9.89	9.88	9.87	9.93	9.89
435	57.47	-----	310.95	513.97	9.37	-----	9.42	9.43	9.41
515	56.27	155.29	305.43	503.68	8.97	9.00	9.08	9.06	9.03
610	54.37	150.35	296.22	491.04	8.36	8.43	8.53	8.60	8.48
710	-----	145.73	286.71	475.68	-----	7.91	7.98	8.05	7.98
810	50.35	140.12	277.66	457.89	7.15	7.29	7.46	7.45	7.34
875	-----	135.86	268.21	446.92	-----	6.85	6.95	7.08	6.96
910	47.52	132.72	262.38	433.94	6.36	6.54	6.65	6.67	6.56
Specimen B									
90	60.92	167.99	329.06	542.02	10.57 × 10 ⁶	10.59 × 10 ⁶	10.60 × 10 ⁶	10.55 × 10 ⁶	10.58 × 10 ⁶
195	59.98	164.72	323.03	535.79	10.24	10.17	10.21	10.30	10.23
300	58.54	162.73	317.66	523.55	9.73	9.91	9.85	9.81	9.83
400	-----	159.38	313.11	516.05	-----	9.50	9.56	9.52	9.53
500	56.35	156.01	305.96	506.89	9.00	9.09	9.11	9.18	9.09
600	54.97	151.13	297.42	493.88	8.55	8.52	8.60	8.70	8.59
700	52.55	146.75	287.62	476.51	7.80	8.02	8.03	8.08	7.98

TABLE 2.- MEASURED FREQUENCIES AND CALCULATED MODULI FOR EACH OF FOUR MODES TESTED - Continued

(c) AZ31A-0 magnesium alloy

T, °F	Frequency, cps, of mode -				Modulus, psi, from mode -				Average modulus, psi
	1	2	3	4	1	2	3	4	
Specimen A									
85	57.07	157.64	308.09	509.83	6.32×10^6	6.36×10^6	6.34×10^6	6.36×10^6	6.34×10^6
215	56.12	154.67	302.79	501.07	6.10	6.11	6.11	6.14	6.11
300	55.27	152.63	298.97	494.74	5.91	5.94	5.95	5.97	5.94
405	53.65	148.97	291.97	485.12	5.56	5.65	5.66	5.73	5.65
500	51.55	144.23	285.96	471.04	5.13	5.29	5.42	5.41	5.31
600	49.37	139.39	277.18	457.10	4.69	4.93	5.09	5.07	4.94
710	-----	132.72	261.78	434.95	-----	4.46	4.52	4.58	4.52
810	45.46	127.46	255.65	414.11	3.96	4.11	4.31	4.15	4.13
910	43.65	121.35	242.98	-----	3.65	3.72	3.81	-----	3.73
Specimen B									
100	57.17	157.74	308.44	510.41	6.36×10^6	6.38×10^6	6.37×10^6	6.39×10^6	6.38×10^6
200	56.25	155.29	303.67	502.23	6.15	6.18	6.16	6.18	6.17
300	55.45	152.98	299.49	495.03	5.96	5.98	5.99	6.00	5.98
400	53.90	149.92	294.34	487.08	5.62	5.74	5.77	5.79	5.73
500	51.64	144.64	287.79	476.78	5.16	5.34	5.50	5.54	5.39
600	49.88	138.83	-----	-----	4.80	4.90	-----	-----	4.85
710	47.30	134.10	262.53	-----	4.31	4.56	4.56	-----	4.47
820	46.17	128.57	254.18	-----	4.10	4.19	4.27	-----	4.19
905	44.42	123.47	244.11	405.82	3.79	3.86	3.93	3.99	3.90

TABLE 2.- MEASURED FREQUENCIES AND CALCULATED MODULI FOR EACH OF FOUR MODES TESTED - Continued

(d) RS-120 titanium alloy

T, °F	Frequency, cps, of mode -				Modulus, psi, from mode -				Average modulus, psi
	1	2	3	4	1	2	3	4	
Specimen A									
80	51.94	143.40	281.21	465.09	16.11×10^6	16.17×10^6	16.21×10^6	16.26×10^6	16.19×10^6
210	50.84	140.28	275.59	455.52	15.42	15.46	15.55	15.58	15.50
310	49.86	137.71	270.54	447.69	14.82	14.89	14.98	15.04	14.93
405	49.08	135.50	265.74	440.00	14.36	14.42	14.45	14.53	14.44
500	48.18	133.10	261.63	432.69	13.83	13.90	14.00	14.04	13.94
600	47.44	130.81	256.83	425.50	13.40	13.42	13.48	13.56	13.46
Specimen B									
83	52.82	145.23	284.14	471.31	16.13×10^6	16.06×10^6	16.02×10^6	16.16×10^6	16.09×10^6
210	51.85	142.90	279.59	462.41	15.53	15.55	15.49	15.54	15.53
300	51.02	140.48	275.11	454.47	15.03	15.00	14.99	15.00	15.00
400	50.12	138.11	270.38	447.17	14.50	14.50	14.48	14.53	14.50
480	49.31	135.58	266.81	441.78	14.03	13.96	14.09	14.17	14.06
600	48.41	133.33	261.63	432.69	13.51	13.50	13.54	13.57	13.53
700	47.44	130.59	256.09	423.79	12.97	12.95	12.97	13.01	12.98
800	46.49	127.60	250.82	414.83	12.45	12.35	12.44	12.47	12.43
895	45.45	125.63	245.24	405.82	11.88	11.96	11.87	11.92	11.91

TABLE 2.- MEASURED FREQUENCIES AND CALCULATED MODULI FOR EACH OF FOUR MODES TESTED - Concluded

(e) Type 303 stainless steel

T, °F	Frequency, cps, of mode -				Modulus, psi, from mode -				Average modulus, psi
	1	2	3	4	1	2	3	4	
Specimen A									
80	61.27	168.76	330.20	545.16	28.64 × 10 ⁶	28.63 × 10 ⁶	28.56 × 10 ⁶	28.54 × 10 ⁶	28.59 × 10 ⁶
200	60.32	166.34	325.84	537.03	27.73	27.78	27.78	27.67	27.67
300	59.60	164.43	322.10	531.48	27.04	27.12	27.12	27.07	27.09
395	58.98	162.54	317.85	525.07	26.46	26.48	26.39	26.39	26.43
500	58.20	160.40	314.38	518.44	25.75	25.76	25.78	25.71	25.75
600	-----	158.37	309.34	511.30	-----	25.10	24.94	24.99	25.01
700	-----	156.10	306.14	503.97	-----	24.35	24.40	24.24	24.33
805	-----	153.60	-----	-----	-----	23.55	-----	-----	23.55
Specimen B									
75	61.47	169.06	330.77	546.42	28.83 × 10 ⁶	28.73 × 10 ⁶	28.66 × 10 ⁶	28.67 × 10 ⁶	28.72 × 10 ⁶
210	60.36	166.44	325.84	539.52	27.77	27.82	27.78	27.92	27.82
400	59.02	162.45	317.48	524.76	26.50	26.45	26.33	26.36	26.41
500	58.24	160.40	314.02	518.44	25.78	25.76	25.73	25.71	25.74
600	57.44	158.28	309.87	511.60	25.05	25.07	25.03	25.02	25.04
700	56.64	156.28	-----	-----	24.33	24.41	-----	-----	24.37
805	-----	153.87	303.67	-----	-----	23.64	23.99	-----	23.81

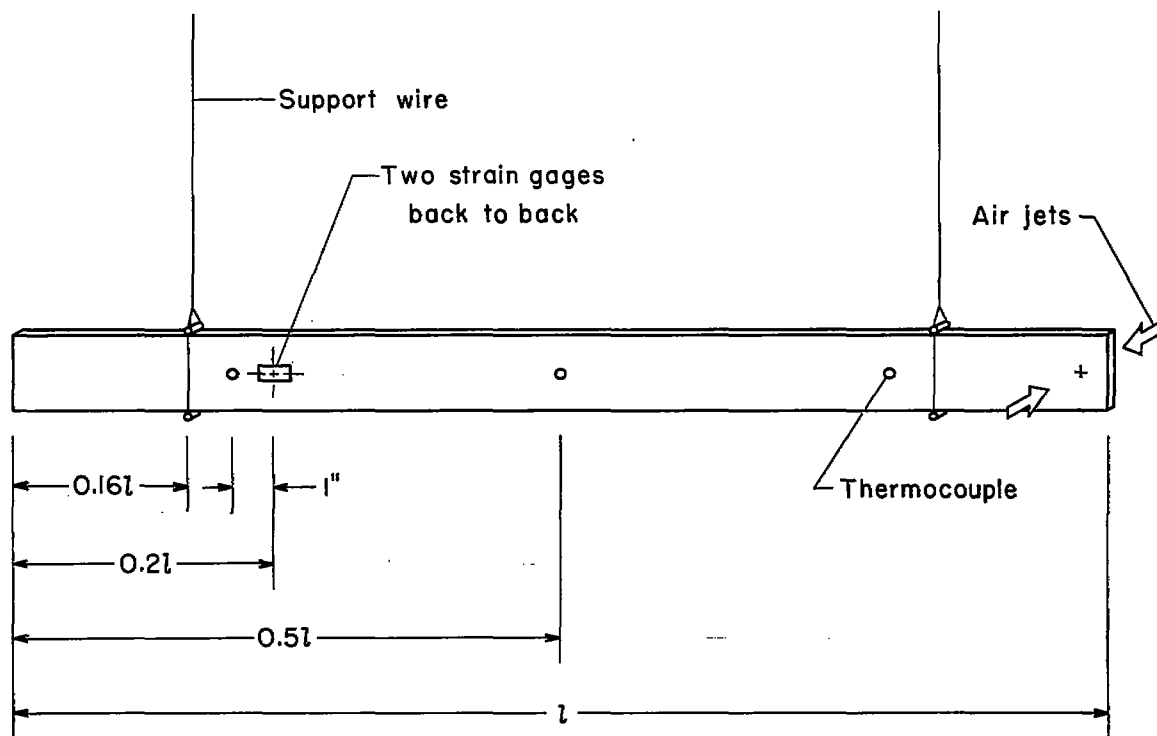
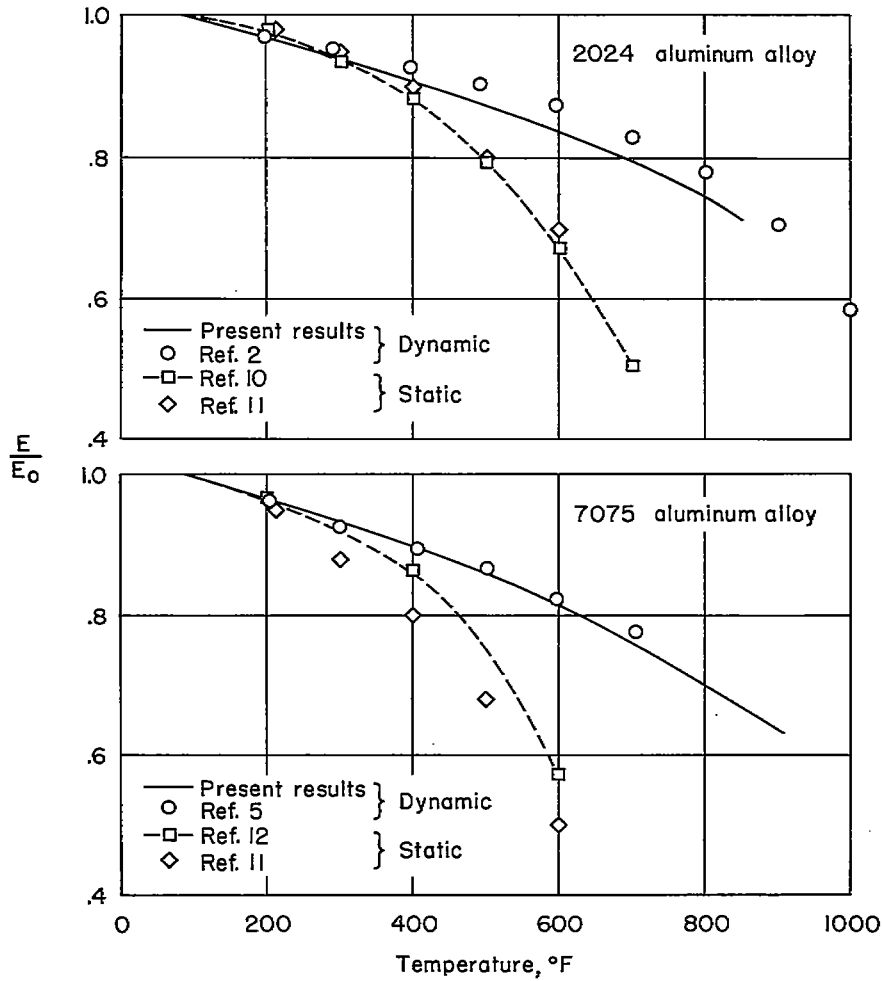
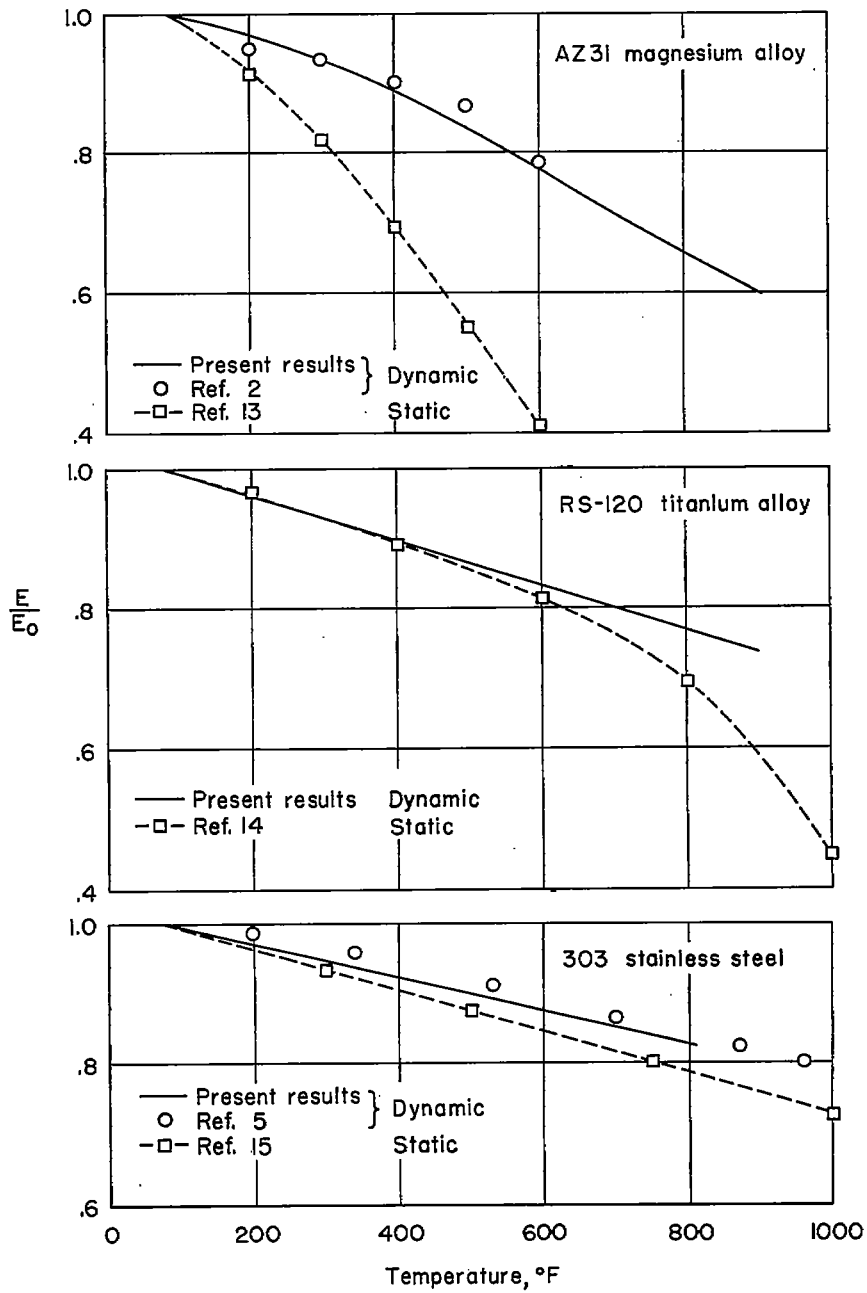


Figure 1.- Instrumentation of beams.



(a) 2024 and 7075 aluminum alloys.

Figure 2.- Variation of modulus ratio with temperature as determined by dynamic- and static-test techniques.



(b) AZ31 magnesium alloy, RS-120 titanium alloy, and type 303 stainless steel.

Figure 2.- Concluded.

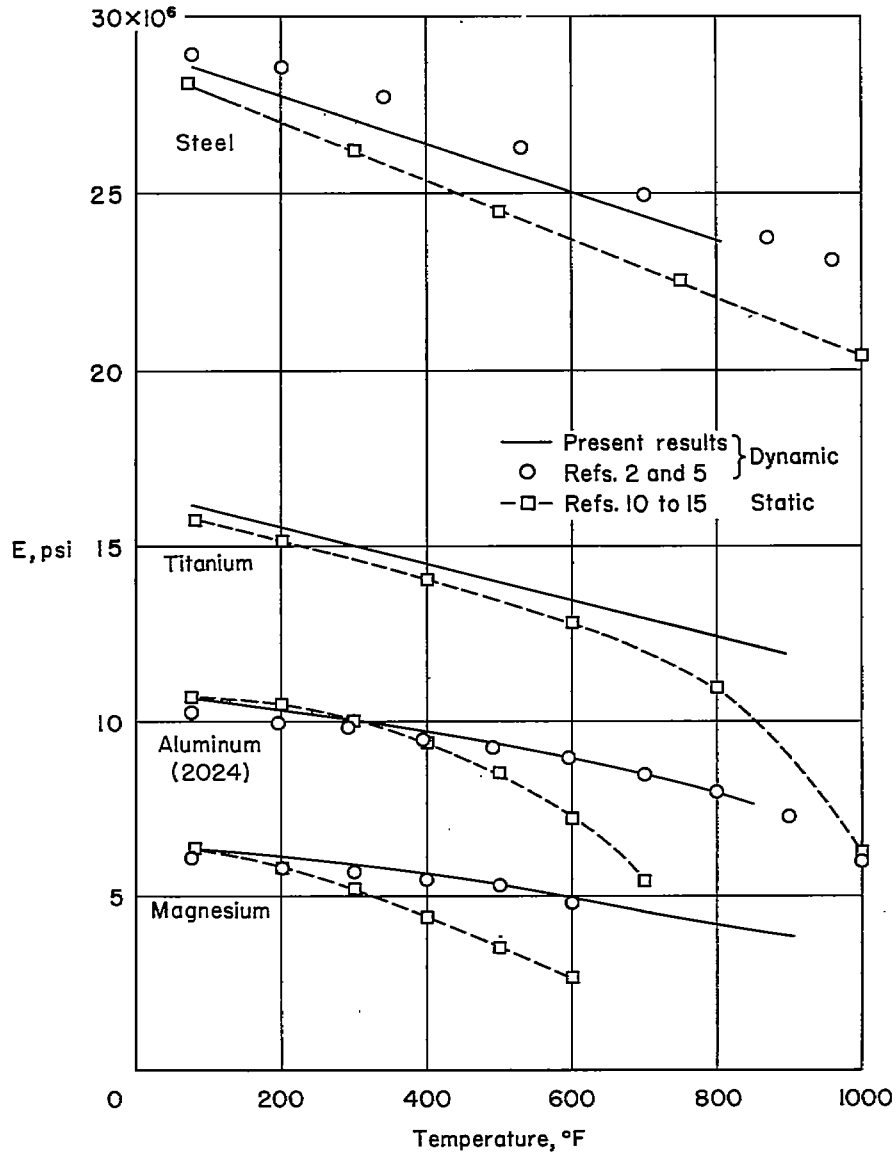


Figure 3.- Variation in modulus with temperature for several of the materials tested.