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Final Report

AN EXPERIMENTAL STUDY RELATING TO THE PREDICTION OF ELEVATED-TEMPERATURE STRUCTURAL BEHAVIOR FROM THE RESULTS OF TESTS AT ROOM TEMPERATURE

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σ_{ys} = yield stress

σ_{ult} = ultimate stress

E = modulus of elasticity

E_c = compression modulus of elasticity

δ = deflection of box beam

T = temperature (absolute or Fahrenheit, as noted)

T_m = melting temperature (absolute)

T (subscript) = temperature

P = load on box beam

p = hydraulic pressure

I = moment of inertia of box beam

M = applied moment at point of failure of box beam

c = distance from neutral plane of beam to extreme fiber

K = proportionality factor

ABSTRACT

A series of 26 aluminum-alloy semi-monocoque box beams was subjected to structural tests comprising rapidly applied destruction loads, and also steady and cyclic loads less than the ultimate load, at temperatures ranging from 75° to 700°F. The test specimens were mounted on a steel jig enclosed in an oven, and loads were applied by means of a hydraulic strut and also by dead weight. Deflections and loads were recorded automatically in the case of rapidly applied loads and manually in the case of steady and cyclic loads. Typical test results are presented in the form of graphs which show the maximum load which can be supported by the box beams at various temperatures and the manner in which the deflection varies with time, load, temperature, and type of loading.

The number of tests was not large, but significant trends were indicated, and it is concluded that by carrying out additional tests similar to those performed in connection with this project it will be possible to develop empirical methods for the estimation of

1. the ultimate strength of a built-up aircraft structure at elevated temperature,
2. the safe life of the structure in terms of flying hours at elevated temperature, and
3. the permissible load factor at any time during the life of the craft,

if the ultimate strength and maximum deflection of the structure at room temperature, and the properties of the material at room and elevated temperatures, are known. The accuracy of these methods will be not less than that required for preliminary design and may, in some cases at least, be sufficient for final design. The use of these methods will greatly speed up the process of designing aircraft which must operate at elevated temperatures, by eliminating the necessity for much expensive and time-consuming testing of structures at such temperatures, and may reduce the need for certain costly elevated-temperature testing facilities, although it is unlikely that all tests at high temperature can be eliminated.

CHAPTER I

SUMMARY OF TESTS, RESULTS, CONCLUSIONS, AND RECOMMENDATIONS

Structural load tests were carried out on a series of 26 identical aluminum-alloy semi-monocoque box beams at constant uniform temperatures ranging from 75° to 700°F. The test specimens were mounted as cantilever beams on a steel jig which was partially enclosed in an electrically heated oven and were loaded with a single concentrated load at the free end. The load was usually applied by means of a hydraulic strut actuated by a motor-driven pump with solenoid-operated valves and an automatic sequence timer for automatic load application. Deflections at eight points were read visually or recorded by means of a motion-picture camera.

Sixteen box beams were loaded rapidly to the ultimate load at room temperature, 300°, 400°, 500°, 600°, and 700°F. Six specimens were subjected to steady loads between 25% and 50% of ultimate load at 500° and 600°F and failed by creep buckling. Two specimens were subjected to repeated applications of 50% of ultimate load at 500° and 600°F and two were subjected to alternating loads of +50% and -25% of ultimate load at 500° and 600°F. These four box beams also failed by creep buckling.

The number of tests in each category was not large, but significant trends were indicated which have potential value in the development of criteria for the structural design of aircraft operating at elevated temperatures and in predicting the useful life of such aircraft. These trends, however, need to be verified and extended by additional investigations. The conclusions drawn from the 26 tests are as follows:

1. If a built-up aluminum-alloy structure fails by buckling at room temperature, it probably will fail at elevated temperature in the same manner and in the same location, although there may be certain exceptions in the case of structures which have very small margins of safety in tension when buckling failure occurs. If a structure fails by tension at room temperature, it probably will fail in the same manner and in the same location at elevated temperature.

It is recommended that additional tests be carried out on specimens which fail by buckling at room temperature, but with small margins of safety in tension, in order to determine if the possible exceptions actually exist.

2. If a built-up aluminum-alloy structure fails by buckling at room temperature, it is probable that the critical deflection under ultimate load at elevated temperature can be predicted empirically with reasonable accuracy if the value of the ultimate load at the elevated temperature can be determined (see conclusion 4).

The critical deflection at elevated temperature will in no case be greater than at room temperature, and in the high-temperature range (above half the absolute melting temperature of the material) will be substantially less. The critical deflection in the high-temperature range is proportional to the ultimate load-modulus ratio, or approximately

$$\left(\frac{\delta_T}{\delta_{75}}\right)_{ult} = K \frac{\left(\frac{P_T}{P_{75}}\right)_{ult}}{\left(\frac{E_T}{E_{75}}\right)} \qquad (5.1)$$

where K is unity below 400°F and 0.90 above 500°F.

It is recommended that additional tests be carried out on specimens which fail at various percentages of yield stress in order to establish the generality of this conclusion. It is also recommended that additional tests be carried out on specimens which fail by tension in order to establish the procedure by which the deflections of such structures under ultimate load at elevated temperature may be predicted.

3. At any given temperature, a built-up aluminum-alloy structure which fails by buckling will always fail when the deflection reaches a certain critical value (which can be predicted approximately by means of conclusion 2) regardless of whether the applied load is rapidly increased to its ultimate value or smaller loads are applied steadily or cyclically over longer periods of time. Therefore, the ultimate strength of a lightly loaded structure at elevated temperature decreases with time, since the load increment required to produce failure will decrease as the deflection under the light load increases and approaches the critical deflection. The maximum permissible load at any time during the life of the structure and the remaining safe life are functions of the amount of permanent set which has already occurred, and this can be measured.

It is recommended that additional tests be carried out on a series of identical structural specimens in order to determine

a. the residual maximum load which can be supported after varying amounts of permanent set have occurred as a result of the application of light loads for various periods of time,
b. the relationship between the residual maximum load, the amount of permanent set present, and the original ultimate strength under rapid loading,
c. the effect, if any, of the type of load (steady or cyclic) on the residual maximum load, and
d. the effect, if any, of repeated cycles of heating and cooling.

The results of these tests will establish the basic criteria for the determination of the useful life of aircraft operating at elevated temperatures.

4. It is probable that the elevated-temperature strength of any built-up aluminum-alloy structure can be predicted empirically, with at least sufficient accuracy for preliminary design purposes, from the results of a test at room temperature, or from the calculated room-temperature strength. In the case of structures which fail by tension, the ultimate strength at any temperature probably will be proportional to the corresponding ultimate tensile strength of the material. In the case of structures which fail by buckling, the prediction can be carried out by means of curves similar to the curve of Fig. 5.5, which shows that the value of Mc/I at failure, as a percent of the corresponding yield stress, remains substantially constant below half the absolute melting temperature of the material, and increases linearly at higher temperatures.

It is recommended that additional tests be carried out on structures which fail by buckling at various percentages of yield stress and also on structures which fail by tension, in order to establish the generality of the above conclusion and to derive the empirical data on which to base the prediction of elevated-temperature strength from the results of room-temperature tests. It is further recommended that similar tests be carried out, using several commonly used alloys.

CHAPTER II

REASONS FOR AND SCOPE OF INVESTIGATION

As a result of a survey of information available in 1952, it was concluded in Reference 1 that nonlinearity of material behavior at elevated temperatures, complicated by variations of temperature and stress levels within the structure of a high-speed aircraft or missile subjected to such temperatures, will prevent the correlation of elevated-temperature strength with the results of room-temperature tests. Because of the time dependence of material properties at high temperatures, current structural design and testing procedures will not be applicable to structures of high-speed aircraft or missiles. It was also concluded that there is no short-time substitute for a creep test and, consequently, the ordinary static test cannot be used as an indication of the creep life of a structure.

The latter conclusion undoubtedly is still valid, but it now appears that there is a distinct possibility that elevated-temperature design criteria, suitable at least for preliminary design purposes, can be deduced empirically from the results of room-temperature strength calculations or tests. However, much additional work must be done before such criteria can be expressly stated.

There is a further possibility that the amount of creep or related testing necessary for the determination of elevated-temperature structural life is much smaller than was formerly envisioned. It must be understood that the life of an aircraft, whether at room temperature or elevated temperatures, can be stated only provisionally. It depends, of course, on the mission of the craft but no two aircraft ever are subjected to the same load-time history. The "life" is therefore a somewhat artificial number which expresses the length of time during which the structure can support a statistically established cycle of loading. It is of greater importance to the pilot to be able to determine when his airplane no longer has a margin of safety under the maximum applied load factor which he may expect to encounter during flight. It now appears that this, too, can be determined.

The principal purpose in undertaking the series of tests reported herein was to check certain tentative conclusions which were reached after a short series of structural tests at elevated temperatures which were reported in Reference 2. These tests consisted of the application of distributed lateral loads to six fins from the AT-6 aircraft. These tests were carried out at temperatures ranging from 75°F to 700°F. The aluminum-alloy fins were mounted on a steel supporting jig and enclosed in an oven. The load was applied by means of a linkage which simulated a uniformly distributed load. The applied loads comprised rapidly applied destruction loads and smaller loads applied for longer periods of time until the structure failed by creep buckling.

The particular conclusions which are of interest here were tentative, due to the small number of tests, and are as follows:

1. If the room-temperature failure of a conventional aircraft structure results from buckling, the elevated-temperature failure of the same structure probably will be of the same type and at the same location.

2. The maximum deflections at failure of conventional structures appear to be comparable to those at room temperature, whether the failure is induced by means of rapidly applied ultimate loads or by smaller loads acting over longer periods of time.

3. The ultimate load of a conventional structure at elevated temperature may be empirically related to the results of room-temperature ultimate tests.

If these conclusions are valid, they will point the way to further investigations for the purpose of developing design criteria which may be used in the preliminary design of aircraft and missiles which will be subjected to elevated temperature and also in the prediction of the safe life of aircraft structures at such temperatures. A considerable amount of elevated-temperature testing can be eliminated, and since all elevated-temperature testing is expensive, this will result in more economical development of airframes for high-speed aircraft and missiles.

The first conclusion appeared to be logical, inasmuch as the buckling strengths of all parts of a structure vary in the same way with temperature. The initial buckling stress is dependent on the modulus of elasticity, which decreases with temperature as shown by Fig. 2.1. The ultimate strength of a buckled column or panel is dependent on the yield strength, which varies with temperature as shown by Fig. 2.2. If a structure consists essentially of a single material, all parts

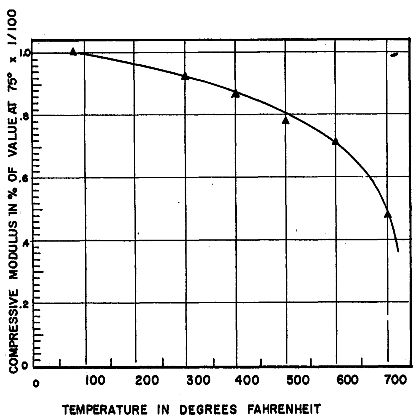


Fig. 2.1. Variation of compression modulus of 24-ST aluminum alloy with temperature.

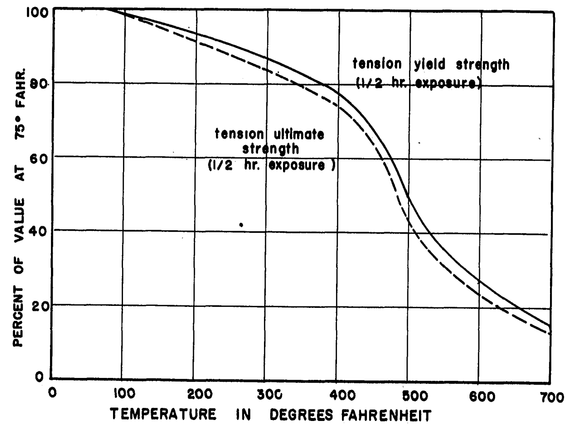


Fig. 2.2. Yield and ultimate strengths of 24-ST aluminum-alloy sheet at elevated temperature (from Reference 4).

are equally affected by heating and the weakest point at room temperature still will be the weakest point at elevated temperature. This conclusion was borne out by the present investigation, although it now appears that there may be certain exceptions, as discussed in Chapter V.

The second conclusion also appeared reasonable inasmuch as the load carried by the structure at failure is reduced at elevated temperature, while the deflection due to a given load is increased because of the reduction in modulus of elasticity as the material is heated. Since the two effects are opposed, it appeared possible that the deflection at failure may not be greatly affected by temperature. If this is true, the deflection of a structure at failure can be determined from a room-temperature test, and the safe distortion due to creep at elevated temperatures can be established at some more or less arbitrary percentage of this value. The life of the aircraft then follows from the time required to develop this distortion as a result of the application of loads and temperatures which can be established by means of statistical studies of the loads and temperatures which the structure is likely to experience in the course of the mission of the craft. This conclusion was modified slightly by the results of the investigation reported herein, as discussed in Chapter V.

Furthermore, this conclusion disposes of the popular misconception that at elevated temperatures an aircraft wing or fuselage may distort to such an extent that it can no longer carry out its function, although it may not fail in the accepted structural sense. A heated bar of iron may, of course, be bent double without breaking, but a built-up structure will fail at deflections comparable to the maximum room-temperature deflection.

The third conclusion rests on the fact that the results of three elevated-temperature destruction tests reported in Reference 2 suggest a variation of ultimate structural strength with temperature which is qualitatively similar to the variation of the ultimate and yield strengths of the material. Verification of such a variation would present the possibility of developing an empirical method for the prediction of the ultimate load of a structure at elevated temperature from the results of room-temperature tests. This would be an invaluable aid in preliminary design, where many types of structures must be investigated during the development of a new prototype. It is possible to calculate the room-temperature strength of a proposed structure with reasonable accuracy by methods which have stood the test of time, whereas the current backlog of experience at elevated temperatures is still very sketchy.

In view of the small number of tests reported in Reference 2, it appeared desirable to check the above conclusions by carrying out a larger number of tests under different conditions of temperature and load. It was felt that the tests should be carried out on identical test specimens, which should be representative of conventional aircraft structures, but need not necessarily be actual aircraft components. The tests should comprise loads which are rapidly increased to the ultimate load at which the specimen fails, steady loads less than the ultimate load, and cyclic loads, also less than ultimate load, which may be applied in one or both directions.

Since these tests were to be carried out in the structural testing oven at The University of Michigan, which has not been operated above 700°F, the specimens were limited to aluminum alloys, and the particular alloy chosen was 24 ST, as the high-strength 75 ST has poorer elevated-temperature characteristics. The test temperatures chosen were 75°, 300°, 400°, 500°, 600°, and 700°F. Rapid ultimate tests only were carried out at 75°, 300°, 400°, and 700°F, since at and below 400° the creep rate is low and steady-load or cyclic-load tests at light loads would be too time consuming. On the other hand, the creep rate at 700°F is extremely rapid and the strength is reduced beyond the point of usefulness, so more than one or two tests would not be justified.

The ultimate and yield strengths of 24-ST aluminum alloy have decreased at 600°F to approximately one-quarter of the room-temperature values. This marks the approximate upper limit of usefulness of aluminum alloys in general, and it is unlikely that much use will be made of such alloys above 500°F, where the strength is about half that at room temperature. This is the sea-level stagnation temperature corresponding approximately to a Mach number of 2.0, so the results of the investigation reported herein will apply principally to aircraft or missiles operating in the transonic or low supersonic range. The endurance of such craft is not large at present, but the future probability of attaining steady-state temperatures in this range is sufficient to justify the development of applicable design procedures.

Aircraft operating in this range have structural members not differing greatly from conventional subsonic aircraft, so the type of structure to be tested should be representative of current practice. The test specimens should be simple and inexpensive to construct and should be substantially alike, so that test results on different specimens will be comparable. The development of such a test structure and the method of testing will be described in the following chapter.

CHAPTER III

DESCRIPTION OF TEST SPECIMEN AND METHOD OF TESTING

Since the test specimen was to be representative of rather conventional aircraft structures, the semi-monocoque skin-and-stringer type was selected. A rectangular box beam with longitudinal stiffeners was chosen for the sake of ease of construction, since several identical specimens were to be fabricated. The beam was mounted as a cantilever with a single concentrated load at the free end. The beam was to fail by buckling in every test, with the failure location near the center of the span in order to eliminate end effects or possible temperature deviations which might result from proximity to the mounting jig or loading device.

A number of box beams were constructed which differed in length, cross section, number and size of stiffeners, skin thickness, number of bays, method of mounting, and method of load application. The specimen which was finally selected as satisfactory for the tests is the three-bay box beam shown in the photographs, Plates 3.1 and 3.2. A cross section of the center bay is shown on the sketch, Fig. 3.1. This is the same as the outer bay, which is shown on Plate 3.1. The box has two shear webs, which are channels 4 inches deep with 7/8-inch flanges, formed from 0.064-inch-thick, 24-ST bare aluminum-alloy sheet, with 1/8-inch inside bend radii. The shear webs face outward, as shown in Fig. 3.1, for ease in riveting. The upper and lower plates are 14-5/8 inches wide and 0.040 inch thick. The stiffeners are 3/4 x 3/4 x 0.064-inch angles, also formed from flat sheet with 1/8-inch inside bend radii. No ribs are used as these would unduly complicate the structure, but 3/4 x 3/4 x 1/8-inch extruded angles are riveted to the outside of upper and lower surfaces in the chordwise direction at spanwise intervals of 15 inches, thus dividing the beam into three bays. The skin and stringers are jig drilled, and the shear webs are drilled on assembly. All rivets are brazier-head, A17-ST aluminum-alloy aircraft rivets, set with pneumatic squeeze riveters. The length of the box beam is 45 inches, and a steel boom is bolted to the outer end for applying the load 15 inches outboard of the tip of the test beam. This boom is shown in the photographs, Plates 3.3 and 3.4. In order to insure that the failure occurs in the center bay, the inboard bay is reinforced with doublers on both shear webs and upper and lower plating, and 3/4 x 3/4 x 1/8-inch extruded stiffeners are spliced to the formed stiffeners, as shown on the photograph, Plate 3.2. The failure always takes place in the second bay and is therefore essentially free of end effects, from both the temperature and stress standpoints.

The oven in which the tests were carried out was designed and constructed for the purpose of testing the AT-6 aircraft fins which were mentioned in Chapter II, and is described in detail in Reference 2. This oven consists of an insulated box 4 x 5 x 8 feet, open at front and rear, and mounted on flanged wheels and rails

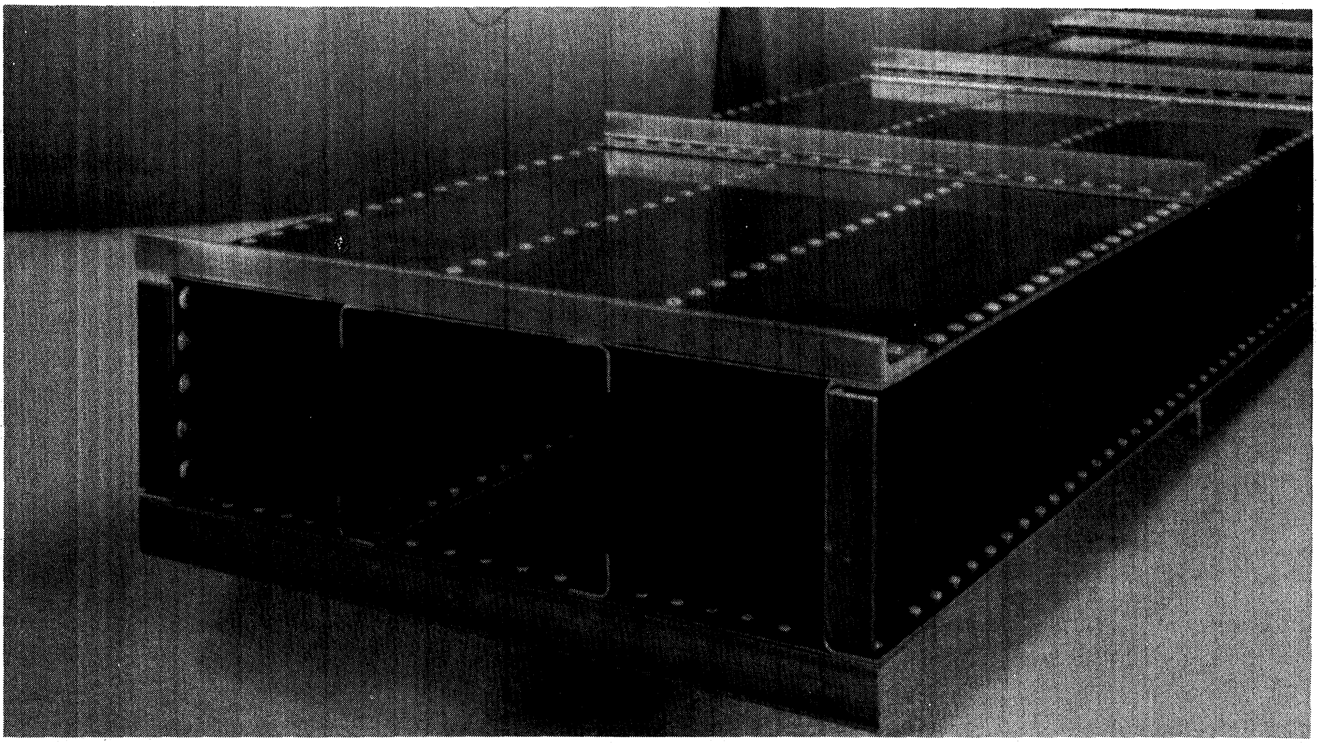


Plate 3.1. Box beam viewed from outboard.

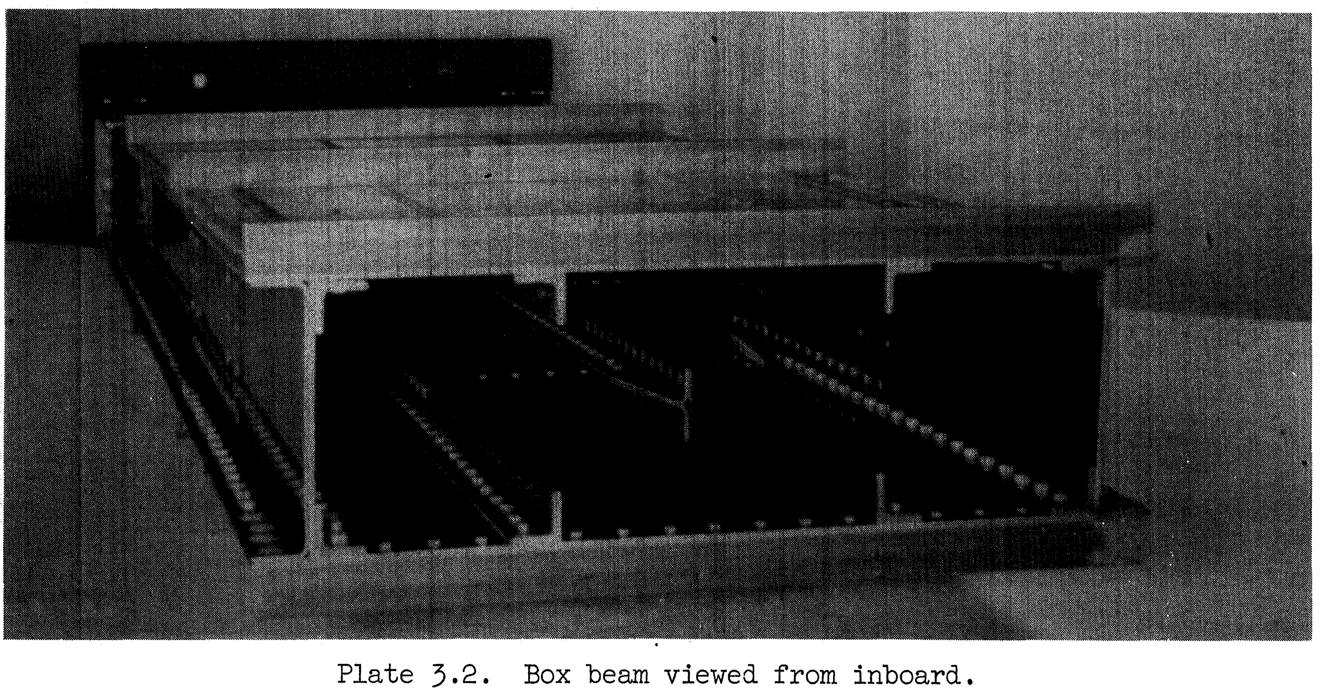


Plate 3.2. Box beam viewed from inboard.

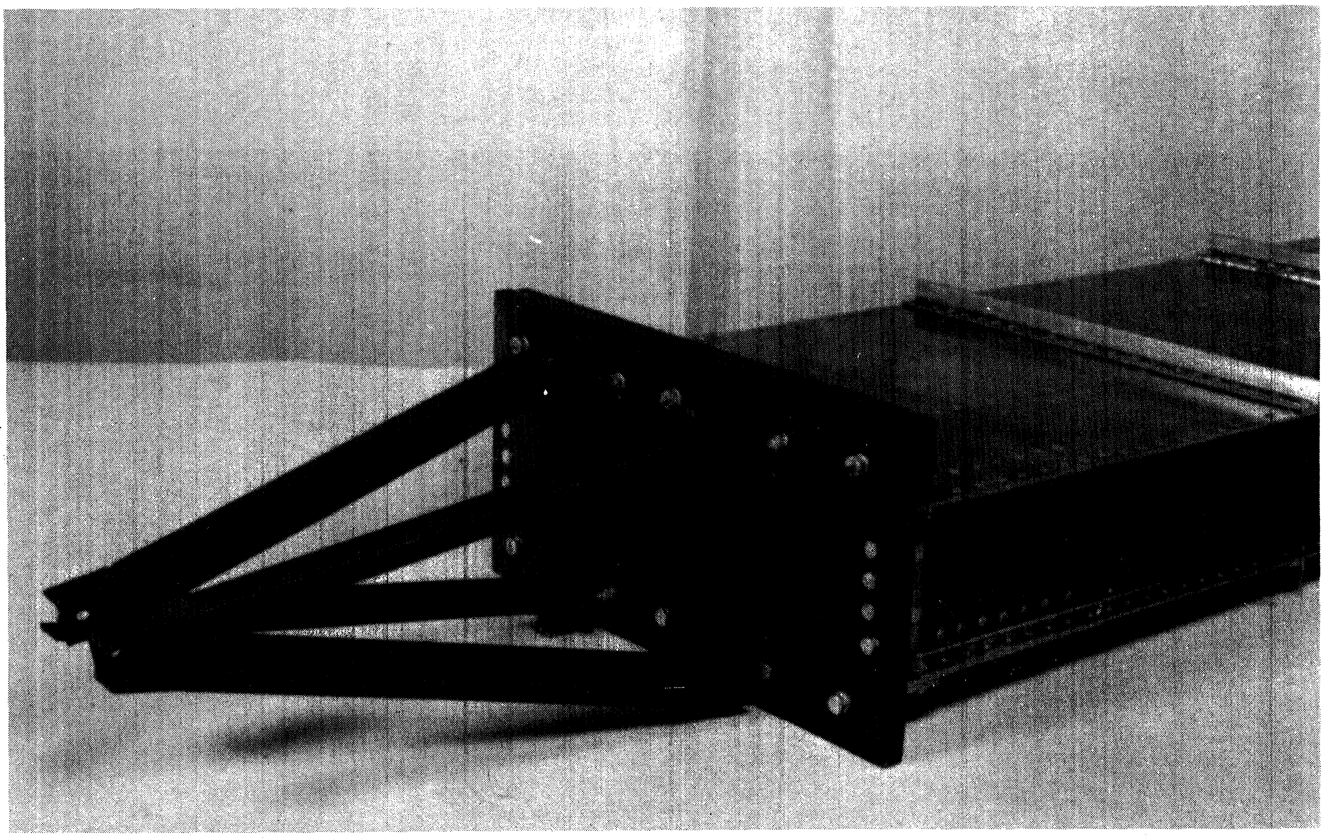


Plate 3.3. Steel boom for load application.

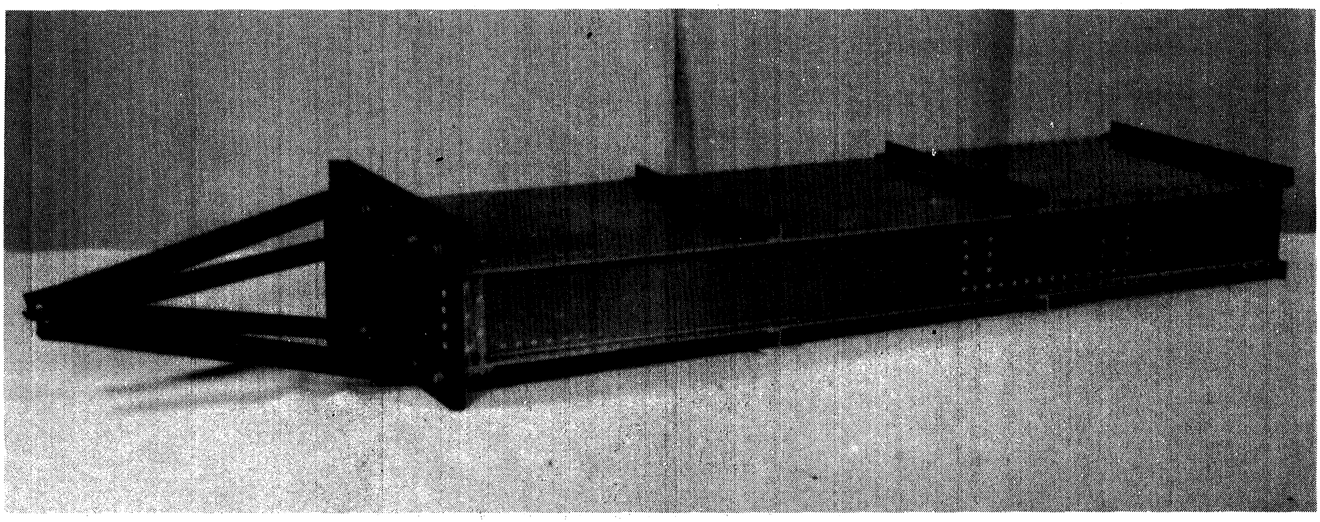


Plate 3.4. Box beam with boom attached.

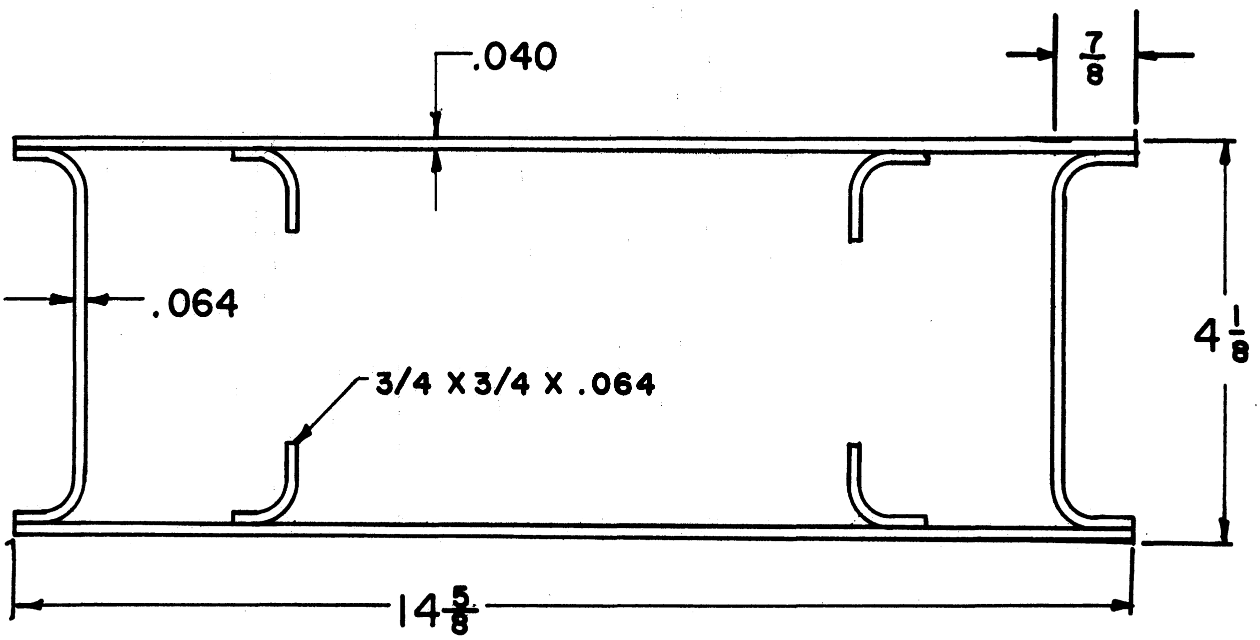


Fig. 3.1. Dimensioned sketch of specimen cross section at center panel.

for ease of access to the test specimen. The front cover, which carries the heating elements, is also mounted on wheels, while the rear cover is permanently mounted on the steel jig which supports the test specimen. The three parts of the oven are shown in the photograph, Plate 3.5. The oven and front cover, or door, can be moved forward for ease in mounting or removing test specimens, and the front cover can be separated from the oven for access to the interior in any position. The supporting frame of the oven was designed to leave the area under the oven virtually free of structural members, with the oven floor located approximately five feet above the floor of the laboratory. This provides space for both the loading and deflection-measuring systems without interfering with the movable portions of the oven.

The hot-air heating system uses electric resistance heaters mounted on the front door of the oven, as shown in the photograph, Plate 3.6, along with a blower for circulation. The air is drawn into the centrally located blower, then forced radially outward through a guiding channel, past the circumferentially located heater coils, along the walls to the far end of the oven, and then back past the test specimen to the blower intake, as shown in the sketch, Fig. 3.2. This circulation pattern minimizes radiation from the test specimen by keeping the inside of the oven walls at a high temperature and provides the maximum mixing length before the air

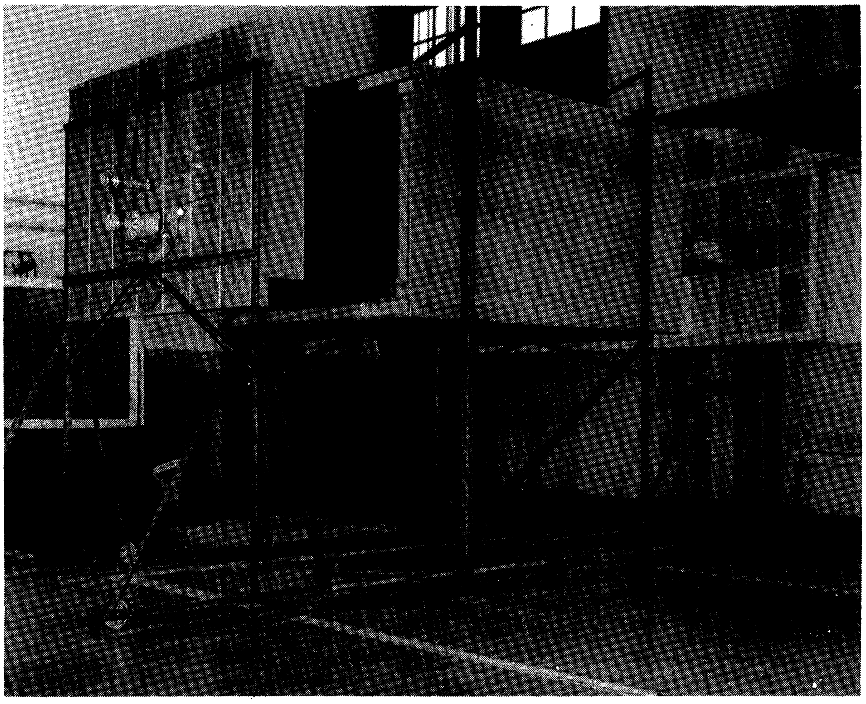


Plate 3.5. Structural testing oven with components separated.

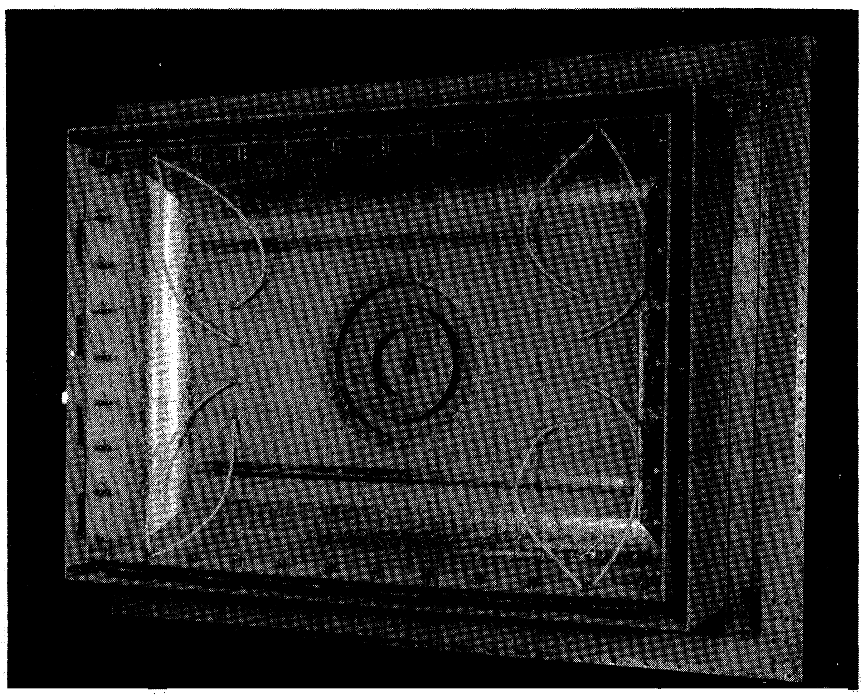


Plate 3.6. Heaters and blower mounted on movable door of oven.

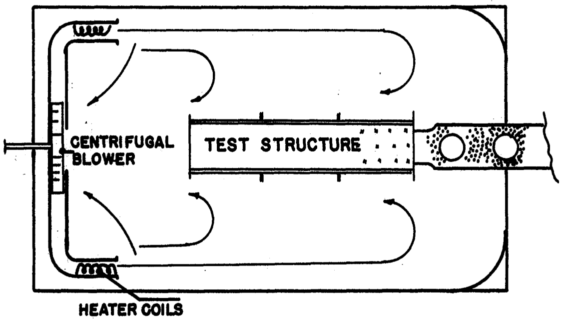


Fig. 3.2. Oven circulation pattern, longitudinal section.

reaches the specimen. This results in very uniform temperatures throughout the specimen. The temperature distribution was determined by instrumenting one box beam with 32 iron-constantan thermocouples, read by means of a Leeds and Northrup portable precision potentiometer. The temperatures in the specimen are both uniform and constant within ± 1°F.

Power for the heaters is supplied from powerstats mounted on a console shown on Plate 3.8. The large central powerstats are used to control the main heaters, and the beam heaters are controlled by the smaller powerstats on either side. Foxboro potentiometer controllers which cut lamp banks in or out of the circuit provide automatic control of the temperature of the test specimen. The control thermocouple is located on the upper surface of the box beam, in the center of the middle bay.

Observation of the specimen during tests is made possible by means of an opening, or window, shown on Plates 3.9 and 3.10. Since the circulation of air is tangential to the oven wall, momentary removal of the window cover produces a very small effect on the temperatures within the oven.

Since it was necessary to pass heavy steel beams through the rear wall of the oven in order to support the test specimen, separate heaters were provided around these beams at the oven wall to prevent quenching of the specimen at the attachment points. The heaters are enclosed in insulated boxes to prevent disturbance of the temperature distribution in the circulating air. These heaters are visible on Plates 3.11 through 3.14.

The steel jig which supports the test specimen, and also the rear door of the oven, consists of two vertical steel channels bolted to the floor and to two heavy steel beams which extend horizontally from the wall at the height of the center of the oven. At the wall, these beams are bolted to a cross channel which is mounted on strong points cast into the concrete wall of the laboratory. Several methods of mounting the test specimen were tried, and the method finally chosen involves the use of steel fittings which are bolted to the horizontal support beams, as shown in the photograph, Plate 3.11. These fittings minimized the local deformation at the root of the test beam, maintained the alignment of successive specimens, and

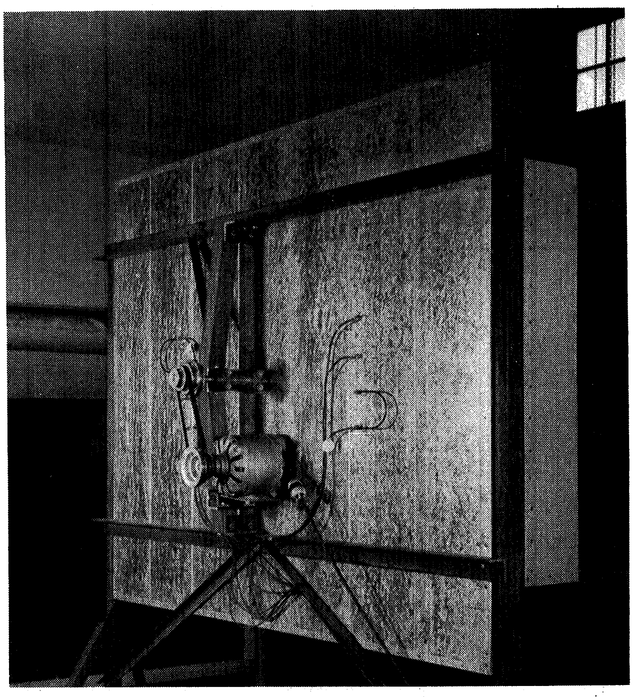


Plate 3.7. Blower motor mounted on movable door of oven.

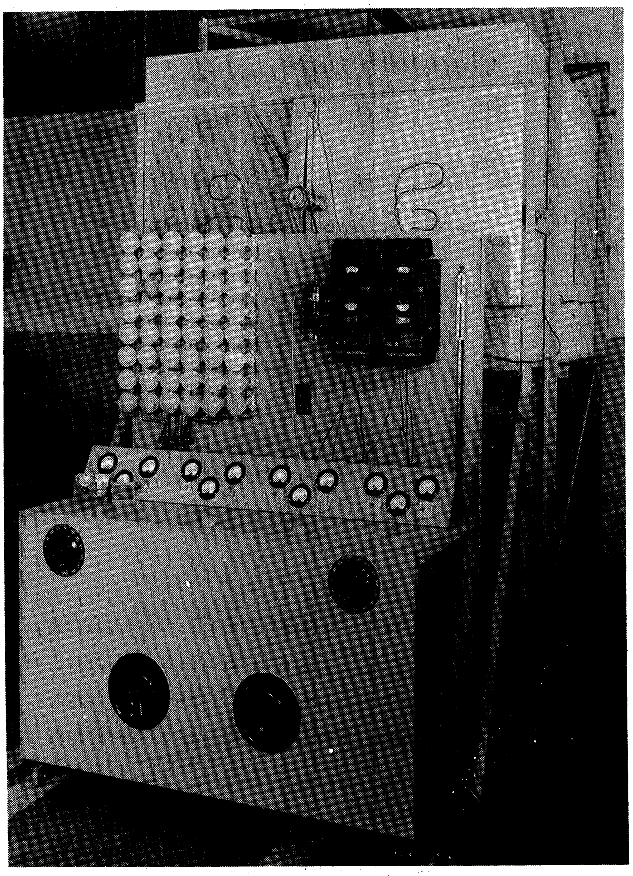


Plate 3.8. Oven control console.

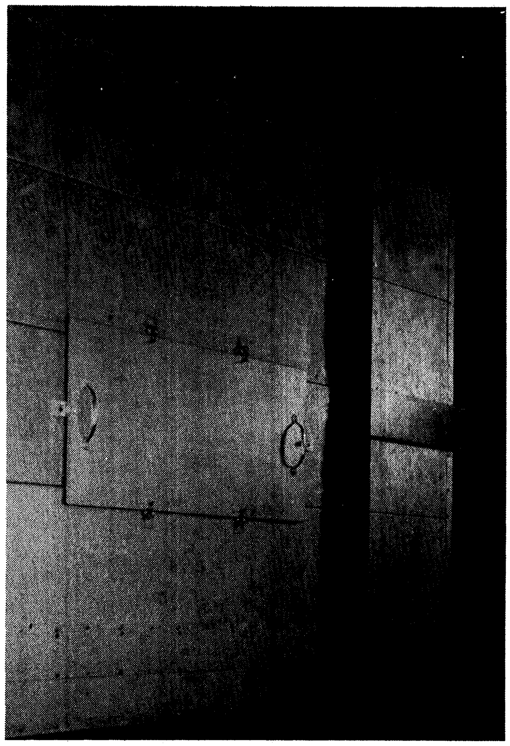


Plate 3.9. Oven window, closed.

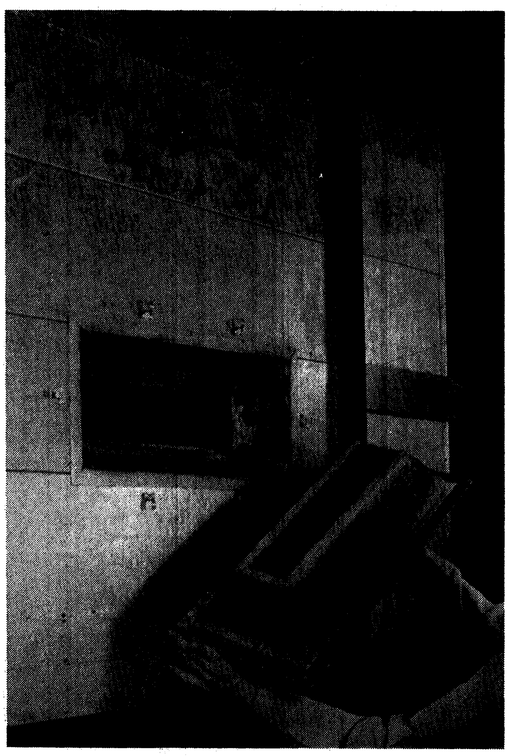


Plate 3.10. Oven window, open.

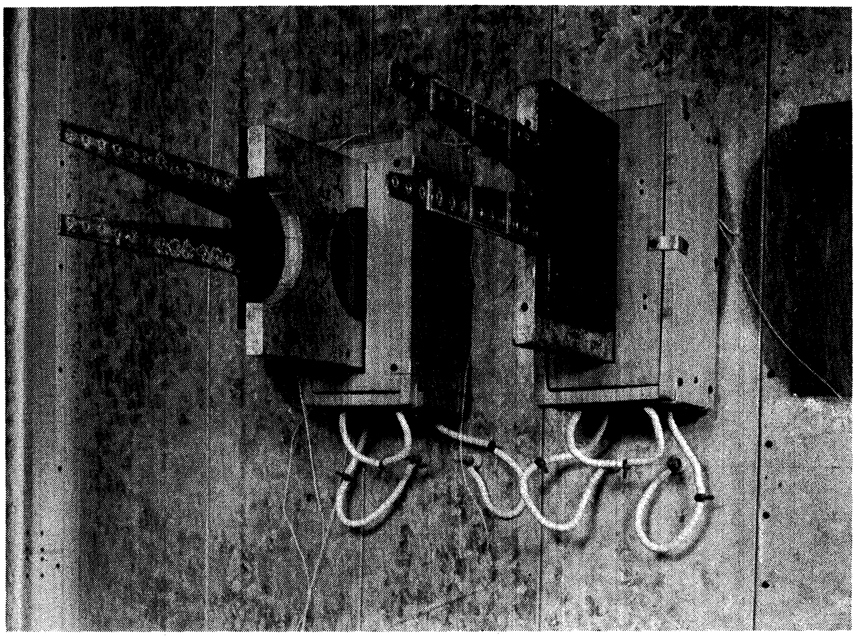


Plate 3.11. Box-beam mounting fittings and beam heaters.

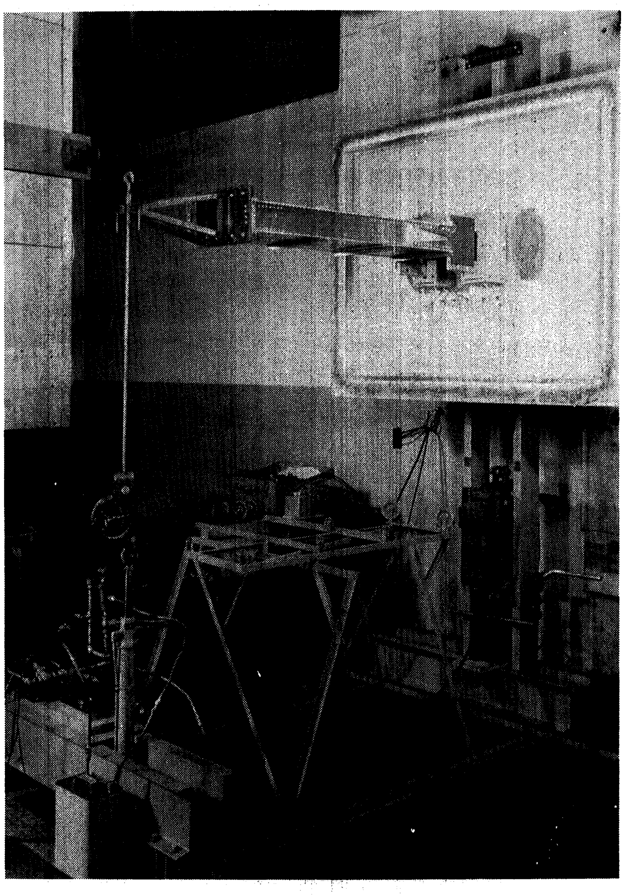


Plate 3.12. Box beam mounted for room-temperature test.

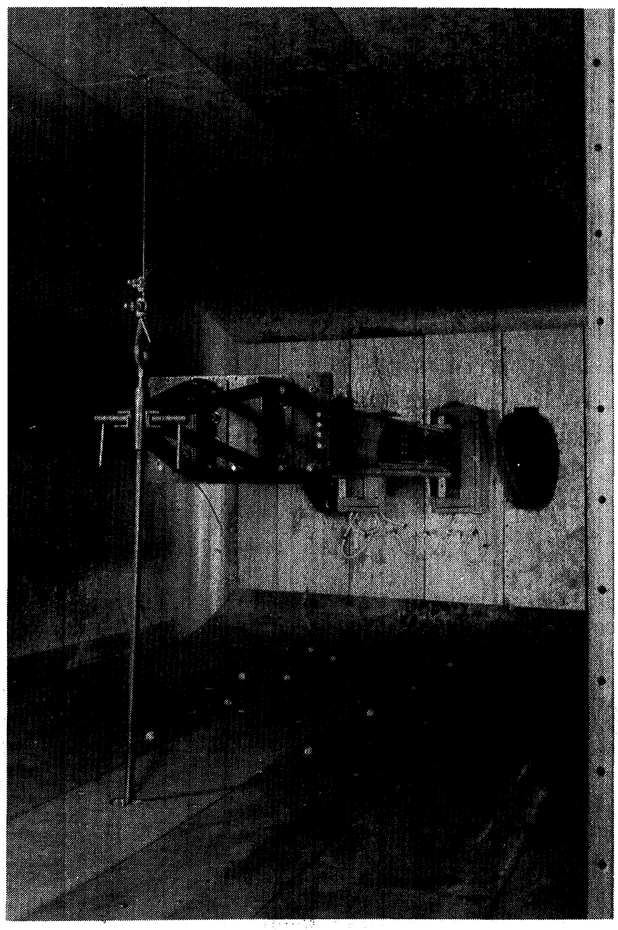


Plate 3.13. Box beam with oven in place.

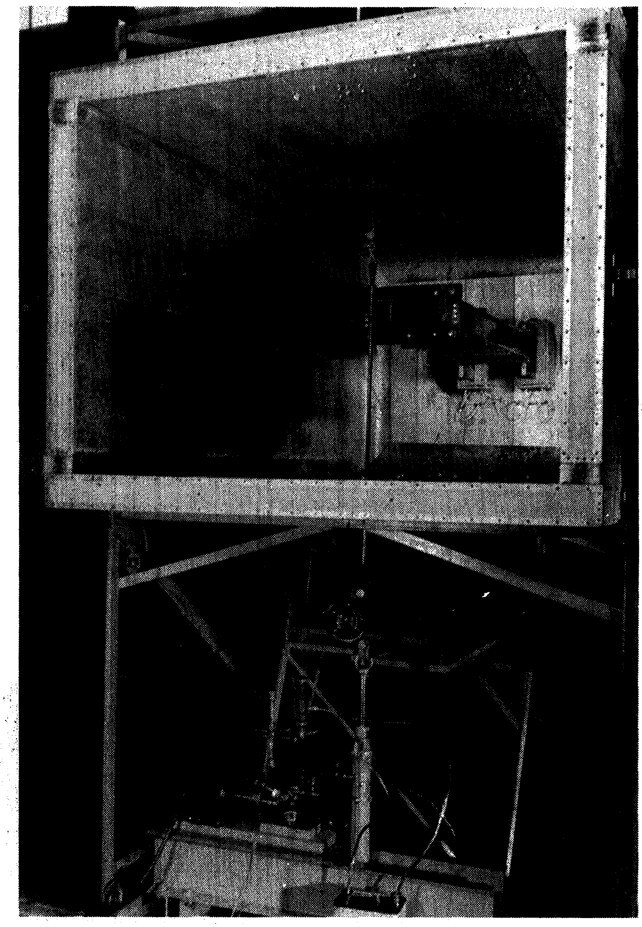


Plate 3.14. General view of test setup with oven door open.

permitted easy and rapid mounting of the specimens. The fittings are permanently attached to the steel jig with bolts and dowel pins to prevent changes in alignment. The box beam is slid into place between the steel fittings, the bolt holes in the box beam are drilled in place, using the holes in the steel fittings as guides, and the box beam is bolted to the fittings with aircraft bolts visible on Plate 3.12.

Beam loads in the plating of the specimen are carried into the spars by shear lag in the reinforced plating of the inner bay, and pass from the spars into the fittings by shear in the bolts attaching the fittings to the shear web. Normal shear is carried from the shear web into the fittings by shear in the same bolts. After the beam has been mounted, and before it is heated or tested, a preliminary load not exceeding 50% of the ultimate load is applied at room temperature in order to ensure that any clearances which may exist in these bolts will not affect later measurements of deflection.

Load is applied to the box beam by means of a boom made up of steel angles and a steel attachment plate, as shown on Plate 3.3. Earlier specimens were five feet long, with four bays, and the load was applied directly to a steel plate which was bolted to the end of the specimen, and the failure occurred in the second bay from the root. However, a saving in labor and material was effected by eliminating the fourth bay and replacing it by the steel boom, which is used repeatedly. Failure still occurs at the same point and with the same moment arm. The presence of the first and third bays ensures that the center bay remains free of end effects.

Except in the case of steady-load tests, the downward load is applied to the end of the boom by means of a hydraulic strut and is read on a tension dynamometer, as shown on Plates 3.12 and 3.14. The load is also read independently by means of a pressure gauge in the hydraulic line. This gauge is mounted on the deflection board, as shown on Plate 3.15, so that both loads and deflections can be recorded at the same time by means of a motion-picture camera. The relationship between pressure and load was established by calibrating the pressure gauge against the direct-reading tension dynamometer, which had itself been calibrated earlier in a Tinius Olsen universal testing machine. Hydraulic pressure is supplied by a motor-driven Vickers gear pump. The pressure, and therefore the load, is controlled by an adjustable pressure-relief valve.

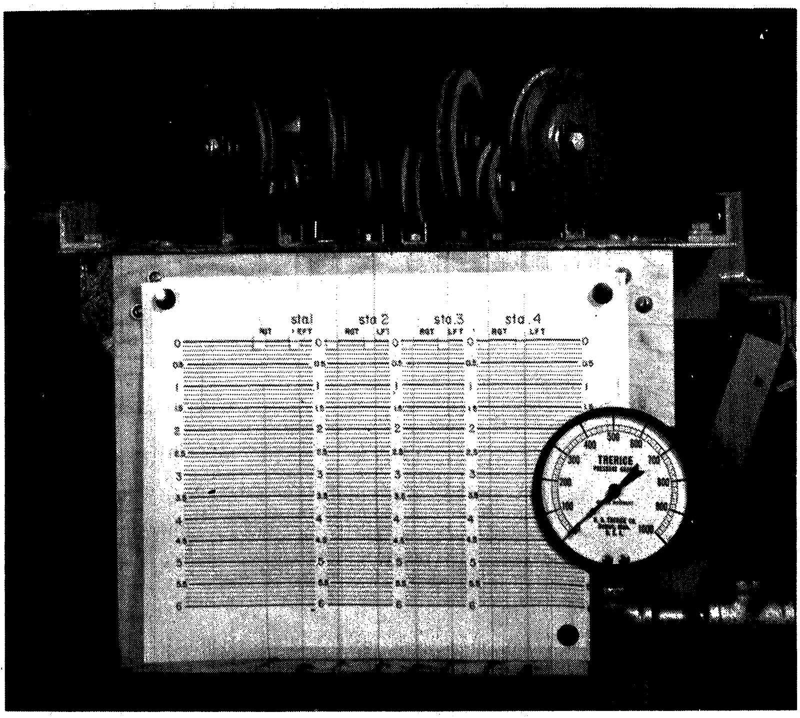


Plate 3.15. Deflection board and pressure gauge.

During rapid-destruction tests, the relief valve is tightened manually, while load and deflection are recorded by means of a motion-picture camera. The cyclic application of downward loads is controlled by a timer which opens and closes the circuit of a solenoid by-pass valve. The value of the downward load is determined by the setting of the pressure-relief valve, and the load is removed by opening the solenoid valve, which vents the hydraulic system to the reservoir. During reversed-load tests, a steel cable is fastened to the end of the boom on the specimen and extends up through the top of the oven, as shown on Plate 3.13, and over two pulleys to a dead weight suspended between the vertical channels of the steel support jig. This weight is visible on Plate 3.12, resting on a hydraulic jack which is used to support the load when it is not in use. For the reversed-load tests, the downward load supplied by the hydraulic strut is equal to the sum of the downward and upward loads which are to be applied to the specimen, and the net load on the specimen is then the desired downward load. When the timer opens the solenoid valve, the pressure is removed from the strut, and the net load on the specimen is the desired upward load, applied by the weight. During steady-load tests, the hydraulic strut is removed and replaced by a suspended platform with dead weights.

Deflections are measured by the following described means. Small steel wires are attached to the box beam at eight points, located as shown on the sketch, Fig. 3.3. These wires extend through small holes in the floor of the oven and over a series of pulleys to a deflection board shown on Plate 3.15. Small weights below the board hold the wires taut, and indices fastened to the wires are used to indicate deflection. The deflections are read visually in the case of steady- and cyclic load tests, while in the case of rapid-destruction tests, the board is photographed by means of a motion-picture camera. The loads and deflections are then transcribed from the film.

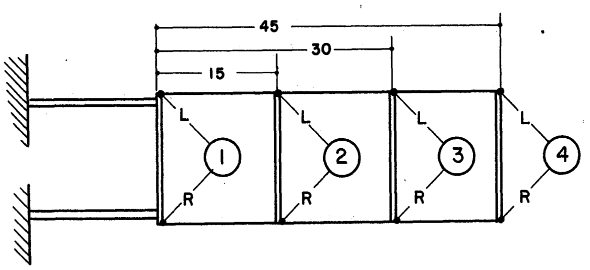


Fig. 3.3. Deflection points for box section, in plan form.

It had been planned initially to correct the deflection readings for jig deflection, but the corrections due to observed jig rotation were small, and the conclusions drawn from deflection measurements were relative rather than absolute. Consequently, no correction was made for jig deflection. The indicated loads are corrected for the dead weights of the specimen, boom, and dynamometer in the manner described in the following chapter. Deflections were read at four stations, but only the average deflection at the tip and the station outboard of the buckle are tabulated in Chapter IV.

CHAPTER IV

TEST RESULTS

The box-beam test specimen and the methods of applying load have been described in a previous chapter. The types of tests carried out in connection with this project are as follows:

1. Rapid-destruction tests, in which the load on the box beam was rapidly increased until failure took place.

2. Steady-load tests, in which a load less than ultimate load was applied continuously to the box beam over a period of time until failure took place.

3. Repeated-load tests, in which a load less than ultimate was applied to the specimen for a short period of time and removed for another short period of time, the load cycle being repeated until failure took place.

4. Reversed-load tests, in which a load less than ultimate was applied to the specimen for a short period of time and removed for another short period of time while a load was applied in the opposite sense, the load cycle being repeated until failure took place.

The actual tests carried out at the various temperatures are tabulated in Table 4.1.

TABLE 4.1

TYPE AND NUMBER OF TESTS

		Rapid-Destruction Tests	Steady-Load Tests	Repeated-Load Tests	Reversed-Load Tests
75°F	No. of Tests	5	--	--	--
300°F	No. of Tests	1	--	--	--
400°F	No. of Tests	2	--	--	--
500°F	No. of Tests	3	1 2	1	1
	% Ult. Load	100	25 50	+50 -0	+50 -25
600°F	No. of Tests	3	1 1 1	1	1
	% Ult. Load	100	25 35 50	+50 -0	+50 -25
700°F	No. of Tests	2	--	--	--

Note: All specimens held at temperature for one-half hour before applying load.

The material properties of 24-ST aluminum alloy are listed in Table 4.2. Values of yield strength as percentages of the corresponding value at room temperature were obtained from Reference 4 and are plotted on Fig. 4.1. The actual value of yield strength at room temperature (75°F) was determined by the average of four tension tests carried out on test specimens machined from the same sheet that was used in constructing the box-beam test specimens. The strain in the tension specimens was read by means of SR-4 electric resistance strain gauges and a Young strain indicator. The values of yield strength at elevated temperature were calculated, using the percentage values obtained from Reference 4.

TABLE 4.2

ELEVATED-TEMPERATURE MATERIAL PROPERTIES
OF 24-ST ALUMINUM-ALLOY SHEET

(1)	(2)	(3)	(4)	(5)	(6)
T	E_T/E_{75}	$\sigma_{ys_T}/\sigma_{ys_{75}}$	σ_{ys_T}	T/T_m	$\sigma_{u_T}/\sigma_{u_{75}}$
75	1.00	1.00	54,000	.322	1.00
300	.94	.87	47,000	.458	.83
400	.875	.78	42,200	.518	.74
500	.78	.50	27,000	.578	.43
600	.70	.27	14,600	.640	.23
700	.535	.15	8,100	.700	.13

(1) Temperature in °F.
(2) Compression modulus, from Reference 3.
(3) Yield stress, from Reference 4.
(4) Yield stress in psi. Room-temperature value by test. Values at elevated temperature from column (3).
(5) Ratio of temperature to melting temperature (absolute).
(6) Ultimate stress from Reference 4.

The values of compression modulus of 24-ST aluminum alloy at elevated temperatures were obtained from Reference 3. These values as percentages of the room-temperature value are listed in Table 4.2 and are plotted on Fig. 2.1. It appears from Reference 3 that there is no systematic variation of modulus with time of exposure to elevated temperature, so these values are considered to be applicable to all tests, regardless of the length of time during which the structure has been held at elevated temperature.

Rapid-destruction tests were carried out using the hydraulic loading system as described in Chapter III. Deflections and pressures were recorded by means of a motion-picture camera. The readings of the pressure gauge were reduced to load on the box beam by a calibration curve, Fig. 4.2. By this means, the relationship between load and deflection can be obtained for any given test. The results of all rapid-destruction tests are tabulated in Tables 4.3 and 4.4. Typical load-deflection curves are shown on Figs. 4.3 and 4.4 at room temperature and 600°F,

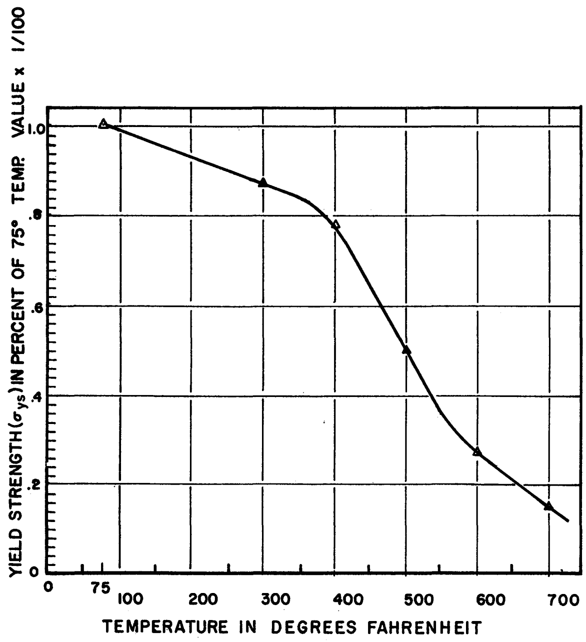


Fig. 4.1. Variation of yield stress (σ_{ys}) of 24-ST aluminum alloy with temperature.

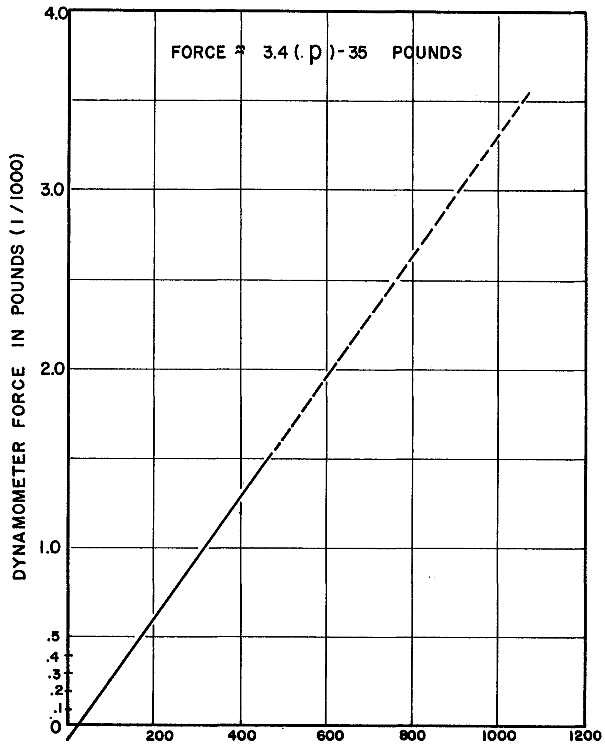


Fig. 4.2. Calibration of pressure gauge.

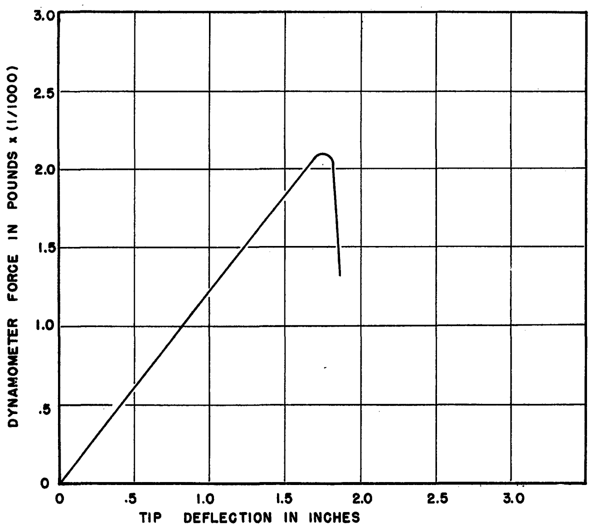


Fig. 4.3. Load-deflection curve for destruction test at 75°F.

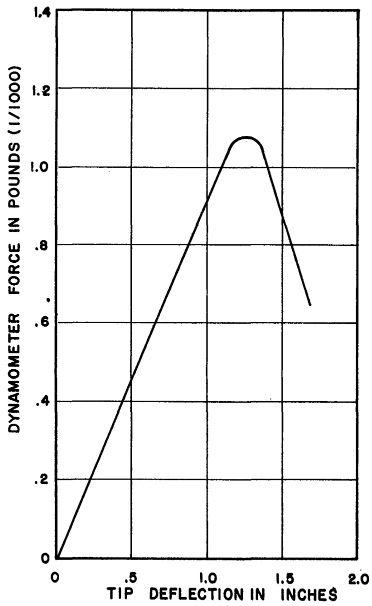


Fig. 4.4. Load-deflection curve for destruction test at 600°F.

TABLE 4.3

RAPID-DESTRUCTION TESTS—SUMMARY OF ULTIMATE LOADS

(1) T	(2) T/T_m	(3) Max. Load P (lb)	(4) $\frac{Mc}{I}$ (psi)	(5) σ_{ys} (psi)	(6) $\frac{Mc}{I}/\sigma_{ys}$	(7) $\left(\frac{Mc}{I}\right)_T / \left(\frac{Mc}{I}\right)_{75}$	(8) E_T/E_{75}	(9) Ultimate Load—Modulus Ratio
75	.322	2090 2090 1890 1990 1970	21,850 21,850 19,750 20,800 20,600	54,000	.381	1.00	1.00	1.00
300	.458	1750	18,300	47,000	.389	.875	.94	.93
400	.518	1753 1757	18,300 18,350	42,200	.435	.875	.875	1.00
500	.578	1700 1620 1600	17,800 16,950 16,750	27,000	.635	.82	.78	1.05
600	.640	1100 1140 1120	11,500 11,800 11,700	14,600	.803	.56	.70	.80
700	.700	662 667	6,930 6,980	8,100	.867	.33	.535	.62

(2) From column (5) of Table 4.2.

(4) $Mc/I = 10.44\ P$ (see Appendix).

(5) From column (4) of Table 4.2.

(6) Average value of $\frac{\text{column (4)}}{\text{column (5)}}$.

(7) Average values of column (4) at temperature T over average value at 75°F.

(8) From column (2) of Table 4.2.

(9) Ultimate load-modulus ratio $= \dfrac{\dfrac{(Mc/I)_T}{(Mc/I)_{75}}}{E_T/E_{75}} = \dfrac{\text{column (7)}}{\text{column (8)}}$.

TABLE 4.4

RAPID-DESTRUCTION TESTS—SUMMARY OF MAXIMUM DEFLECTIONS AT TIP AND STATION 3

(1)	(2)	(3)	(4)	(5)
T (°F)	Maximum Deflection in Inches		Maximum Deflection as Percent of Average at 75°F	
	Tip	Station 3	Tip	Station 3
75	1.73	.95	100	100
	1.85	1.03		
	1.82	.97		
	1.81	.96		
	1.80	.95		
300	1.80	.97	100	100
400	1.74	.94	97	97
	1.74	.94	97	97
500	1.77	.88	98	91
	1.81	.92	100	95
	1.77	.88	98	91
600	1.50	.74	83	76
	1.30	.68	72	70
	1.36	.66	76	68
700	.92	.44	51	46

respectively. These show that the deflection increases almost linearly with load up to a certain point, where the structure is deeply buckled. After this, the load falls off while the deflection continues to increase. The greatest value of load and the deflection at which it occurs are then recorded as the ultimate load and deflection corresponding to the temperature at which the test was carried out.

The loads as read from the pressure gauge on the dynamometer were corrected for the dead weight of the box beam, boom, dynamometer, etc., in the following manner. The moment arms of the boom, dynamometer, tension rod, and the portion of the specimen outboard of the failure station were measured, and the resulting moments at the failure station were calculated. A load of 40 pounds at the end of the boom will produce the same moment, and therefore a correction of 40 pounds was added to the load as read. This corrects the moment, but leaves a very small error in the shear, but this is of no importance, as shear stresses were not taken into consideration during this investigation.

Steady-load tests were carried out by replacing the hydraulic strut with a dead weight and allowing the box beam under test to support the weight until failure took place. Deflections were read visually at varying intervals, depending on the rate at which the deflection was changing. A running plot of deflection as a function of time was maintained during each test, and deflection readings were taken at closer intervals as the rate of change of deflection increased toward the end of the test.

The maximum deflection in the case of the steady-load tests cannot be established in the same way as in the case of the rapid-destruction tests because the load is constant. In the former case, if the deflection is plotted as a function of time, the resulting graph is similar to a creep curve. This is illustrated by Fig. 4.5. This shows that the deflection due to elastic deformation is established as soon as the load is applied. The deflection then increases at a decreasing rate during the first part of the test, as in the case of transient creep. Eventually, a steady rate of change of deflection is established, as in the case of steady-state or second-stage creep, and this continues for the greater part of the test. At length, the rate of change of deflection begins to increase again at an increasing rate, as in the case of third-stage creep, until failure takes place.

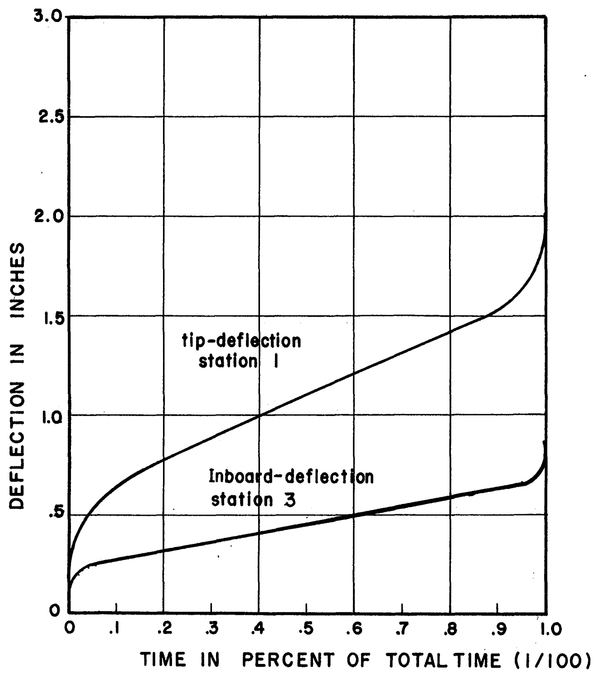


Fig. 4.5. Deflection-time curve for steady load test; 25% of ultimate load at 600°F.

The variation of deflection during the early part of the test is due largely to transient and steady-state creep of the material in both tension and compression. After buckling has been initiated, the additional deflection and the final failure result from creep buckling. Even though the load on the box beam is less than that necessary to cause buckling in the compression surface when the load is first applied, after some time at elevated temperature buckles appear and gradually increase in intensity until collapse of the beam occurs.

For purposes of comparison with other types of tests, it was felt that the value of deflection which is to be specified as the maximum, or critical, deflection should correspond to some time after the appearance of the increasing rate of change of deflection which corresponds to third-stage creep in a creep curve. The deflections which are recorded in Table 4.5 were read from curves similar to Fig. 4.5 at arbitrary times ranging from 95% to 98% of the time required to produce failure. If time had permitted a few more tests, it undoubtedly would have been possible to establish more logical criteria for the determination of critical deflection.

TABLE 4.5

SUMMARY OF STEADY-, REPEATED-, AND REVERSED-LOAD TESTS

(1) Type of Test	(2) T (°F)	(3) Applied Load (lb)	(4) Applied Load Percent of Ult. Load	(5) Time to Failure (hr)	(6) Max. Deflection in Inches Tip	(7) Max. Deflection in Inches Station 3	(8) Max. Defl. as % of Avg. Value at 75°F Tip	(9) Max. Defl. as % of Avg. Value at 75°F Station 3
Steady Load	500	395	24	468.15	1.74	.76	97	78
		825	50	10.22	1.65	.78	92	80
		825	50	12.42	1.75	.82	97	85
	600	280	25	45.10	1.60	.70	89	72
		390	35	8.20	1.55	.65	86	67
		560	50	1.68	1.50	.64	83	66
Repeated Load	500	825	50	17.28	1.65	.82	92	85
	600	560	50	2.08	1.35	.67	75	69
Reversed Load	500	+ 825 - 412	+ 50 - 25	19.43	1.70	.80	94	82
	600	+ 560 - 280	+ 50 - 25	2.68	1.30	.69	72	71

Repeated-load tests were carried out as described in Chapter 3. A wide range of on-off load cycles can be obtained with the timer, but it was arbitrarily decided in this case to use a cycle in which the load is applied for a period of time twice the length of time in which the load is off. The cycle chosen was 70 seconds on and 35 seconds off, as 35 seconds is about the minimum time in which the eight deflections can be read and recorded.

The variation of deflection with time is exemplified by Figs. 4.6 and 4.7. The curve of deflection under load is quite similar to the deflection curve for the steady-load tests. However, there is now a second curve which represents the deflection with the load removed, or the permanent set at any given time. These two curves diverge slightly, showing that the incremental deflection of the structure under load is somewhat greater toward the end of the test, when well-developed buckles have appeared in both lower plating and shear web. The maximum deflections recorded in Table 4.3 were found in the same manner as for the steady-load tests.

The reversed-load tests were similar to the repeated-load tests, except that the load cycle was plus-minus instead of on-off. Since the loads on an aircraft

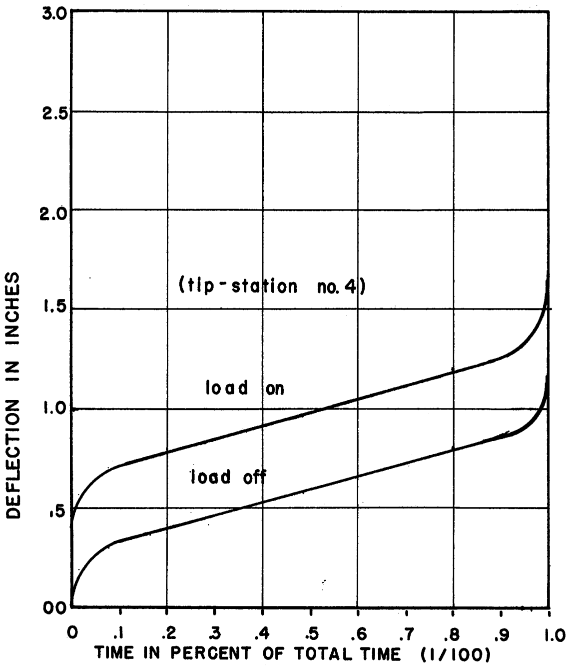


Fig. 4.6. Deflection-time curve for repeated-load test; 50% of ultimate load at 600°F.

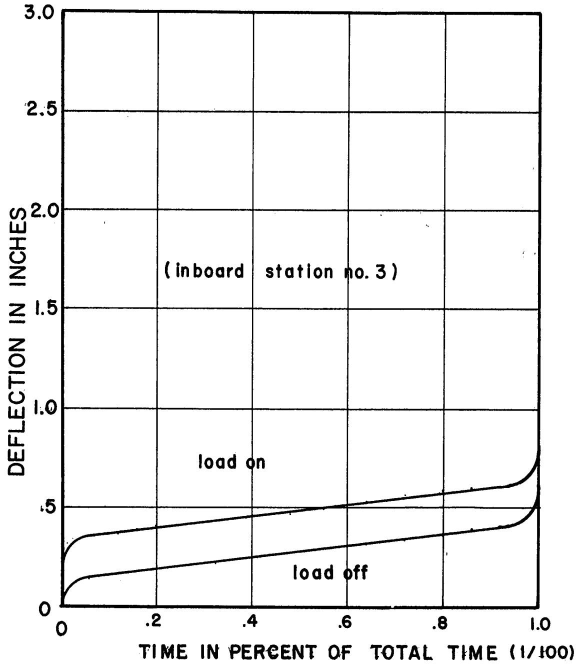


Fig. 4.7. Deflection-time curve for repeated-load test; 50% of ultimate load at 600°F.

structure are always greater in one direction than in another, the loads arbitrarily chosen for this test were +50% and -25% of ultimate load at 500° and 600°F. Time did not permit more than these two tests.

In the case of both repeated- and reversed-load tests, during the time interval that the load was applied, the deflection was not constant, but increased slightly in the direction of the load application. It was therefore necessary to read the deflections systematically (in this case, from tip to root) in order to avoid increased scatter of test points. This behavior was predicted by Figs. 2.3 and 2.4 of Reference 2, which indicate qualitatively the behavior of structures or materials under repeated and reversed stress cycles, respectively. It was hoped that this could be investigated in detail for a few cycles of larger load by the use of the motion-picture camera. However, sufficient time was not available.

After some of the tests on box beams had been completed, the values of modulus of elasticity at various elevated temperatures, as listed in Table 4.2, were checked in the following manner. Within the elastic range, the deflection of the box beam under a given load should vary inversely as the modulus of elasticity, or the deflection, δ, at any temperature, T, is related to the deflection at 75°F by the equation

$$\delta_T = \frac{E_{75}}{E_T} \times \delta_{75} \qquad (4.1)$$

If the load, P, is different at elevated temperature than at room temperature,

$$\delta_T = \frac{E_{75}}{E_T} \times \frac{P_T}{P_{75}} \times \delta_{75} \quad . \tag{4.2}$$

From Fig. 4.3 the room-temperature test deflection at the tip station of the box beam under a load of 1000 lb is

$$\delta_{75} = 0.81 \text{ in.}$$

From Fig. 2.1 the modulus of elasticity at 600°F is 70% of the room-temperature value. Therefore, under a load of 500 lb, the deflection at 600°F should be

$$\delta_{600} = \frac{100}{70} \times \frac{500}{1000} \times 0.81 = 0.578 \text{ in.}$$

The actual deflection under these conditions, from Fig. 4.4, is seen to be 0.56 in. This is within 5% of the calculated value, which is a reasonable check on the modulus value.

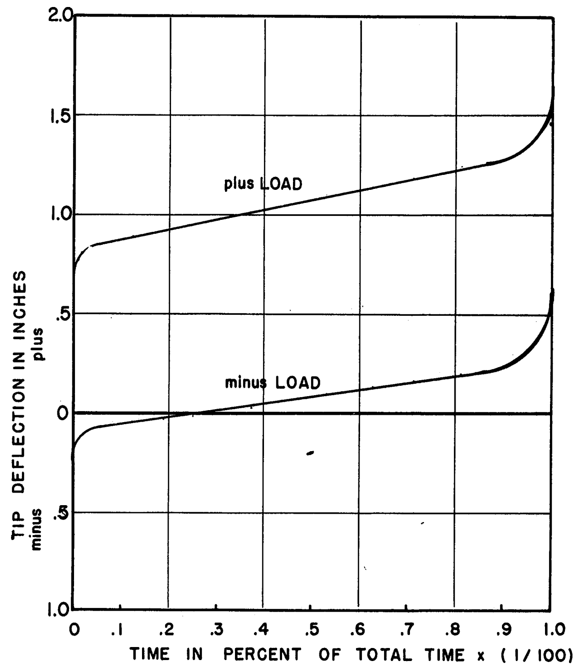


Fig. 4.8. Deflection-time curve for reversed-load test plus 50% ultimate / minus 25% ultimate (at 600°F).

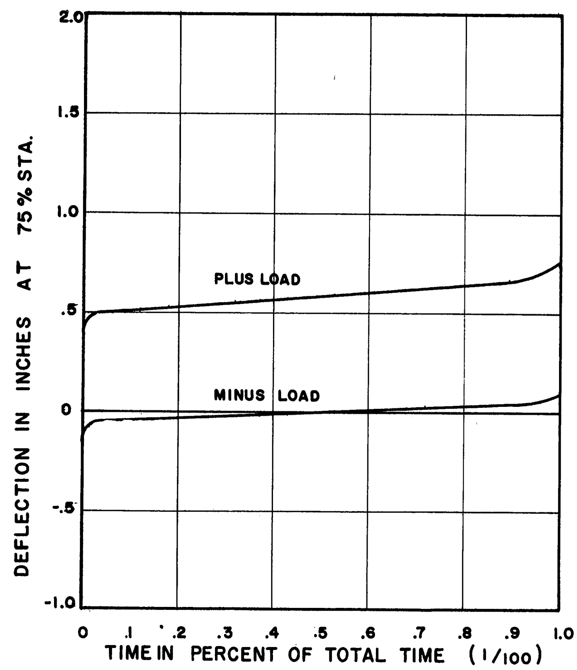


Fig. 4.9. Deflection-time curve for reversed-load test plus 50% ultimate / minus 25% ultimate (at 600°F).

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Metallurgists frequently refer to the temperature ranges above and below approximately half the absolute melting temperature of a metal as the high-temperature and low-temperature ranges, respectively, and the properties of the structural metals are markedly different in the two ranges. This is exemplified by the behavior of aluminum alloys. In the low-temperature range, the ultimate and yield stresses generally decrease with increasing temperature, but the variation with temperature is not large. As shown by Fig. 5.1, the yield stress of 24-ST aluminum alloy after one-half hour at half the melting temperature (approximately 375°F) is still over 80% of the value at room temperature. In the high-temperature range, the yield and ultimate stresses decrease rapidly, both with temperature and with duration of exposure to elevated temperature. For instance, after one-half hour at 70% of the melting temperature, the yield stress of 24-ST aluminum alloy is less than 15% of the room-temperature value. This is too low to be of any value in structural applications, so the useful range in the case of this alloy is limited to temperatures below about 65% of the melting temperature.

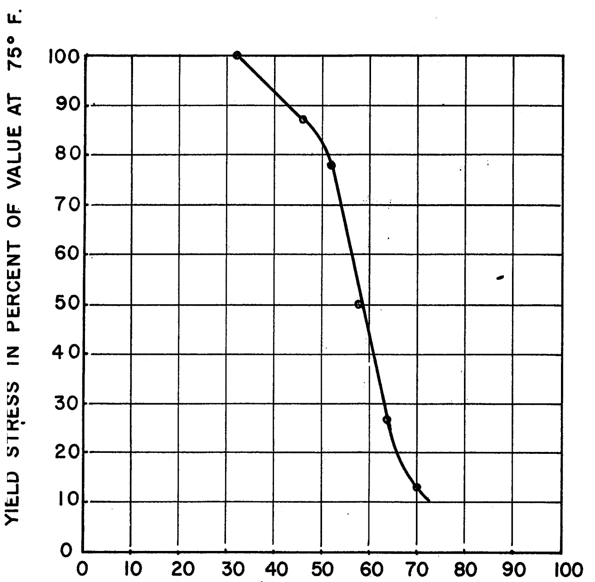


Fig. 5.1. Variation of yield stress of 24-ST aluminum alloy with temperature (one-half hour exposure).

Another distinguishing characteristic of the high-temperature range is the fact that in this range creep becomes significant. In the case of 24-ST aluminum alloy, a steady tension creep rate of 0.00001 inch per inch per hour is developed under a stress equal to half the yield stress at 375°F, which is approximately half the melting temperature, whereas at 300°F, this creep rate is not developed below the yield stress (Reference 4). As a consequence, in the low-temperature range, creep is customarily neglected in structural design at stresses below the yield stress. The effect of creep is plainly evident in the results of the load tests on the box beams used in this investigation. For instance, at 600°F the box beams were able to support 25% of the corresponding ultimate load for about a day and a half, while under 50% of ultimate load, failure occurred in about an hour and a half. At room temperature such loads can be supported indefinitely. The life of a structure in the high-temperature range is therefore limited, because of creep, and is dependent on the stress level. The series of 26 tests described in Chapter IV sheds additional light on the tentative conclusions drawn from the series of six tests on AT-6 aircraft fins which were reported in Reference 2. The first conclusion from the earlier tests, as stated in Chapter I, is undoubtedly true; that is, for a series of identical structures, built essentially of a single alloy, if the failure during a room-temperature test is due to buckling, then at elevated temperatures the failure probably will be of the same type and in the same location, regardless of whether the failure results from the rapid application of the maximum load that the structure can support, the steady or cyclic application of smaller loads, or even the application of loads which are reversed in direction at intervals. Plate 5.1 shows a series of four box beams which were tested by the application of rapid-destruction loads at temperatures of 75°F, 300°F, 500°F, and 600°F, respectively. Plate 5.2 shows a series of four specimens, all of which were tested at 600°F, but with different types of loading. One of these failed as a result of the application of a destruction load during a period of approximately 20 seconds, the second was loaded with 50% of this load and failed after 1.68 hours, the third supported an intermittently applied load of the same magnitude for 2.08 hours, while the fourth was loaded alternately with 50% of ultimate load in one direction and 25% in the other direction, which resulted in failure after 2.68 hours. All failures are at the same location, and the buckle pattern is substantially the same in all cases. In fact, it is impossible to distinguish between the specimens except by means of the labels.

No tests have been carried out on structures which fail by a tension break

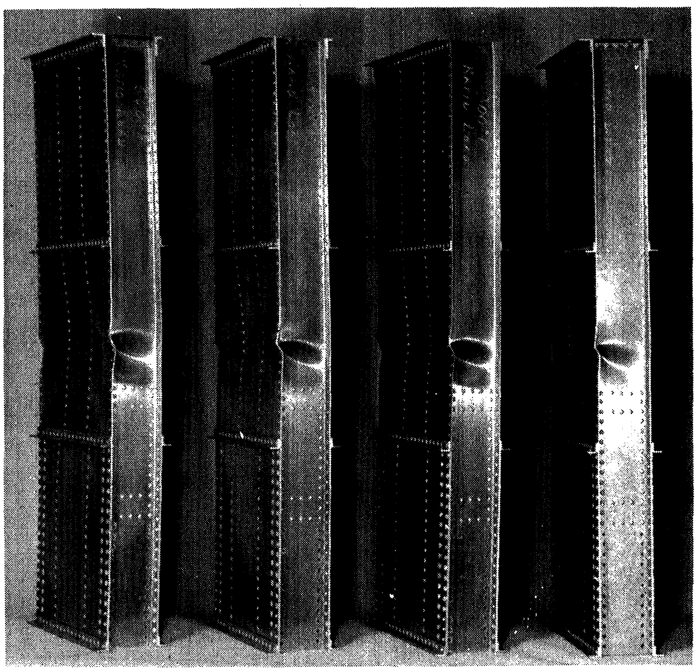


Plate 5.1. Box beams after destruction tests at 75°, 300°, 500°, and 600°F.

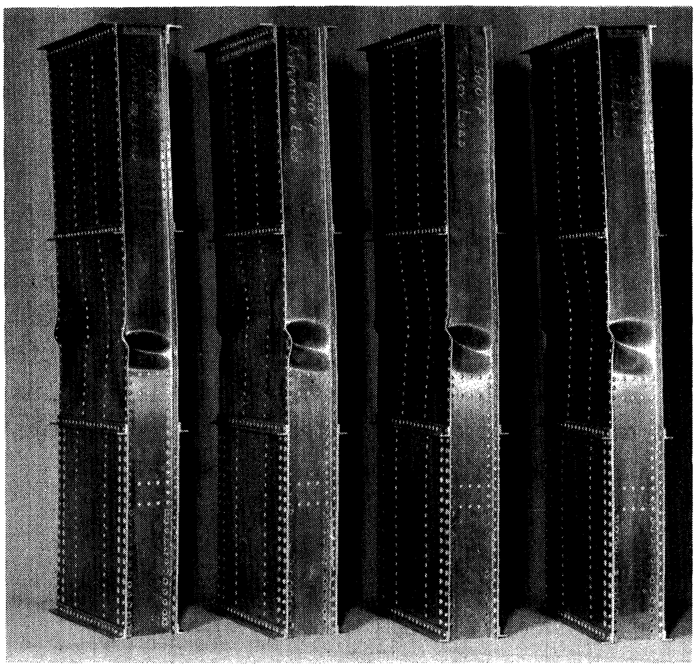


Plate 5.2. Box beams after destruction, steady-load, repeated-load, and reversed-load tests at 600°F.

instead of by buckling. The load at which such a structure would fail in tension at elevated temperature should be proportional to the ultimate strength of the material at the temperature in question. As shown by Fig. 2.2, both yield strength, which governs the ultimate load on a structure in the case of buckling failure, and the ultimate strength, which governs the ultimate load in the case of tension failure, decrease with temperature, but the ultimate strength, in the case of 24-ST aluminum alloy, decreases at a slightly more rapid rate. Furthermore, as discussed later in this chapter, the buckling ultimate strength of the box beams, as a percent of yield strength, increases with temperature. Therefore, if a structure fails by tension at room temperature, it cannot fail by other means at elevated temperature. However, this introduces the possibility that if the margin of safety in tension is only slightly positive when a structure fails by buckling at room temperature, then at elevated temperature the same structure may fail by tension. This tendency will be counteracted, to some extent at least, by the greater total elongation in tension at elevated temperatures, but additional tests will be required to determine if this is the case.

In the light of tests carried out to date, the following conclusion is set forth:

<u>Conclusion 1</u>. If a given structure is tested at room temperature, and an identical structure is tested at elevated temperature, it is probable that the failure at elevated temperature will be of the same type and in the same location as the failure at room temperature. It is possible that there may be an exception in the case of a structure which fails by buckling at room temperature but

which has a very small positive margin of safety in tension at the same load. Additional tests will be required in order to determine if this possibility exists.

It was tentatively concluded, as a result of the tests reported in Reference 2, that when a structure fails by buckling, the deflection at failure will be approximately the same at elevated temperatures as at room temperature. When the deflections of a structure are small, so that the material is stressed within the elastic range and no portion of the structure has buckled, thus altering the geometry and therefore the stress distribution, the deflection at any point will be proportional to the load and to the reciprocal of the modulus of elasticity. Under such conditions, the deflection of a structure at any temperature, T, is related to the deflection at 75°F by the relation

$$\frac{\delta_T}{\delta_{75}} = \frac{P_T/P_{75}}{E_T/E_{75}} \quad . \tag{4.2}$$

For convenience, the right-hand side of the above equation will be designated as the "load-modulus" ratio. In theory, Equation 4.2 does not hold true except under the conditions of small deflections, elasticity, and nonbuckling, as stated above. However, the engineer is frequently able to draw usable conclusions from the judicious use of formulae and equations under conditions which violate the assumptions used in their derivation. A familiar example is the concept of "modulus of rupture," which uses the formula for extreme fiber stress in a beam as a means of determining the ultimate loads which can be supported by beams of certain cross sections and materials. In the present case, if the loads and corresponding deflections are those at ultimate load, the right-hand side of Equation 4.2 becomes the "ultimate" load-modulus ratio, and for the box beams tested in connection with this investigation, average values of this ratio are plotted on Fig. 5.2 as functions of temperature. There is considerable scatter, but the value appears to remain substantially constant at unity until the temperature has reached at least half the melting temperature, and to decrease at higher temperatures.

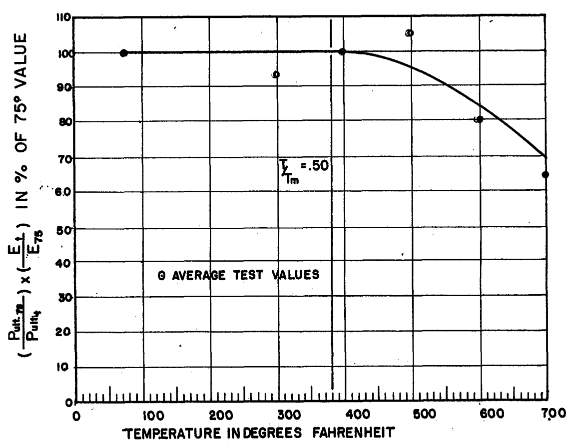


Fig. 5.2. Ultimate load-modulus ratio as a function of temperature.

From an examination of Fig. 5.2, it would be expected that the deflections of this structure at ultimate load should be substantially the same at temperatures up to at least 400°F, and to decrease at higher temperatures. That this is the case is indicated by Figs. 5.3 and 5.4, which show test points corresponding to deflections under ultimate load at various temperatures and various types of loading, with the curve of Fig. 5.2 superimposed for purposes

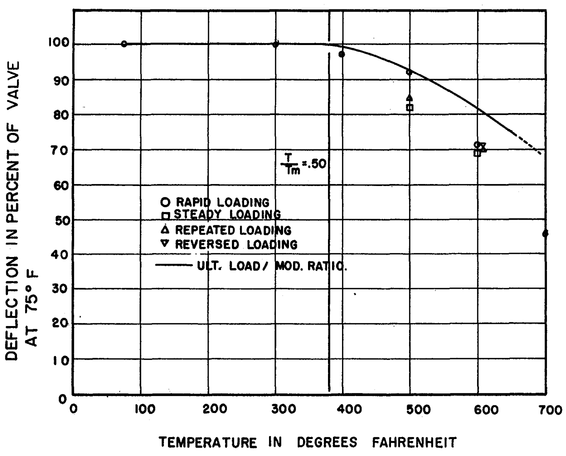


Fig. 5.3. Average deflection at the tip station.

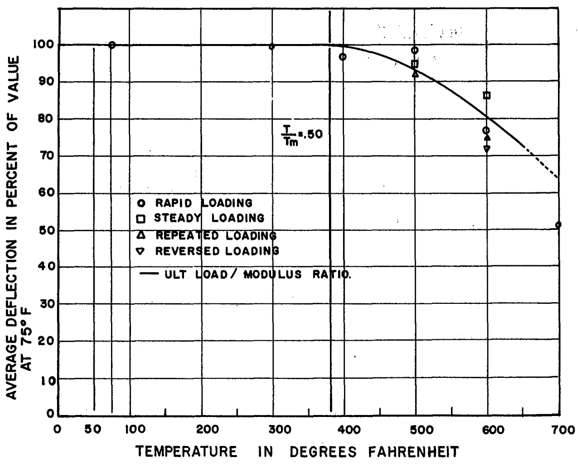


Fig. 5.4. Average deflection at outboard station of center panel.

of comparison. There is considerable scatter, but in general, the correlation is as good as can be expected in view of the assumptions used in the derivation of Equation 4.1, as well as the limited number of test data.

The following conclusion summarizes the foregoing discussion:

Conclusion 2. The deflection at ultimate load of a built-up aluminum-alloy aircraft structure which fails by buckling is substantially independent of temperature up to at least 400°F and decreases somewhat above this value. If the ultimate load at any given temperature is known or can be calculated, the corresponding deflection can be estimated approximately by means of the ultimate load-modulus ratio (Equation 4.1) if the values given by this ratio in the 500° to 600°F range are reduced by about 10%, or

$$\left(\frac{\delta_T}{\delta_{75}}\right)_{ult} = K \frac{\left(\frac{P_T}{P_{75}}\right)_{ult}}{\left(\frac{E_T}{E_{75}}\right)} , \qquad (5.1)$$

where K is unity below 400°F and 0.90 above 500°F.

Since the maximum deflection at elevated temperature is never greater than room temperature, and is actually less at extreme temperatures within the useful range, there is no danger that excessive deflection due to elevated temperature can cause malfunction of any mechanical part of an aircraft at loads less than ultimate. If the mechanism is satisfactory under the maximum allowable load at room temperature, then it will not be rendered inoperative by deflection alone at elevated temperatures.

At any given temperature there was no significant difference in the deflections at failure, whether the failures were caused by rapidly applied loads, steady loads of smaller magnitude, or cyclic loads in one or both directions. This fact is of considerable importance in estimating the life of aircraft, which are normally subjected to variable loads that are predominantly in one direction, but with occasional reversals. At room temperature these loads, which are well below the ultimate load, produce elastic deformations which result in no permanent set, and, apart from the question of fatigue, the ultimate strength of an aircraft component is substantially constant throughout its life, which may be thousands of hours of flying time, or many years of elapsed time. At elevated temperatures the permanent distortion under light loads increases with time, and since the structure always fails when the deflection reaches a certain critical value, the useful life is limited to a value less than the time required for the applied load to develop the critical deflection. The maximum load which can be supported at any time is that load which will produce the critical deflection. As the permanent set under light loads increases, the added load increment which will cause failure decreases, so that the ultimate strength of the structure is not constant, but decreases with time. Therefore, at elevated temperatures the allowable load factor on an aircraft will decrease with time, and the useful life of the aircraft will end when this permissible load factor falls below a certain value which depends on the mission of the aircraft. The probable remaining life at any time should be determinable as a function of the amount of permanent set which can be observed in critical portions of the structure. Whether this is also true of structures which fail by tension can be established only by additional tests.

The conclusion discussed above is summarized as follows:

> Conclusion 3. At any given temperature a built-up aluminum-alloy structure which is critical in buckling will always fail when the deflection reaches a certain maximum value, regardless of whether the applied load is rapidly increased to its ultimate value, or whether smaller loads are applied steadily or cyclically over longer periods of time. The permissible load on a lightly loaded structure at elevated temperatures decreases with time, since the load increment required to produce failure decreases as the deflection under lighter loads increases and approaches the critical deflection. The ultimate strength and the probable remaining life of the structure at any given time are therefore functions of time and of the amount of permanent set observable in critical parts of the structure.

A theoretical means of predicting the ultimate strength of a structure at elevated temperatures from the results of room-temperature tests does not appear to be capable of development, as practically all theories of structural behavior assume that the structure is stressed well below the yield point and that the deflections are sufficiently small that the stress distribution is unaffected. However, an empirical means of predicting elevated-temperature strength with reasonable accuracy would be quite as acceptable to the structural designer, and it now appears possible that such an empirical procedure can be developed.

If a structure fails by tension, it has already been shown that the structure will fail in the same manner at any temperature within the useful range. The load at which failure occurs probably will be proportional to the ultimate strength of the material at the temperature in question. However, additional tests should be carried out in order to substantiate this.

Using the value of Mc/I at ultimate load, or the modulus of rupture, as an indication of the maximum stress level in the structure at the point of failure, in the case of structures which fail by buckling, this value appears to be approximately a constant percent of the corresponding yield stress at temperatures up to half the melting temperature (absolute). Above this value, the percentage increases almost linearly with temperature, as shown in Fig. 5.5, at least within the useful range. The reason for the fact that both the high-temperature and low-temperature branches of the curve are nearly linear is apparent from an examination of Fig. 5.1, which shows the yield stress of 24-ST aluminum alloy as a function of the absolute temperature. This curve is nearly linear in the low-temperature range and also in the high-temperature range up to about 65% of the melting temperature, which is the approximate upper limit of the useful range for this alloy. It is probable that neither of these curves is exactly linear, but they approximate linearity, and the use of straight lines will make it easier to use Fig. 5.5 or other similar curves for the prediction of the elevated-temperature strength of other configurations.

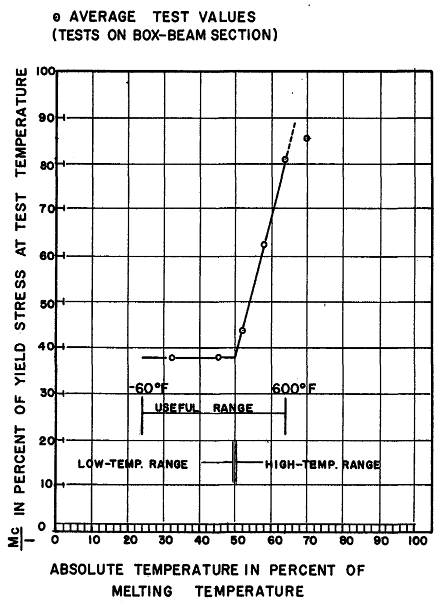


Fig. 5.5. Ratio of Mc/I to yield stress as a function of temperature ratio for 24-ST aluminum-alloy box beam (one-half hour exposure).

It is probable that for any structure, at least if the failure is by buckling, the value of modulus of rupture as a percent of yield stress will vary with temperature in a manner similar to Fig. 5.5, except that in the low-temperature range the value of modulus of rupture will depend on the configuration of the structure. Thick-skin structures will fail at higher percentages of yield stress than thin-skin structures with light stiffeners. In either case, the percentage probably will increase in the high-temperature range, as in the case of Fig. 5.5, and it should be possible to determine a family of such curves for any given alloy by testing a number of specimens which differ in stiffness, so that failures of the different specimens at room temperature will take place over a wide range of stresses. If a single family of curves can be used to represent, with reasonable accuracy, the behavior of all specimens constructed from a given alloy, then it will be possible to predict, with similar accuracy, the elevated-temperature strength of any structure from the results of a test at room temperature. In the case of preliminary design, the calculated room-temperature strength of a proposed structure can be used to estimate the strength at any temperature.

Conclusion 4. It is probable that the elevated-temperature strength of any structure can be predicted, with at least sufficient accuracy for preliminary design purposes, from the results of a test at room temperature. If the structure fails by tension, the failing load at elevated temperature probably will be proportional to the elevated-temperature ultimate tensile strength of the material. If the structure fails by buckling, the elevated-temperature strength can be estimated by means of curves similar to Fig. 5.5. Further testing will be required to substantiate this conclusion and to derive the required families of curves for different alloys.

The four conclusions set forth above open the way for the development of simplified means for establishing the suitability of any aircraft structure for use at speeds which result in the production of steady elevated temperatures in the primary structure, and also the development of simplified procedures for the design of such craft. These procedures will be applicable to the design of aircraft or guided missiles which will operate for sustained periods of time in the low supersonic flight range. It may be possible to eliminate much elevated-temperature testing, which is inherently expensive and requires elaborate and costly facilities, and thereby develop high-speed aircraft more economically.

However, much additional work remains to be done before such simplified procedures can be established. Accordingly, it is highly desirable that studies and tests necessary in order to develop these procedures be initiated without delay. The following specific recommendations relate to the four conclusions previously discussed.

1. It is recommended that structural tests be carried out on specimens having a tension margin of safety at room temperature slightly greater than the margin of safety in buckling, in order to determine if such a structure will fail by buckling at room temperature and tension at elevated temperature, and, if so, to determine the magnitude of the ultimate load at elevated temperature in comparison with the load which would be predicted on the basis of buckling failure.

2. It is recommended that structural tests be carried out at elevated temperatures on specimens which fail in tension, in order to determine whether the ultimate load-modulus ratio can be used to predict the deflection under ultimate load or whether some function of total elongation can be used.

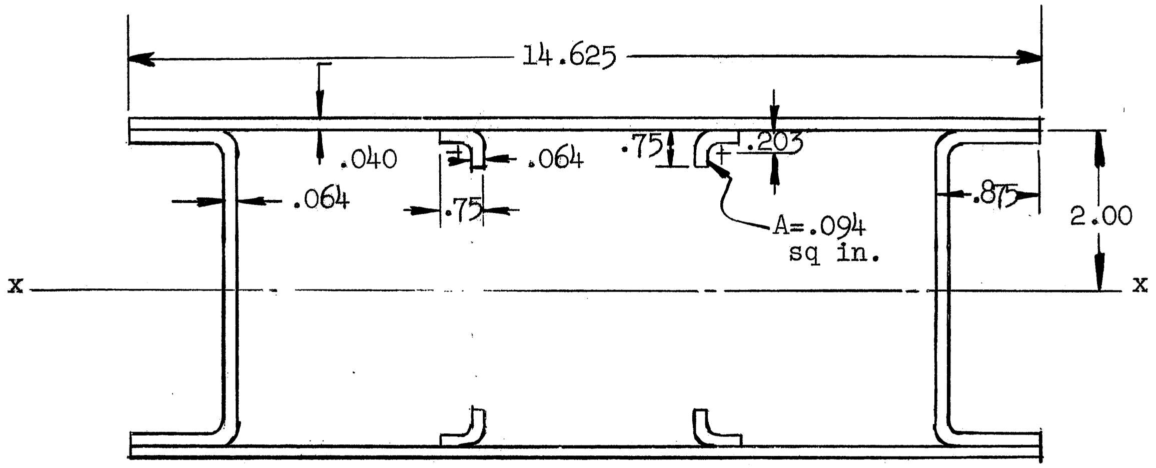
3. It is recommended that structural tests be carried out on a series of identical specimens in order to determine procedures for predicting the residual maximum load which can be supported after various amounts of permanent set have occurred as a result of the application of light loads for various periods of time, to determine if the type of load (steady or cyclic) affects the residual maximum load, and to determine the effect of repeated cycles of heating and cooling. These tests will establish the basic criteria for the determination of the useful life of aircraft which operate at elevated temperatures.

4. It is recommended that structural tests be carried out on structures which

fail by buckling at various percentages of yield stress, and also on structures which fail by tension, in order to establish the generality of conclusion 4, and to derive the empirical data on which to base the prediction of elevated-temperature strength from the results of room-temperature tests. The structures tested should be constructed of several commonly used alloys.

APPENDIX

MOMENT OF INERTIA OF BOX BEAM AT MIDSECTION



Dimensions in inches

$$I_{xx} = 2 \times 14.625 \times 0.040 \times 2.02^2 + 4 \times 0.875 \times 0.064 \times 1.968^2$$

$$+ 4 \times 0.094 \times 1.797^2 + 2 \times 1/12 \times 0.064 \times 4.00^3$$

$$= 7.473 \text{ in.}^4$$

Moment arm from point of failure to point of load application = 39 in.

$$\therefore M = 39 P$$

where P is total applied load including dead-weight correction

$$\therefore \frac{Mc}{I} = \frac{39P \times 2.00}{7.473} = 10.437 P$$

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