U.S. Department of Commerce, Bureau of Standards

RESEARCH PAPER RP662

Part of Bureau of Standards Journal of Research, vol. 12, 1934

TEST OF A FLAT STEEL-PLATE FLOOR UNDER LOADS

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ABSTRACT

In cooperation with the American Institute of Steel Construction, Inc., a flat steel-plate floor was tested under loads to determine its strength and whether the floor behaved as a unit when loads were applied. The span was 18 ft. and the floor was built of 4-in 7.7-lb per ft steel I-beams and steel plates, 24-in wide and ¼-in thick. Strain-gage and deflection readings were taken.

Continuous manual welds joining the plates to the I-beams, made by using bare metallic electrodes (5/32-in diameter) and the direct-current arc-welding process, united the plates and the beams so that they behaved as a unit when loads were applied.

The measured stresses and the measured deflections were in substantial agreement with values computed by the ordinary theory of beams.

This floor carried a load of 420 lb per sq ft for 5½ days without any indication of collapse. The deflection under this load was 3⅞ in. After this load was removed the permanent deflection was 2¾ in.

The results of this test give no indication as to the maximum spacing of the beams for which the entire width of the plate is effective. The results indicate that for ordinary spans if the spacing of the beams does not exceed 100 times the thickness of the plate the entire width may be assumed effective when designing a flat steel-plate floor of the type tested.

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I. INTRODUCTION

The American Institute of Steel Construction has developed a type of floor which they call a "battledeck floor." Such a floor consists of rolled steel I-beams and steel plates laid parallel to the beams so that the joints are over the middle of the upper flange. The edges of the plates are not in contact but are separated a distance about equal to the thickness of the plates. The plates are welded to each other and to the flange of the I-beam. The welds may be either continuous or intermittent.

The floor may be fireproofed. If resistance to fire is not necessary, linoleum, rubber tile, etc., may be applied directly to the upper surface of the floor.

In cooperation with the Bureau of Standards, the American Institute of Steel Construction, Inc., outlined a program to determine the strength and, also, the resistance of battledeck floors to fire.

The loading test on one floor was made by the engineering mechanics section of the Bureau. S. H. Ingberg, chief of the fire resistance section of the heat and power division, assisted in planning the loading test. The results are given in this paper.

The Institute was represented by F. H. Frankland, Director of Engineering Service. The floor was fabricated under the direction of C. W. Welch, research associate, who assisted in making the loading test.

II. PURPOSE

The loading test of this steel-plate floor was made to determine:

1. The strength of the floor.
2. Whether the following assumptions are justified:

(*a*) The floor behaves as a unit when loads are applied, i.e., the welds joining the beams and plates neither fail nor deform permanently.

(*b*) The entire width of plate between beams may be considered as effective in computing stress and deflections.

III. THE SPECIMEN

1. THE BATTLEDECK FLOOR

The test floor and the restraining frame are shown in figure 1. The floor consisted of six ¼-in steel plates and seven 4-in 7.7-lb per ft steel I-beams spaced 24 in on centers. The four middle plates were about 23¾-in wide and the two outer plates about 32⅔-in wide, extending 8½ in over the outer beams, nos. 1 and 7. The edges of the plates and the upper flanges of the beams were joined by continuous, open, square butt welds as shown in figure 2, extending the entire length of the beams. The outer plates were fastened to the outer beams by 6-by ⅜-in intermittent fillet welds between both edges of the flanges and the under side of the plates. The spaces on one side of the beam were opposite the welds on the other side; thus the total length of these welds on each outer beam was approximately equal to the length of the beam.

The I-beams of the floor were supported on angles bolted to the restraining frame of 30-in, 240-lb per ft steel I-beams reinforced by 6- by ⅝-in diaphragms. This frame was part of the fire-resistance chamber in which, for convenience, the loading test was made. There was clearance between the edges of the outer floor plates and the sides of the frame.

As shown in figure 3, the ends of the beams rested on the 3-in leg of the steel angles, A, 4 by 3 by ⅜ in, fastened to the frame by high-strength steel bolts, B, ¾-in in diameter and spaced 12 in on centers.

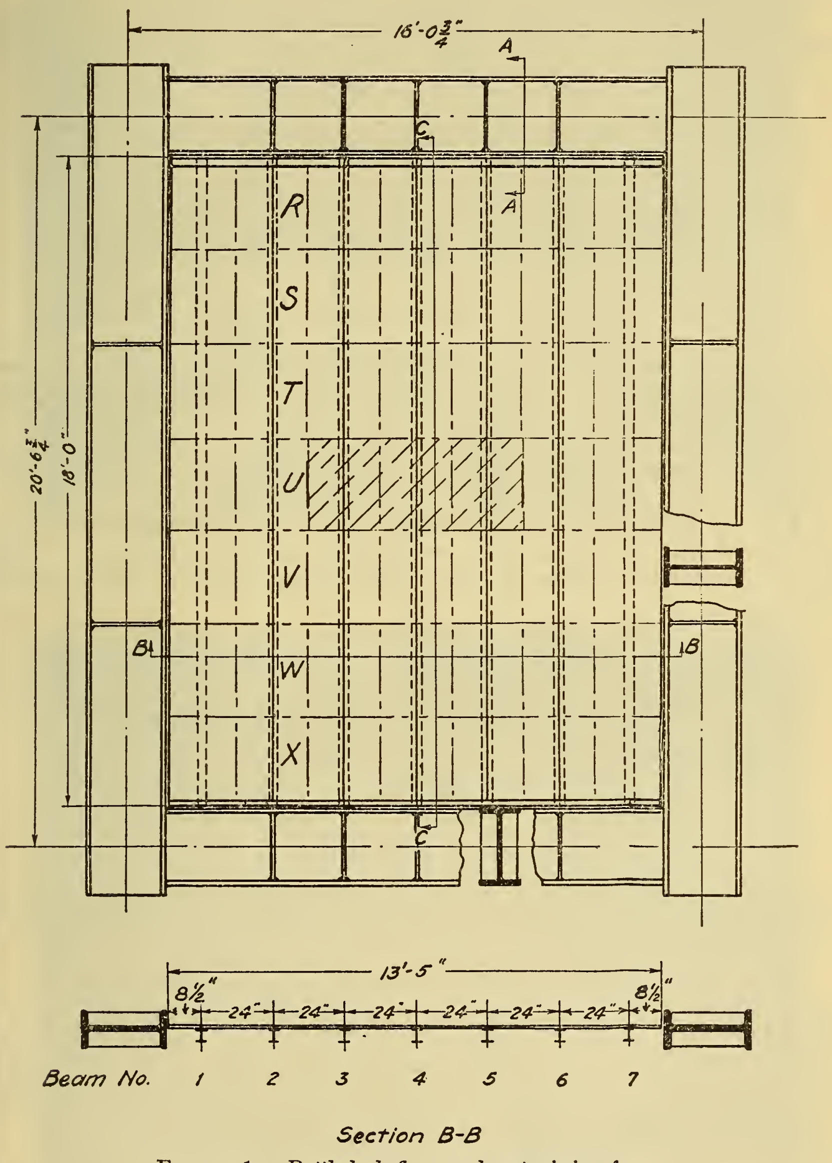

FIGURE 1.—*Battledeck floor and restraining frame.*

The bottom flanges of the beams were fastened to the angles by ⅜-in fillet welds, C, about 2-in long, one on each side. In order to secure an appreciable restraint at the ends of the floor, 3½- by 3- by ⅜-in steel angles, D, were bolted to the restraining frame by ¾-in high-strength steel bolts, E, spaced 12 in on centers, and the plates were fastened to the toes of the angles by $\frac{3}{8}$-in continuous fillet welds, *F*.

All the welds were manual, direct-current arc welds made with $\frac{5}{32}$-in bare electrodes.

The completed floor, ready for test, is shown in figure 4. It is evident that the beams were only "commercially" straight. Although

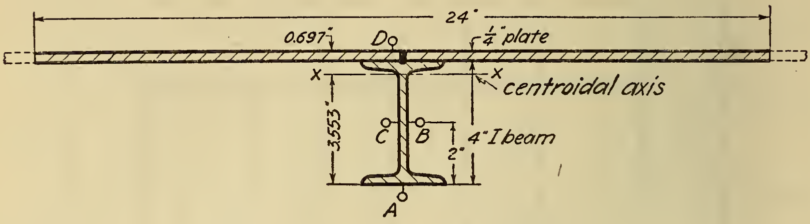

FIGURE 2.—*One beam element of the floor.*

the nominal width of the butt welds in the plates was ¼ in, in some places these welds were $\frac{3}{8}$-in wide because the edges of the plates were not perfectly straight. Since the plates were not perfectly flat, in some places the restraining angles were not in contact with the plates. At these places the fillet welds were larger than the nominal size, $\frac{3}{8}$ in.

For the purposes of computation the floor was considered as consisting of beam elements, one of which is shown in figure 2. They were T-sections having a very wide upper flange. The nominal

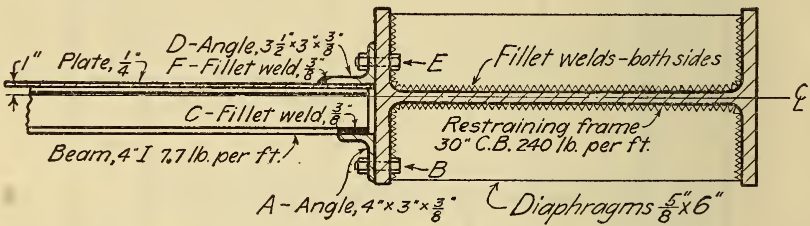

FIGURE 3.—*A longitudinal section at the end of the floor.*

properties of this beam element and therefore of the battledeck floor, are given in table 1.

TABLE 1.—*Nominal properties of the battledeck floor*

Depth of I-beam	4.0 in.
Weight of I-beam	7.7 lb per lin ft.
Thickness of plate	0.25 in.
Weight of plate and weld	20.4 lb per lin ft.
Total weight of I-beam, plate, and weld	28.1 lb per lin ft.
Average weight of floor	14.05 lb per sq ft.
Cross-sectional area (1 beam and 1 plate 24 in wide)	8.21 sq in.
Distance of the centroidal axis of the floor from the bottom of the I-beam	3.553 in.
Moment of inertia of the cross section of the floor about the centroidal axis (1 beam and 1 plate 24 in wide)	13.32 in.^{4}
Section modulus of floor (1 beam and 1 plate 24 in wide)	3.75 in.^{3}

2. MECHANICAL PROPERTIES OF THE I-BEAMS

Standard A.S.T.M. tensile specimens having a gage length of 8 in and reduced section 1½-in wide were cut from one of the beams which was not used in fabricating the floor. One specimen was cut

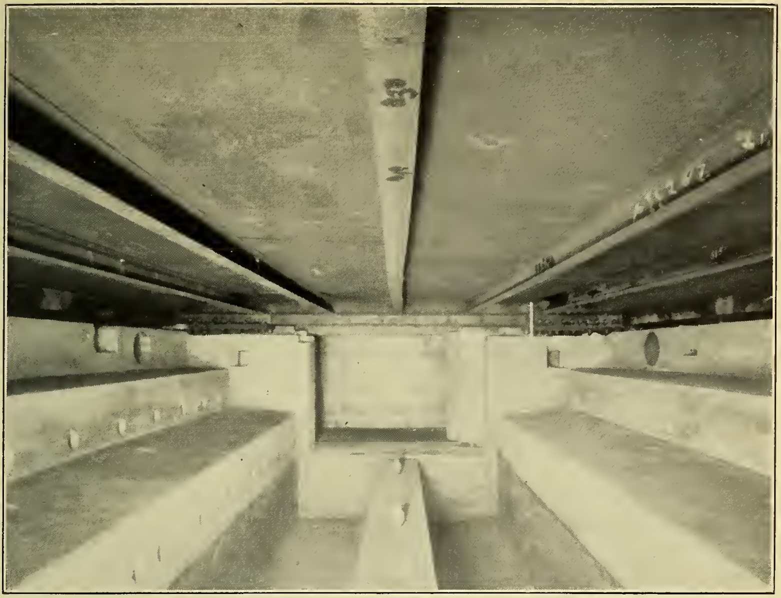

FIGURE 4.—*Lower surface of the completed floor ready for test.*

FIGURE 5.—*The floor under a nominal load of 420 pounds per square feet of loaded area.*

Deflection at midspan 3⅞ inches. After the load had been removed the permanent deflection at midspan was 2¾ inches from each of the flanges and one from the web of the I-beam. The yield point was taken as that stress under which the specimen showed an extension of 0.002 in. per inch in excess of that computed from Young's modulus of elasticity for the specimen. The results of the tests are given in table 2.

Table 2.—*Mechanical properties of the* I-*beams*

Specimen	Yield point	Tensile strength	Young's modulus of of elasticity	Elongation in 8 in
	Lb per sq in	*Lb per sq in*	*Lb per sq in*	*Percent*
Flange	33, 600	58, 900	30, 000, 000	27. 3
Do	33, 700	58, 500	30, 600, 000	27. 0
Web	28, 900	60, 000	29, 400, 000	28. 8

IV. METHOD OF TEST

1. LOADS

Seven equal areas, R to X, as shown in figure 1, were laid off above each beam by lines drawn midway between the beams and at equal intervals across the beams. The floor was loaded with equal weights of pig iron on each area except the three central areas, U, shown shaded in the figure. The center of gravity of the load on each area was approximately over the centroid of the area except that pigs were not piled on the portion of the plate overhanging the outer beams, nos. 1 and 7.

Strain-gage and deflection readings were taken for nominal loads of 40, 80, 100, 120, 140, 160, 180, and 200 lb per sq ft. The actual loads were sometimes greater and sometimes less than the nominal loads. The differences were about 3 lb per sq ft for loads up to 100 lb per sq ft and about 7 lb per sq ft for loads greater than 100 lb per sq ft. The actual loads for each area over each beam were used in the computations.

After the load of 40 lb per sq ft had been applied over the entire floor, the load on area U above beams nos. 3, 4, and 5 was not increased when greater loads were applied to the remainder of the floor. This allowed strain-gage readings to be taken on the upper surface of the floor. For loads greater than 200 lb per sq ft when no readings were taken the loads were again applied uniformly to the entire floor.

The floor under a nominal load of 420 lb per sq ft is shown in figure 5.

Although the floor would have carried a greater load, it was considered inadvisable to increase the load because the frame, which was a permanent part of the fire-resistance chamber, had deformed considerably. The deflection of the floor at midspan under this load of 420 lb per sq ft was 3⅞ in. This load remained on the floor for 5½ days. After the load was removed, the permanent deflection at midspan was 2¾ in.

2. STRAIN-GAGE READINGS

The locations of the gage lines, all of which were parallel to the beams, are shown in figures 2 and 6.

Two-in gage lines, *A*, *B*, *C*, and *D*, were placed adjacent to the ends and at midspan of beams nos. 3, 4, and 5. These gage lines were designated by the number of the beam followed by *M* for those at midspan and *E* for those adjacent to the end, and finally a letter

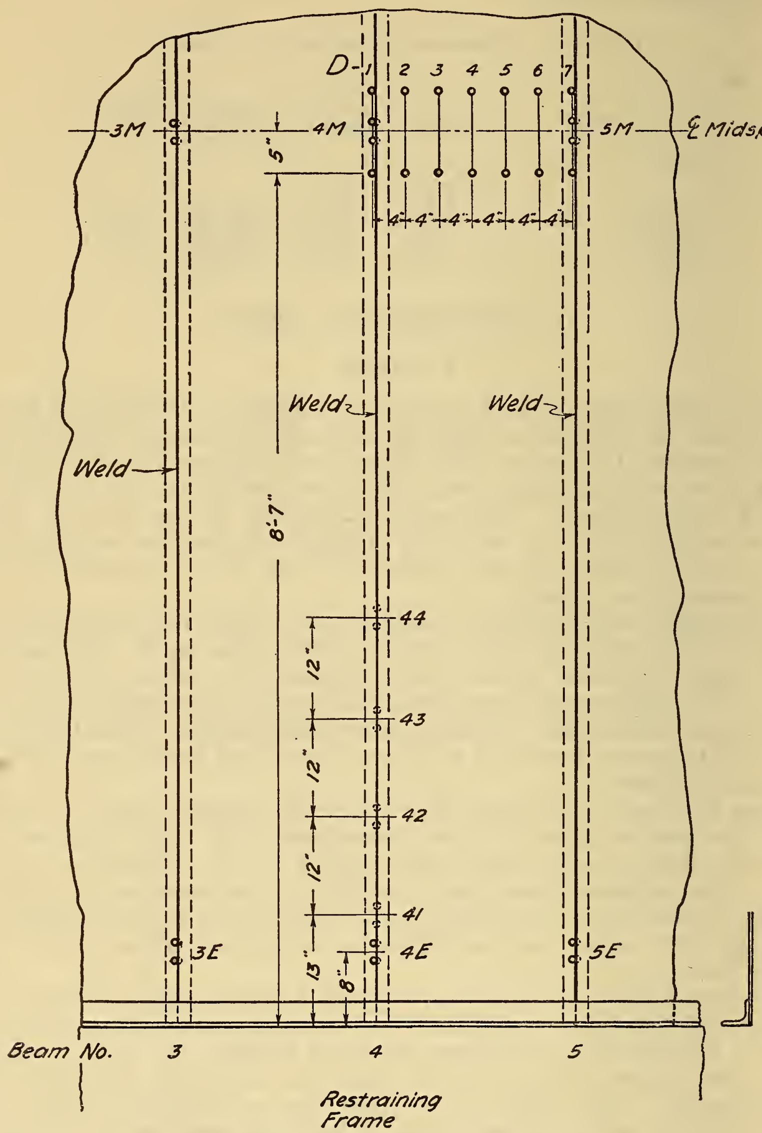

FIGURE 6.—*Location of the gage lines.*

indicating the location on the cross section of the beam element. Gage line *A* was in the middle of the lower flange, *B* and *C* on opposite sides of the web at midheight, and *D* on the upper surface of the plate about ¼ in from the edge of the weld. Thus, gage line 4*EC* was adjacent to the end of beam no. 4 on the side of the web at midheight.

Four additional 2-in gage lines were laid off on the lower flange of beam no. 4. They were spaced 12 in on centers along the beam and were designated 41, 42, 43, and 44.

Seven 10-in gage lines were laid off, longitudinally, at midspan on the upper surface of the floor between beams nos. 4 and 5. These gage lines were spaced about 4 in apart and were designated *D*1, *D*2, *D*3, *D*4, *D*5, *D*6, and *D*7.

Whittemore fulcrum-plate strain gages were used. Each instrument was provided with a "Last Word" dial micrometer reading directly to 0.0001 in. Tenths of a division were estimated. For a Young's modulus of elasticity of 30,000,000 lb per sq in, the stress corresponding to one division on the dial (0.0001 in) was 1,500 lb per sq in for the 2-in instrument and 300 lb per sq in for the 10-in instrument.

3. STRESSES

The stresses obtained from the strain-gage readings were called "measured stresses" to distinguish them from the stresses computed from the dimensions of the floor, the loads, etc., which were called "computed stresses".

The strain (inches per inch) in the floor, caused by change in the loading, was obtained by dividing the difference in the strain-gage readings by the gage length. The measured stress was obtained by multiplying the strain by the Young's modulus of elasticity. The average modulus, 30,000,000 lb per sq in found for the beams was used.

For the 2-in strain gage, it was estimated that, under favorable conditions, the measured stresses might be in error by about 1,000 lb per sq in; for the 10-in strain gage by about 400 lb per sq in.

4. DEFLECTIONS

The deflections of beams nos. 1, 2, 3, and 4 were measured.

A wire was stretched between points on the web of the beam about ¾ in above the lower flange and about 1 in from each end. A mirror having a scale was attached to the web at midspan behind the wire. The scale was graduated in tenths of an inch and the deflection estimated to the nearest 0.01 in. The wire was not placed in the plane of the centroidal axis of the floor because this axis was so close to the lower surface of the plate that it would have been impossible to read the deflection. At the higher loads the plate would have come into contact with the wire. For this test the errors in the deflections due to the location of the wire are believed to be negligible.

V. RESULTS WITH DISCUSSION

1. THE MIDDLE BEAM ELEMENT

The strength and the deflection of a flat steel-plate floor depend upon many things, one of the most important of which is the condition at the ends. In order to simulate the end condition of a floor which is continuous over the supports, the ends of this floor were secured to the frame. The frame, therefore, exerted a negative bending moment on the ends of the floor. Because measuring the negative moment presented unusual difficulties, it was decided to

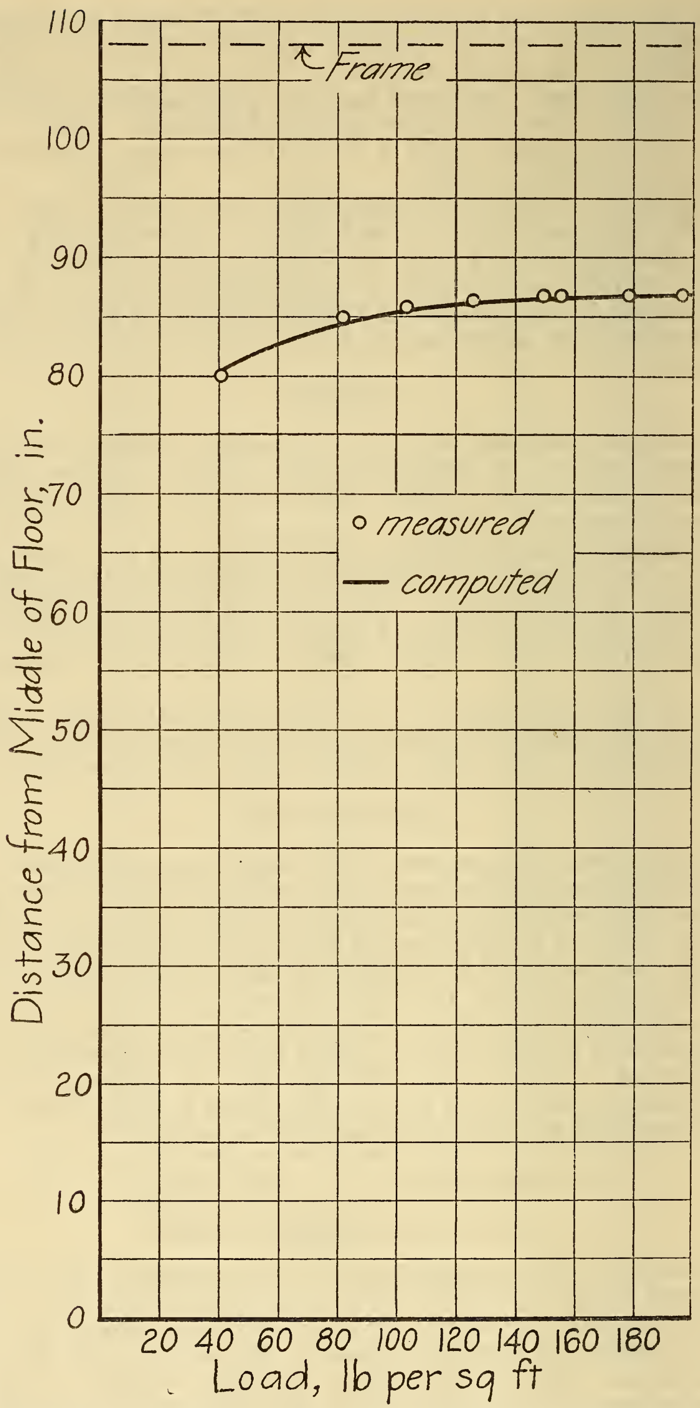

FIGURE 7.—*Movement of the point of zero stress along the bottom flange of beam no. 4 as the load increased.*

determine the point of zero stress in the lower surface of the middle beam from the strain-gage readings on gage lines 41 to 44 with the expectation that this determination, with the other data, would be sufficient to allow the stresses and deflections for the middle beam element to be computed, and that the stresses and deflections in the other beam elements would be approximately the same.

The distance from midspan of the beam was plotted as abscissa and the measured stress as ordinate, and then a faired curve drawn

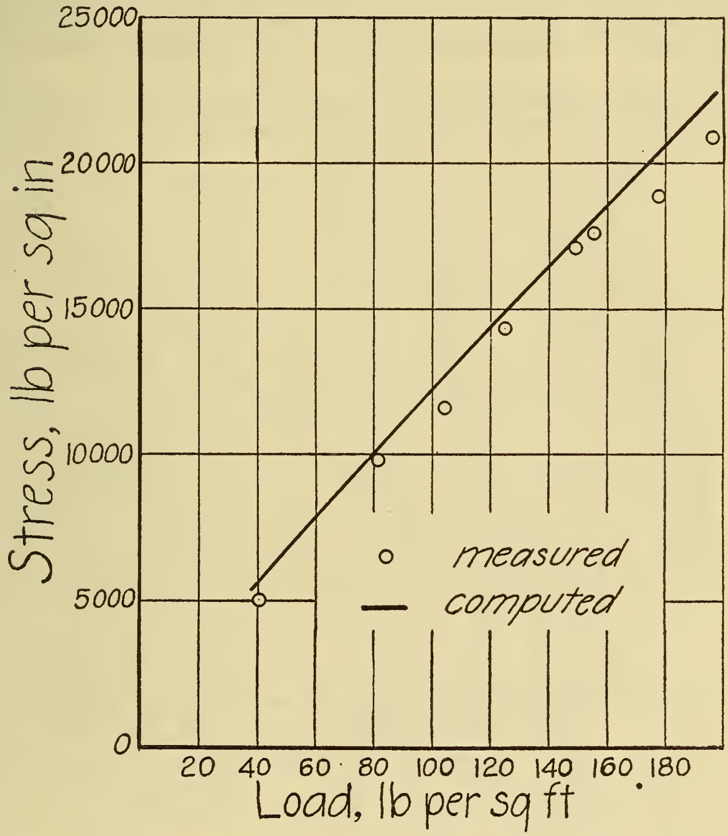

FIGURE 8.—*Stresses in the bottom flange of beam no. 4 at midspan.*

among the points. The point of zero stress was taken where the curve crossed the axis and its distance from midspan of the floor determined. These values are shown in figure 7.

The measured stresses, at gage line *A*, in the bottom flange of beam no. 4 at midspan are shown in figure 8 and the measured deflections in figure 9.

Assuming that there were only vertical forces and negative moments on the ends of the floor it was found that the computed values of the stress on the bottom of beam no. 4 at midspan and of the deflection did not agree with the measured values. Further study led to the belief that the frame might also have exerted tensile forces on the floor. For the middle beam element, assuming that the entire width of the plate (24 in) was effective, values of the tensile force and the negative moment were found which gave computed values of the stress, the deflection, and the point of zero stress on the lower flange agreeing with the measured values within the errors of observation. These values of the tensile force and the negative moment for each 2-ft width of floor were 7,100 lb and 20,000 lb in, respectively, for a load of 40 lb per sq ft and 12,700 lb and 62,700 lb in, respectively, for a load of 200 lb per sq ft. For intermediate loads the values varied linearly. The computed values for the location of the point of zero stress are shown in figure 7, those for the tensile stress at midspan in figure 8 and those for deflection in figure 9.

Due to the tensile forces the point of zero stress on the bottom flange of the beam does not occur at the same section as the point of

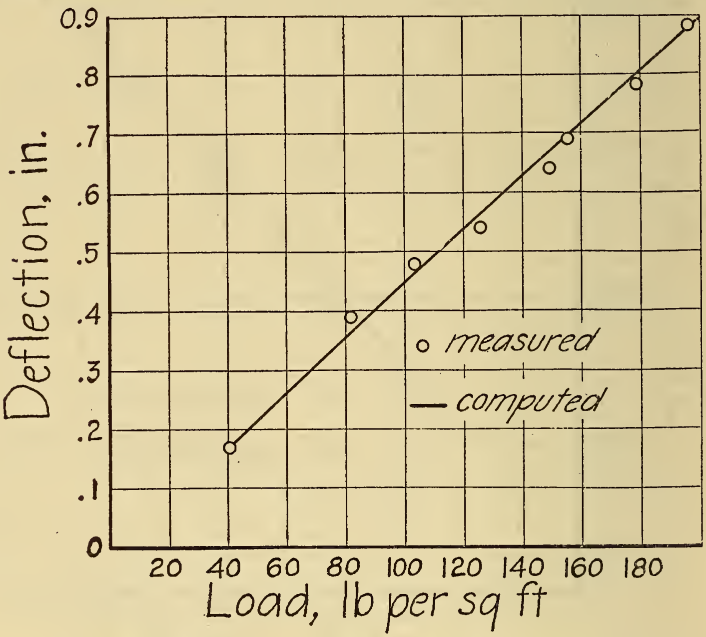

FIGURE 9.—*Deflections of beam no. 4 at midspan.*

inflection. Although the ends of the floor were restrained, the negative moment did not "fix" the ends, i.e., cause the centroidal surface of the beam element to be horizontal at the frame. The computed slope at the ends ranged from 0.0013 for a load of 40 lb per sq ft to 0.010 for a load of 200 lb per sq ft.

2. BEAM ELEMENTS NUMBERS 3, 4, AND 5

The measured stresses at the ends of beam elements nos. 3, 4, and 5 are shown in figure 10 and also the computed values for beam no. 4. The measured stresses at midspan of beam elements nos. 3, 4, and 5 are shown in figure 11 and also the computed values for beam no. 4. The measured values for gage lines *EA*, *EB*, *EC*, *MA*, *MB*, and *MC*, which were below the plates, are consistent within the error of the strain-gage readings but are greater than the computed values for beam no. 4. Those for *EA* on the bottom flange of the beam are greater than the computed values, probably because the lower flange was welded to the frame near these gage lines.

The measured values of the stresses in the upper surface of the plate, gage lines *ED* and *MD*, are very erratic, probably because these gage lines were on the top of the plates and it was impossible to keep the gage holes clear although they were cleaned frequently. Sand and scale dropped from the pigs when the load on the floor was increased and a strong breeze blew through the building. Rain water collecting on the top of the floor also added to the difficulty of obtaining accurate strain-gage readings on the upper surface.

Beam elements nos. 3, 4, and 5 were similarly loaded with pig iron, but beams nos. 3 and 5 probably carried a somewhat heavier load due to the action of the adjacent beams nos. 2 and 6 which did not have the reduced load on area *U*.

The measured deflections at midspan for beam elements nos. 1, 2, 3, and 4 are shown in figure 12. The computed values for beam no. 4 are shown in figure 9. That beam no. 2 had the greatest deflection is probably due to the fact that beams nos. 1 and 2 did not have the reduced load on area *U*; and that the center of gravity of the load on beam no. 1 was between beams nos. 1 and 2.

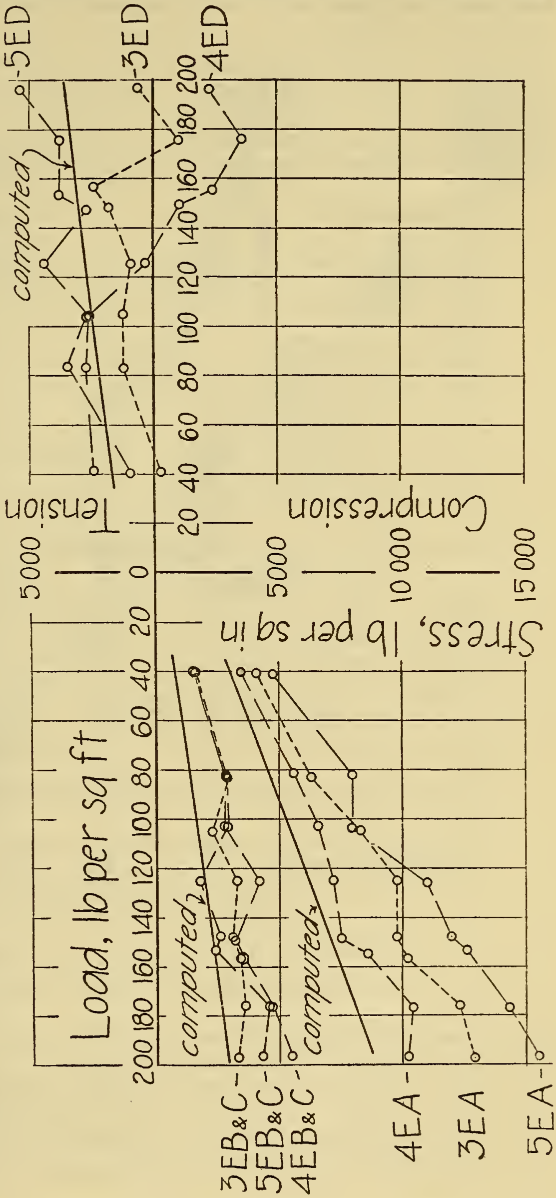

Figure 10.—*Measured stresses at the ends of beam elements nos. 3, 4, and 5.*

The computed values are for beam element no. 4.

The actual load on beam no. 1 was therefore somewhat less and that on beam no. 2 somewhat more than the nominal load. The deflection of beam no. 3 was between that of beams nos. 2 and 4

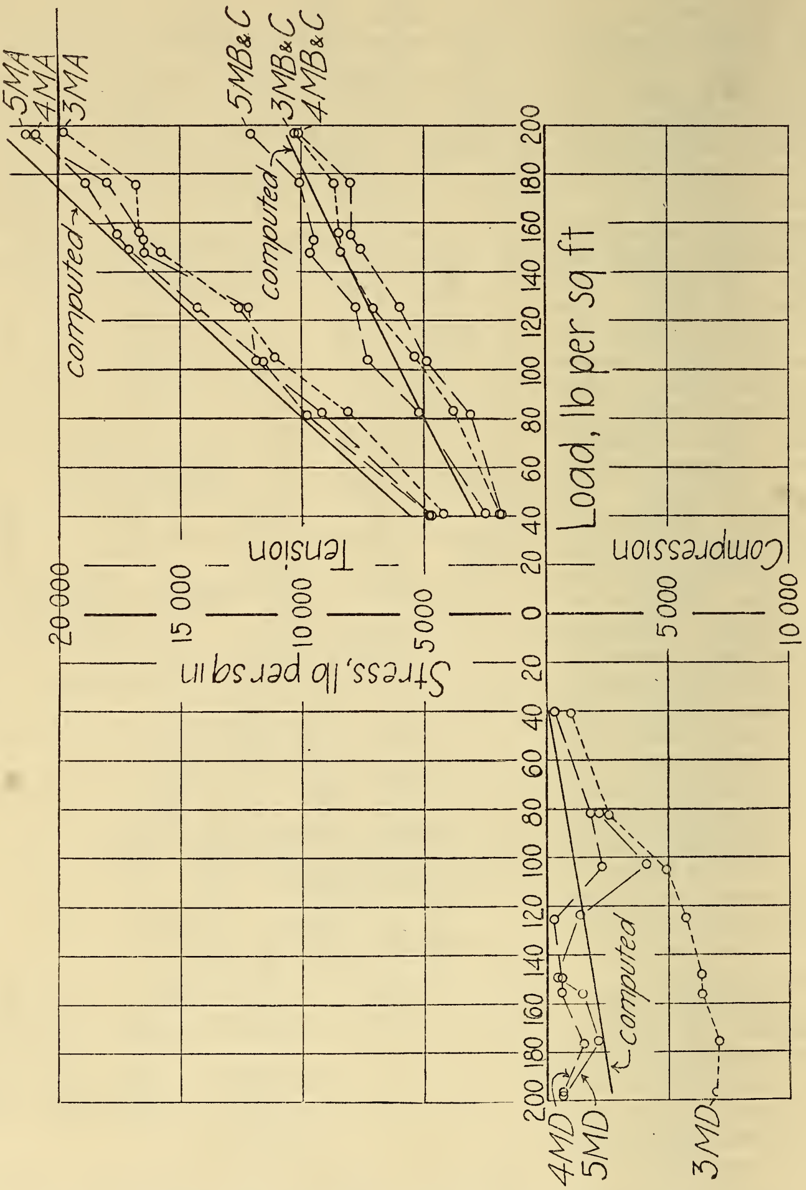

FIGURE 11.—*Measured stresses at midspan of beam elements nos. 3, 4, and 5.*

The computed values are for beam element no. 4.

indicating that the deflection of a beam is dependent not only upon the load on that beam element but is affected somewhat by the loads on adjacent beams by a partial transfer of loads through the plates.

In making all of these computations, it was assumed that the full width of the plates was effective in carrying the load. The results of the computation gave no indication that this assumption was not justified, nor was there any unquestionable experimental evidence to support the assumption (figure 13, showing the distribution of stress across the plate adds some support). Kármán [1] indicates, however, that under conditions not unlike those of the test floor, with the exception that the beams are spaced at infinite distances instead of 24 in, an effective width of about 40 in may be expected unless the

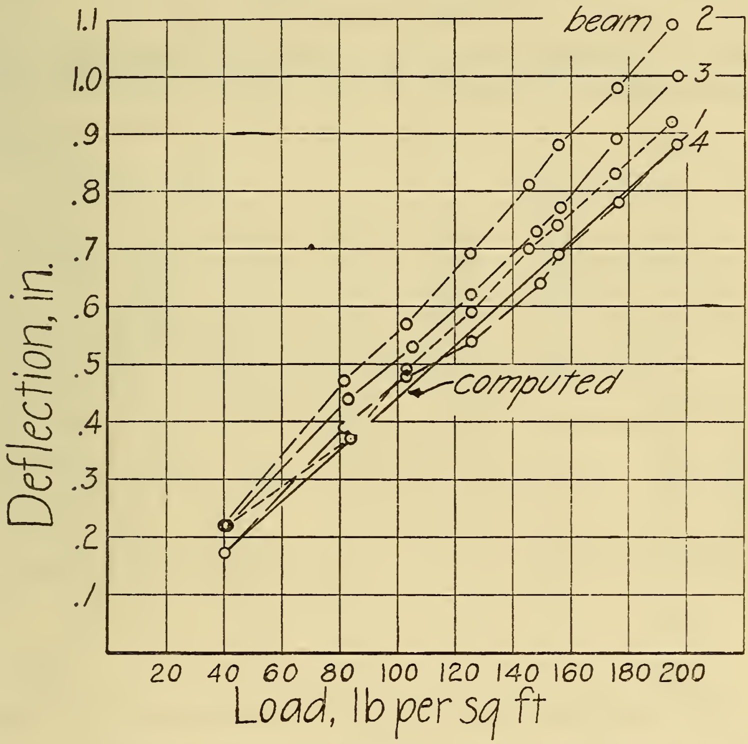

FIGURE 12.—*Measured deflections at midspan for beam elements nos. 1, 2, 3, and 4*

The computed values are for beam element no. 4.

plate is so thin that it will buckle (no buckling was observed in the plates of the test floor). It may be noted that if the effective width were only 8 in instead of the full 24 in, the section modulus, and thus the strength would be reduced only 5 percent. However, the moment of inertia of the cross section would be reduced almost 20 percent, which would increase materially the calculated deflections.

3. THE PLATES

The measured longitudinal stresses in the plate between beams nos. 4 and 5 are shown in figure 13. Computed values for the gage lines over the beams ($D1$ and $D7$) are shown in figure 11, gage lines

[1] Die mittragende Breite, Beiträge zur technischen Mechanik und technischen Physik, p. 114, Julius Springer, Berlin, 1924.

4*MD* and 5*MD*. The values are erratic, presumably due to difficulty in maintaining clean gage holes. Those for *D*6 were especially unsatisfactory. The measured stresses for the nominal load of 180 lb per sq ft were for all gage lines greater than those for the nominal load of 200 lb per sq ft. No reasonable explanation of this inconsistency was found. Making allowance for the errors in these measured stresses, the average stress near the middle of the plate between the beams was somewhat lower than the average measured stress over the beams.

4. THE ASSUMPTIONS

None of the results obtained on this steel plate floor indicate that the assumptions 2 (a) and (b) are not justified. The floor behaves

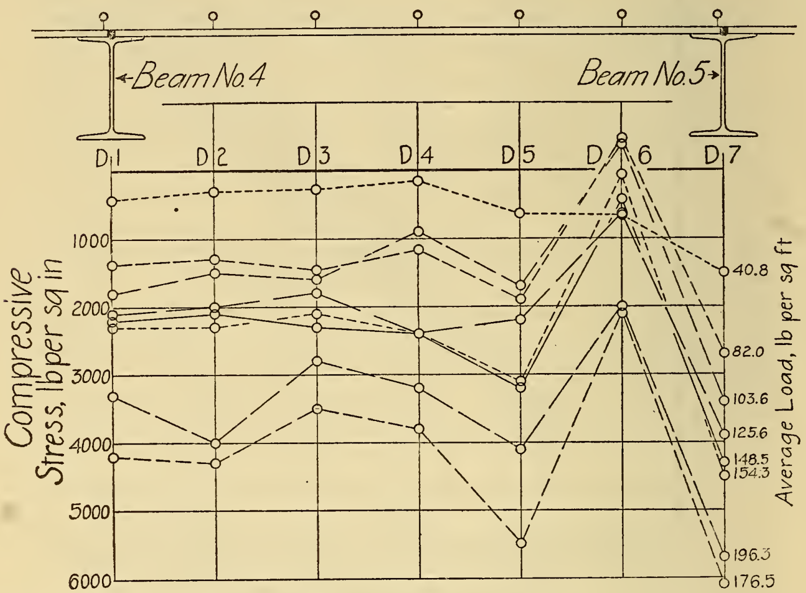

FIGURE 13.—*Longitudinal stresses at midspan in the plate between beams nos. 4 and 5.*

The computed values for *D*1 and *D*7 are shown in figure 11, gage lines 4*MD* and 5*MD*.

as a unit when loads are applied. There was no visible evidence that the welds joining the beams and plates were either ruptured or permanently deformed. The measured stresses do not indicate that the strength of the welds joining the beams and plates was insufficient to cause the floor to behave as a unit.

There is no indication that the axis of average stress in the floor does not coincide with the horizontal line through the centroid of the cross section of the floor.

The measured stresses and the measured deflections of the floor under load agree within the errors of observation with the computed values, when the moment of inertia and the section modulus were obtained from the nominal dimensions of the floor.

The results of this test on a flat steel-plate floor indicate that for ordinary spans, if the spacing of the beams does not exceed 100 times the thickness of the plates, the full width of the plates may be considered effective and the methods used by engineers in designing steel beams may be used with satisfactory results when designing battledeck floors.

VI. CONCLUSIONS

The results of a loading test of a battledeck floor of 18-ft span, built of 4-in 7.7-lb per ft rolled steel **I**-beams spaced 24-in and ¼-in rolled steel plates indicated that:

1. The continuous manual welds joining the plates to the **I**-beams made by using bare metallic electrodes (5/32-in diameter) and the direct-current arc-welding process united the plates and the beams so that they behaved as a unit when loads were applied.
2. The measured stresses and the measured deflections were in substantial agreement with values computed by the ordinary theory of beams.
3. This floor carried a load of 420 lb per sq ft for 5½ days without any indication of collapse. The deflection under this load was 3⅞ in. After the load was removed the permanent deflection was 2¾ in.
4. The results of this test gave no positive indication as to the width of the plate which may be considered effective. There is a strong presumption, however, that under conditions of loading and length of span not totally unlike those of the test an effective width up to 24 in may be assumed in designing with ¼-in plate.

WASHINGTON, January 16, 1934.