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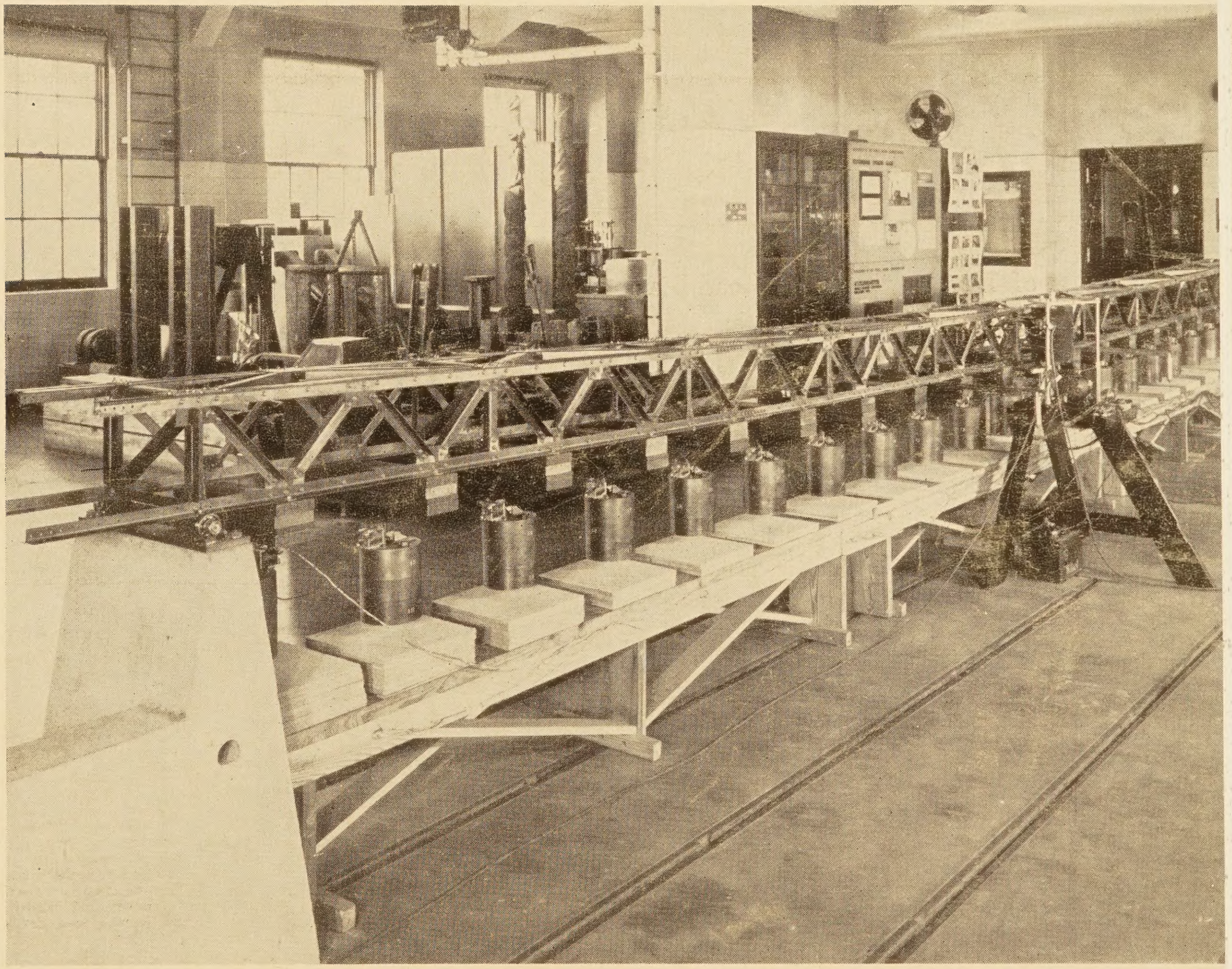

Bolted truss used in tests of structural damping

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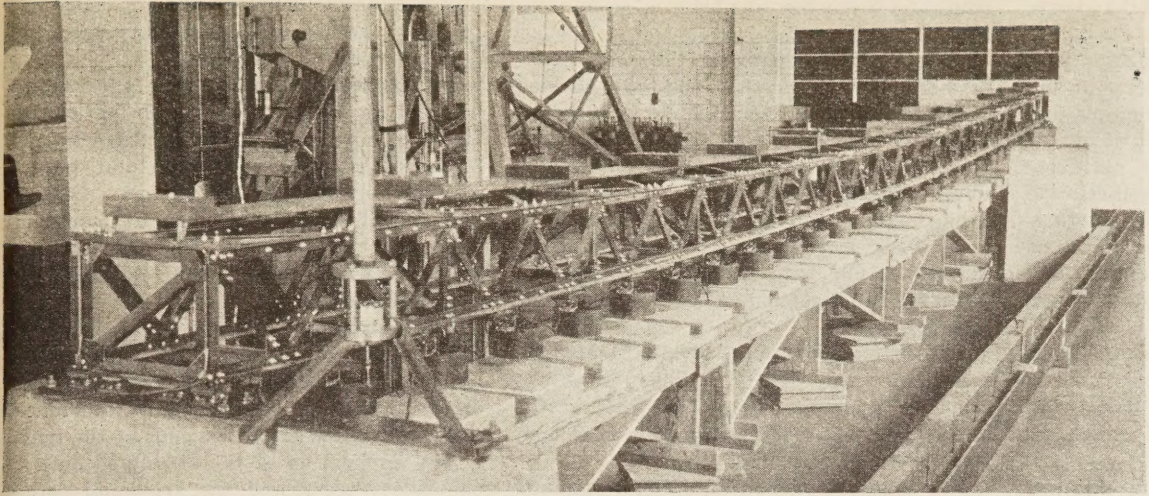

Figure 1.—General view of truss with simulated deck in place.

Tests of Structural Damping

Reported by LESLIE W. TELLER
Chief, Structural Research Section,
and ERNEST G. WILES
Highway Physical Research Engineer

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

In connection with a program of research sponsored by the Advisory Board on the Investigation of Suspension Bridges, information regarding the self-damping characteristics of steel structural members was needed. The literature contained little or no data on the subject. At the request of the Advisory Board, the Bureau of Public Roads conducted a series of tests which developed a considerable amount of useful data on the self-damping characteristics of both solid and trussed structural members together with data which show the possibilities of dry or Coulomb friction as a means for energy absorption within a framed structure. The details of the entire study are described in this report.

FOLLOWING the catastrophic failure of the suspension bridge across the Tacoma Narrows in the State of Washington, shortly after it was opened in 1940, there was organized, under the sponsorship of the Bureau of Public Roads, a technical body of broad representation known as the Advisory Board on the Investigation of Suspension Bridges. The objectives, organization, and membership of this body are well known and need not be repeated here.

At the request of the Advisory Board, as a part of its extensive investigational program, the studies of structural damping described in this report were made in the research laboratories of the Bureau of Public Roads. A condensed account of these studies has been published previously.[1] The present report is intended to describe the experimental work more fully than was possible in the A.S.C.E. paper and, further, to present certain additional data obtained as the program was concluded.

Since the failure of the Tacoma Narrows Bridge was caused by vibrations set up by wind action, the investigational work of the Advisory Board has included extensive tests of both full models and sectional models under the controlled conditions of a wind tunnel. Necessarily these models are dimensioned to a greatly reduced scale and it is not possible, as a practical matter, to reproduce in the model all of the structural details of the prototype. For this reason, in the fabrication of full models—that is, models of entire structures—it has been the practice to simulate the stiffness of the stiffening girders or stiffening trusses of the prototype by means of solid steel members and to simulate their shapes by other means in order that the aerodynamic action of the model would be similar to that of the prototype.

It is desirable that the energy which a suspension bridge receives from the wind be dissipated to the maximum extent possible by friction and by other means so that the energy remaining will not be able to cause excessive vibrations in the bridge. Friction within the structure offers one important means for absorbing energy received from without.

The Basic Question

Since movement at the joints of stiffening trusses may be an important source of friction, a question naturally arose as to whether or not, in the case of a full model, the substitution of a solid member for a trussed member might lead to significant differences in energy absorption and thus affect the validity of certain data obtained in the wind tunnel tests. The investigational work described in this report was undertaken initially to find an answer to this question. In addition the tests provided basic data useful in a theoretical approach to the problem of structural damping in suspension bridges[1]. The results obtained in the early work led to some expansion of the initial program in order that other useful information on structural damping might be obtained while the experimental facilities were available.

In general, damping is the dissipation of energy that a vibrating structure receives

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[1] *Structural damping in suspension bridges*, by Friedrich Bleich and L. W. Teller. Transactions, American Society of Civil Engineers, vol. 117 (1952), p. 165 (also printed as a separate, Paper No. 2486).

from external exciting forces, in the course of which part of the external energy is transformed into molecular energy and part is dissipated to surrounding objects or the atmosphere. The structural damping discussed in this report is the result of one or more of the following: imperfect elasticity of the material, friction due to small relative displacements in the joints of the structure, and friction at sliding expansion joints of a simulated floor system, at sliding end bearings, or at the sliding surfaces of mechanical brakes.

The program of damping tests was originally recommended by the Committee on Model Studies of the Advisory Board and was approved by the Executive Committee of the Board at a meeting held in New York on October 8, 1943. The results obtained were placed before the Board in a series of four progress reports dated March 1945, April 1946, May 1948, and July 1949, respectively. The data contained in these reports were released in condensed form in the A.S.C.E. paper previously referred to.[2]

To carry out the program, three test specimens were obtained through the cooperation of the American Institute of Steel Construction and the Inland Steel Company. These were a bolted truss, a rolled **H**-section, and a solid bar of rectangular cross section. The material of which the truss was made was a low alloy steel of relatively high strength, while that in the **H**-section and the rectangular bar was carbon steel with 0.20–0.25 percent carbon. The specimens were supported at the ends in a horizontal position on either a 36-foot, 10-inch, or a 28-foot, 4-inch span length, as will be described in detail later.

Scope of Investigation and Summary of Indications

The expanded program of the investigation authorized by the Advisory Board consisted of four principal parts, plus a number of subordinate collateral investigations. Some supplemental studies were also made to develop additional information. The nature of the investigations and summarized findings are described in the following paragraphs.

Principal studies

1. A comparison was made of the self-damping characteristics of a trussed structural member with that of solid structural members in equal stiffness, when vibrated in the first symmetric mode.

The character of the amplitude decay for the two solid sections tested was definitely exponential while that for the bolted truss was more complex, being apparently the result of a combination of the imperfect elasticity of the material with plastic yielding and friction due to small displacements in the joints. In these tests there was, of course, end bearing friction and air friction, but the former was present as a constant and the latter was believed to be relatively unimportant.

In comparisons between the solid members and the bolted truss, the truss showed considerably more capacity for self-damping, particularly at the higher amplitudes (or higher dynamic stresses). With the joints tightly bolted the decrement values ranged from about 0.006 at 1,000 p.s.i. to about 0.030 at 10,000 p.s.i. dynamic stress in comparison with a range of 0.003 to 0.007 for the **H**-section at the same limits of dynamic stress.

The decrement values for all three specimens increased with an increase in amplitude (or dynamic stress), the rate of increase being greatest with the truss and least with the **H**-section.

For small amplitudes and small dynamic stresses the decrement values were of the general order of 0.004 for all specimens. The decrement values for the solid members did not exceed 0.007 in any of the tests. For the truss, however, values as high as 0.073 were found at high initial amplitudes (and high dynamic stresses) in combination with low bolt tension in the bolted connections.

2. In the case of the bolted truss, a determination was made of the effect on damping of bolt type, bolt tension, and the procedure used in arriving at a given level of bolt tension.

The tightness of the bolted connections had a pronounced effect on the damping of the truss, particularly at the larger amplitudes (or dynamic stresses). The tighter the bolts, the lower were the decrement values.

The damping action of the joints in the truss when tightly bolted apparently was influenced more by the pressure of the surfaces held in contact by the bolts than it was by the fit of the bolts in the holes.

Tests with the bolted truss to study the effect of bolt tightening sequence on damping showed a measurable effect, it being least with the bolts tightened to the greatest degree of tension. The care taken in the bolt tightening procedure in all tests with the truss seems fully justified.

3. A study of the effects of a variation in dead load on the self-damping characteristics of the bolted truss showed that variation in the dead load of the order of 50 percent caused no measurable change in the damping characteristics of the truss.

4. A study was made of the effect of dry or Coulomb friction, externally applied, on the damping characteristics of the bolted truss. The Coulomb friction was developed in three different ways—by mechanical brakes, by sliding bearings at the ends of panels of a simulated floor system, and by sliding end bearings.

The external application of dry or Coulomb friction greatly increased the damping of the bolted truss.

Where mechanical brakes that employed metal plates rubbing together without lubrication were used to develop frictional forces for damping purposes, more dependable action was obtained with opposing surfaces of bronze and steel than with two ferrous metals in contact.

The damping obtained from the rubbing of steel on bronze without lubrication follows the laws of Coulomb friction—that is, it varies directly with the total normal pressure on the friction surfaces, is independent of their area, and is nearly independent of velocity. The effective coefficient for the condition of this test was about 0.13–0.14.

The increase in the damping of the bolted truss obtained by the application of the simulated deck sections was quite similar in character to that obtained with mechanical brakes in operation at the ends of the truss.

The application of the simulated deck to the bolted truss and the frictional forces developed at the sliding shoes of the deck sections added slightly but measurably to the stiffness of the truss during its dynamic oscillation. The effect was somewhat greater at small amplitudes than at large amplitudes of motion.

The substitution of sliding end bearings of bronze on cold rolled steel for the wheel bearings used at one end of the truss developed a strong damping force.

Collateral studies

The collateral investigations authorized by the Advisory Board were necessary to develop control data for the main investigation and for other purposes. Among the more important were:

(*a*) Determination of the ultimate strength and character of failure of a chord splice in tension and of a chord section in compression, as used in the bolted truss.

(*b*) Establishment of relations between load, deflection, and critical strain in each of the three specimens.

(*c*) Determination of the maximum tightening torque for the bolt-nut combinations used in the truss.

(*d*) Segregation of air damping effect when the truss was equipped with a simulated floor system.

The application of the plywood plates to the truss, in lieu of the steel deck panels of equal frontal area, increased the damping to a degree that could be measured, although the effect of the added air resistance on damping was relatively small.

(*e*) Determination of the coefficient of friction for the sliding bearings used.

(*f*) Determination of the chemical composition and physical properties of the steel in each of the three specimens.

Supplemental studies

After the work authorized by the Advisory Board had been completed, some supplemental studies were made which developed additional information of interest and value.

A. The damping characteristics of the truss with riveted connections were compared to its performance with bolted connections.

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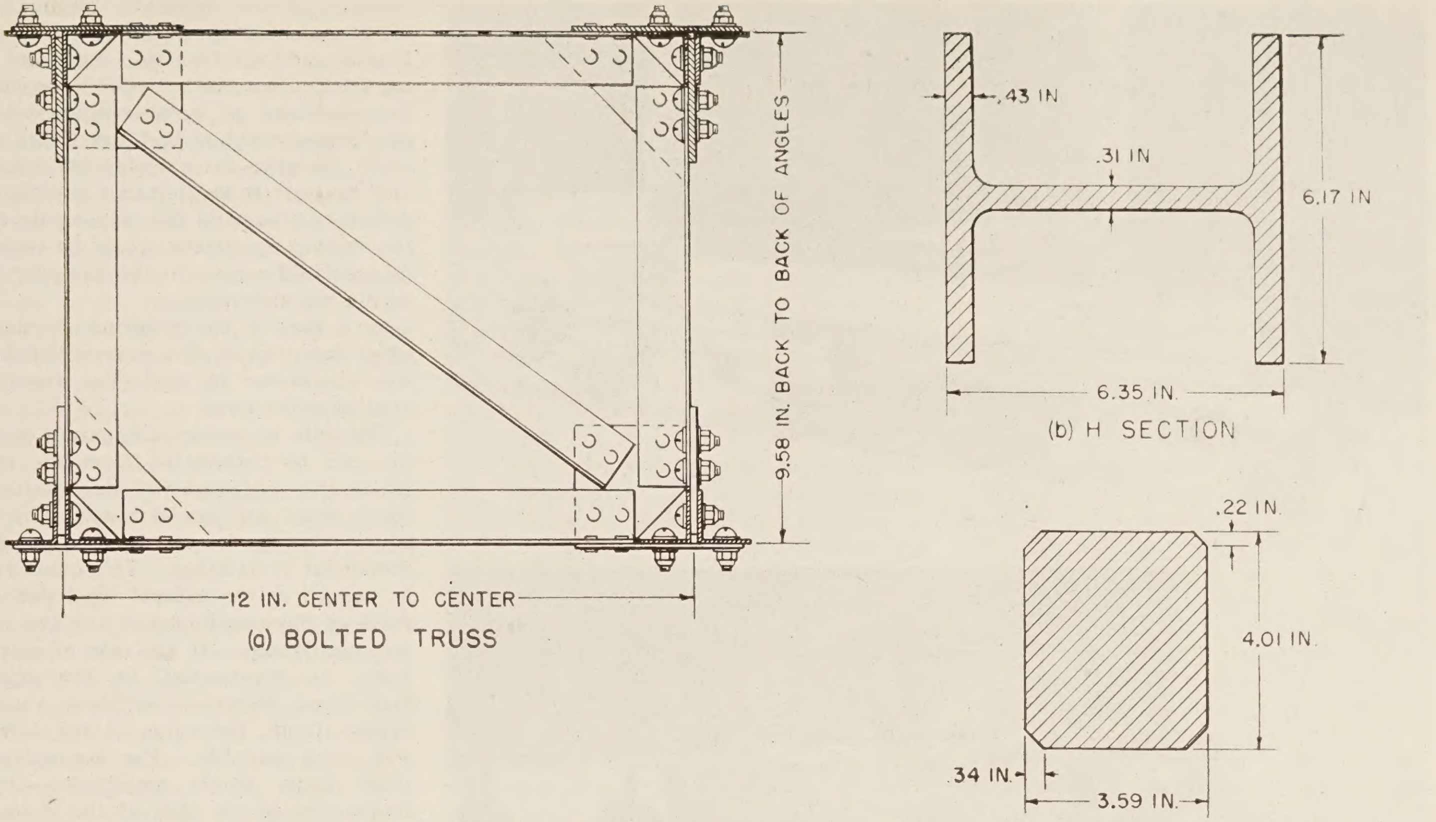
[2] See reference, footnote 1, p. 203.



(a) BOLTED TRUSS

(b) H SECTION

(c) SOLID RECTANGULAR BAR

Figure 2.—Cross-section dimensions of the three specimens tested.

Tests with the truss with all chord connections riveted showed considerably less evidence of movement at the connections than did the tests with the bolted truss, particularly at higher amplitudes and higher dynamic stresses. Much greater damping was evident at all amplitudes than was found for the comparable solid member (**H**-section).

B. From comparison of logarithmic decrement values determined from strain decay data with those obtained from deflection decay data, it is indicated that, with suitable instrumentation, damping can be satisfactorily determined from continuous records of strain decay in tests of this type.

C. Measurements of rotation and translation at the ends of the **H**-section were found to be in good agreement with theory.

D. In comparisons of the theoretical and observed performance of the bolted truss it was found that a somewhat better correlation was obtained when a correction for the initial sag of the trussed member between end supports was introduced into the computations.[3]

Table 1.—Comparison of physical characteristics of specimens

	36′–10″ span length				28′–4″ span length			
	Truss [1]		H–section		Truss (shortened)		Rectangular bar	
	Planned	Tested	Planned	Tested	Planned	Tested	Planned	Tested
Moment of inertia:								
From cross section..........in.^{4}..	19.1	20.3	19.1	16.9	19.1	20.3	19.1	19.0
From load deflection..........in.^{4}..	....	20.7	....	16.6	....	20.4	....	18.9
Weight per foot:								
Specimen proper..........lb..	6.72	7.26	27.50	24.00	6.72	7.59	48.70	48.26
Attached dead-load weights......lb..	20.78	21.13	0	0.16	41.98	41.96	0	0.36
Total dead weight..........lb..	27.50	28.39	27.50	24.16	48.70	49.55	48.70	48.62
Maximum deflection from dead weight..........in..	2.06	[2] 2.05	2.06	2.05	1.28	[3] 1.24	1.28	1.27
Natural period..........sec..	0.41	0.39	0.41	0.41	0.32	0.31	0.32	0.32

[1] The following comparable values were obtained for the truss with all chord connections riveted: Moment of inertia from load deflection, 20.6 in.^{4}; maximum deflection from dead weight, 1.90 in.; natural period, 0.39 sec.

[2] Permanent set of 1.97 in. developed during testing with machine screws. Total deflection at end of test 4.02 in.

[3] Permanent set of 0.66 in. developed during testing with machine screws. Total deflection at end of test 1.90 in.

Table 2.—Physical properties of the steel in each specimen

Source and number of specimens	Ultimate strength	Yield strength (0.10 percent offset)	Modulus of elasticity	Reduction in area	Elongation (2 inches)	Rockwell hardness
	P.s.i.	*P.s.i.*	*P.s.i.*	*Percent*	*Percent*	
Truss (4)..........	73,700	55,600	30,664,000	65	32	B 83
H-section (4)..........	61,800	38,800	30,377,000	64	40	B 68
Bar [1] (2)..........	57,000	25,000	30,590,000	19	18	B 61

[1] The material in the bar does not meet the tensile strength requirements of A.S.T.M. Designation A7–49T, specification for steel for bridges and buildings. This should have no significance insofar as the data obtained in these tests are concerned since the maximum stresses in the bar as tested were approximately 11,000 p.s.i.

The Test Specimens

While a search of the literature disclosed a certain amount of data on the damping characteristics of complete structures, particularly bridges of various span lengths, and data from a number of studies of the self-damping properties of steels of various types by means of laboratory tests on small specimens, there seemed to be no information on the self-damping characteristics of structural members made of steel. For this reason the investigation is believed to be unique. The test methods and instrumentation used in the tests were unusual in a number of respects and may be of general interest to the profession, so they are described fully in this report.

As mentioned previously, the specimens furnished for the test program were a bolted truss, a rolled **H**-section, and a solid rectangular bar, all with cross-sectional dimensions as shown in figure 2. These were originally designed to provide sections of equal stiffness—that is, equal moments

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[3] See footnote 1, p. 203.

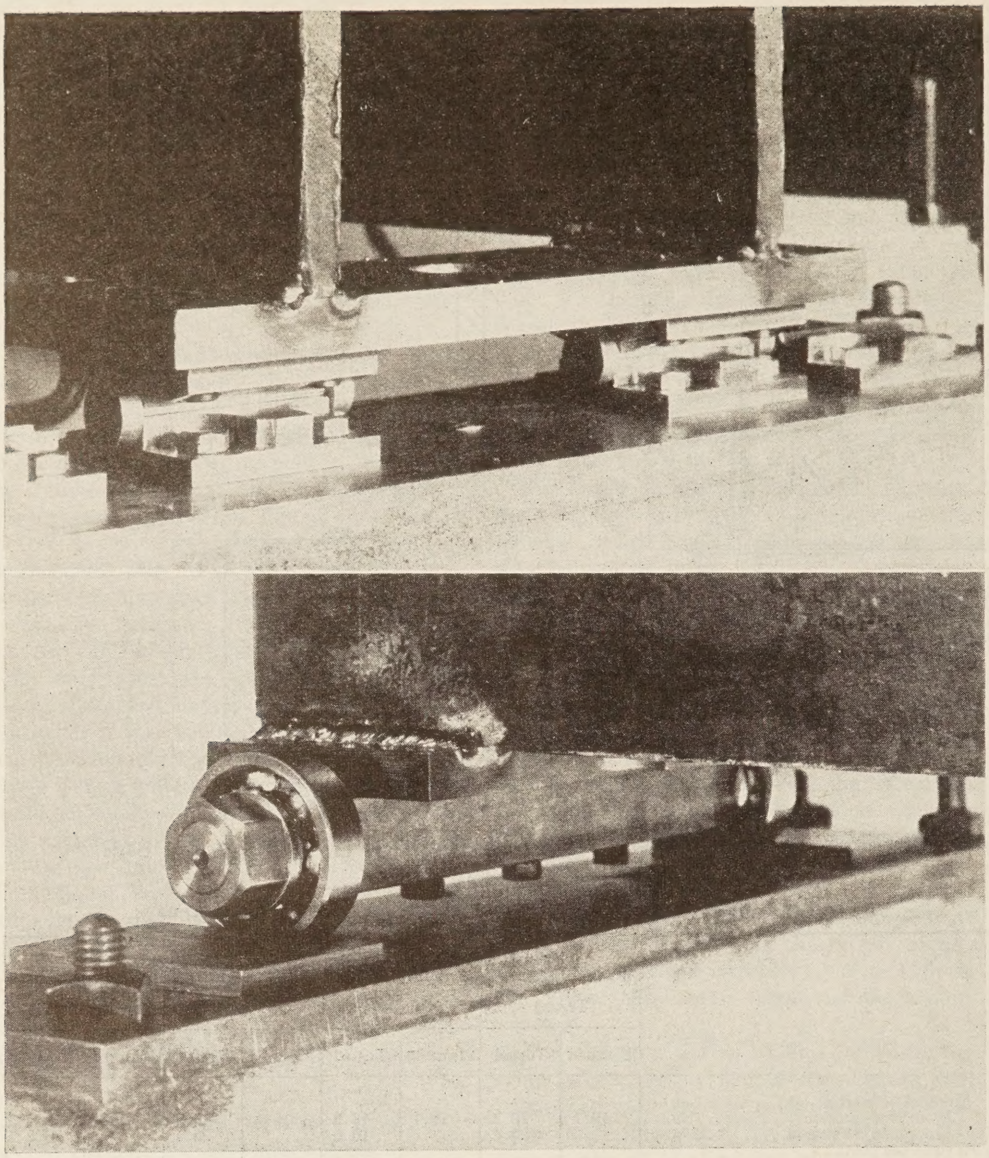


Figure 3.—Rocker bearing (above) and wheel bearing (below) used to support the specimens. The H-section is shown here.

of inertia. As furnished, however, there was some departure from the planned dimensions and a corresponding variation was found in the moment of inertia. The moment of inertia of the truss was slightly greater while that of the **H**-section was somewhat smaller than the moment of inertia of the rectangular bar.

The truss and the **H**-section were compared on a span length of 36 feet, 10 inches, and the truss (shortened) and the rectangular bar were compared on a span length of 28 feet, 4 inches.

In these comparisons, it was originally planned that the specimens being compared would be of equal weight and stiffness so as to have equal periods of vibration and equal dead-load deflections. For various reasons there were some deviations in the weights, dimensions, and stiffness of the test specimens as furnished, as may be noted in data which follow. There is no evidence, however, that the deviations mentioned were of sufficient magnitude to affect adversely the comparisons which have been made.

Since the weight of the truss as furnished was of the order of 250 pounds in contrast to 900 pounds for the **H**-section and 1,400 pounds for the bar, it was necessary to add a considerable amount of weight to the truss for the comparative tests. This weight was in the form of rectangular steel bars attached transversely at the lower panel points. These attached panel-point weights will be referred to as dead-load weights.

Certain pertinent information as to the weight, stiffness, and other physical characteristics of each specimen are given in table 1. Certain data on the physical properties of the material in each specimen are given in table 2.

Test Procedure

The general method of test was quite simple. The specimen was supported as a simple beam at the span lengths mentioned. It was excited to a given degree of oscillation in the first symmetric mode in the vertical plane. Having developed the desired amplitude, the oscillations were allowed to die out naturally through damping caused by internal friction, end bearing friction, and air friction. Since end bearing friction may be assumed to be constant for specimens of equal weight and since air friction could, at best, exert only a very small damping force under the conditions of these tests, it was felt that any important differences found in the data obtained with the various specimens would be caused by inherent differences in the damping forces within the specimens.

In a part of the program the damping effect from the friction sources listed above was augmented by controlled dry friction applied to the truss.

The rate of energy dissipation or damping can be determined from the way in which the oscillations of the specimen die out or decay, and can be measured by means of a quantity known as the logarithmic decrement of damping. This quantity may be defined as the natural logarithm of the ratio of the amplitudes of any two successive oscillations. If the rate of amplitude decay is exponential in character the logarithmic decrement will have a constant value; if not, the value of the decrement will be a variable. For convenience, in these tests, single amplitudes—that is, movements to one side of the mean position—have been used for decrement determinations. The method of analysis will be described later.

To support the specimen, substantial concrete pedestals were built. To the top of each pedestal a steel plate was attached after being carefully leveled. At one end of the span, rocker bearings were fastened to the plate to permit rotational movement of the specimen in the vertical plane, but to restrain it from any translatory motion. At the opposite end of the span the plate was used to provide a plane surface on which ball-bearing wheels attached to the specimen could roll. Details of these end bearings may be seen in figure 3.

Control of Oscillations

The means used to develop controlled oscillations in the specimens will be understood by referring to figure 4. Along the specimens, at intervals equal to the panel length of the truss, weights were suspended in such a manner that all could be released simultaneously. These weights were cylindrical in form, made of cast iron, and weighed 19.5, 34.5, or 51.75 pounds each, depending upon the test condition for which used. To distinguish them from dead-load weights that were attached to the specimens for various purposes, these suspended weights will be referred to as live-load weights in this report.

The live-load weights were supported by steel hooks extending downward from the specimen. Each hook terminated in a short horizontal knife edge. On this knife edge rested a weight support consisting of a pivoted trigger held in place by a latch which could be tripped by a solenoid, the entire mechanism being mounted on the suspended weight. By connecting the solenoids in series all of the weights could be released simultaneously by closing one switch.

In order to determine whether or not the pivoted trigger interfered in any way with the free fall of the suspended weight, tests were made in which the free fall was compared to that of an identical weight supported on a wire and released by melting the wire. Space–time traces of the two falling weights were found to be identical.

In most of the tests on the 36-foot, 10-inch span length 26 live-load weights were used, while on the 28-foot, 4-inch span length the number was 20.

A wooden bench and pads of celotex were provided to catch the released weights as the tests were made (fig. 4).

With this means of excitation it was possible to duplicate any desired test condition as many times as the program required.

Measurement of amplitude

In the majority of the tests the amplitude of the oscillation was recorded at midspan by means of a sharply pointed steel stylus, attached to the specimen in a position such that it could be brought into light contact with a smoked paper wrapped around a slowly revolving drum. By means of a solenoid under automatic control, the stylus traced on the smoked paper complete cycles of the vertical motion of the oscillating specimen. Usually these records were made for the initial oscillation and those that occurred during the first second of each 10-second interval thereafter.

During the intervening 9 seconds the stylus was retracted from contact with the paper in order to reduce to a minimum the damping from stylus friction. That this was accomplished to a satisfactory degree was indicated by tests which showed that the **H**-section vibrated perceptibly for about 13 minutes after the release of the live-load weights with no stylus contacts and for about 12 minutes with stylus contacts at 10-second intervals, as described above.

A time trace with 1-second intervals was also placed on the record by another stylus controlled by a calibrated pendulum.

The details of this deflection-recording equipment are shown in figure 5, and figure 6 is a photograph of a record (in negative form) as taken from the drum and laid flat. The drum frequently made more than one complete revolution during the course of a test, as it did in the case of the test record shown in figure 6. The traces of greatest amplitudes, recorded at 10-second intervals, were those made during the first revolution of the drum. Those with the next smaller amplitudes were made during the second revolution of the drum, and so on. The 1-second time-interval trace appears at the top.

In some of the later tests, where the damping rate was high and the intermittent recording could not be used effectively, a different method was used. In this a magnetic-reluctance pickup unit was employed with a galvanometer type oscillograph for recording. A 2,000-cycle carrier current was used in the system. Because of its limited displacement range the pickup unit was located near the rocker-bearing end of the truss, and the proportionality of vertical movement at this point with that at midspan was established by a comparison of simultaneous recordings. With this system there was no physical contact between the recording system and the moving specimen.

Strain gages used

Strain gages were placed on each specimen at midspan to provide data on the maximum stresses developed for the various conditions of test. These were of the electrical resistance type, known commercially as SR-4 gages, cemented to the specimen and used in conjunction with a static strain indicator or an oscillograph. One of the

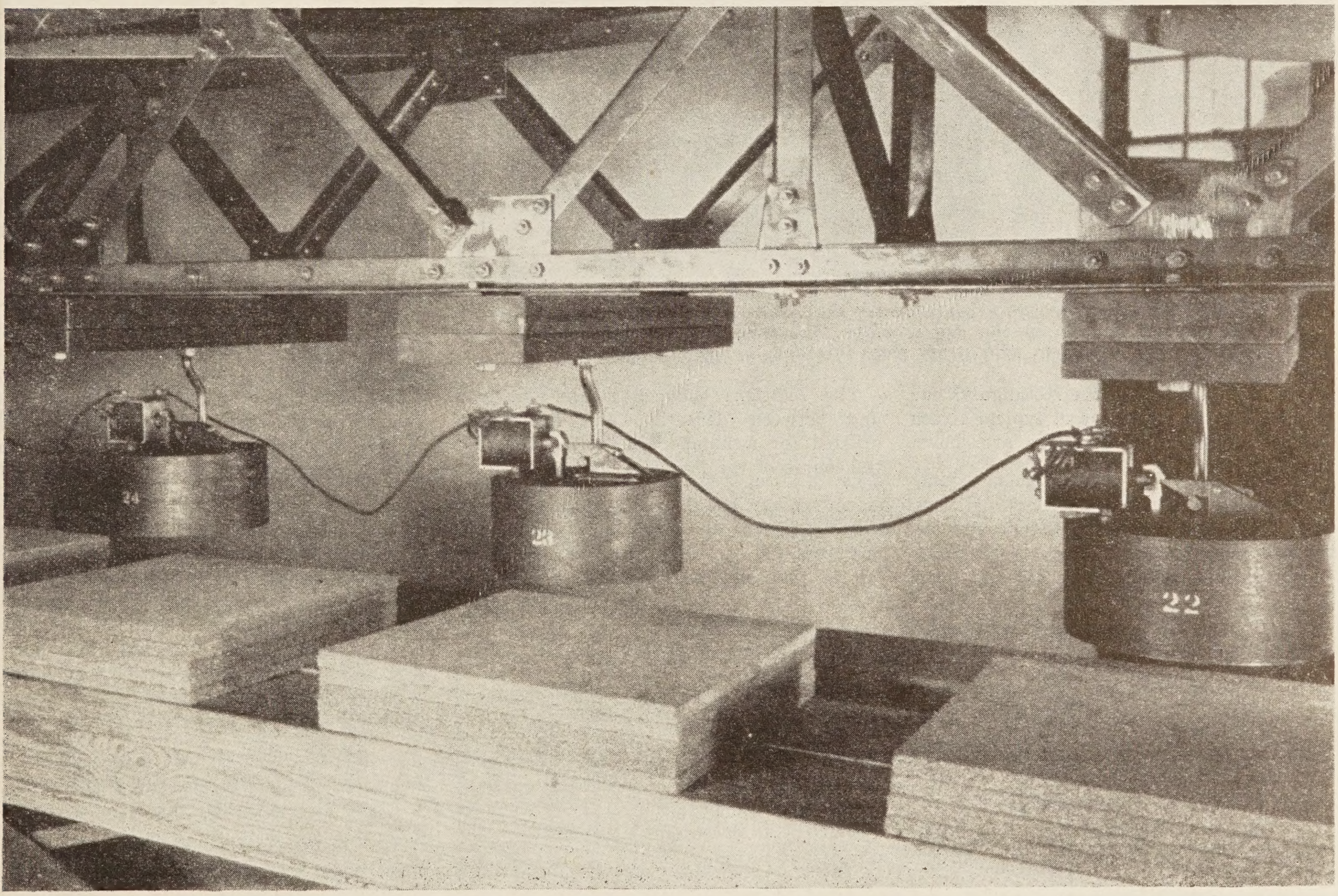


Figure 4.—Details of the weight-release mechanism.

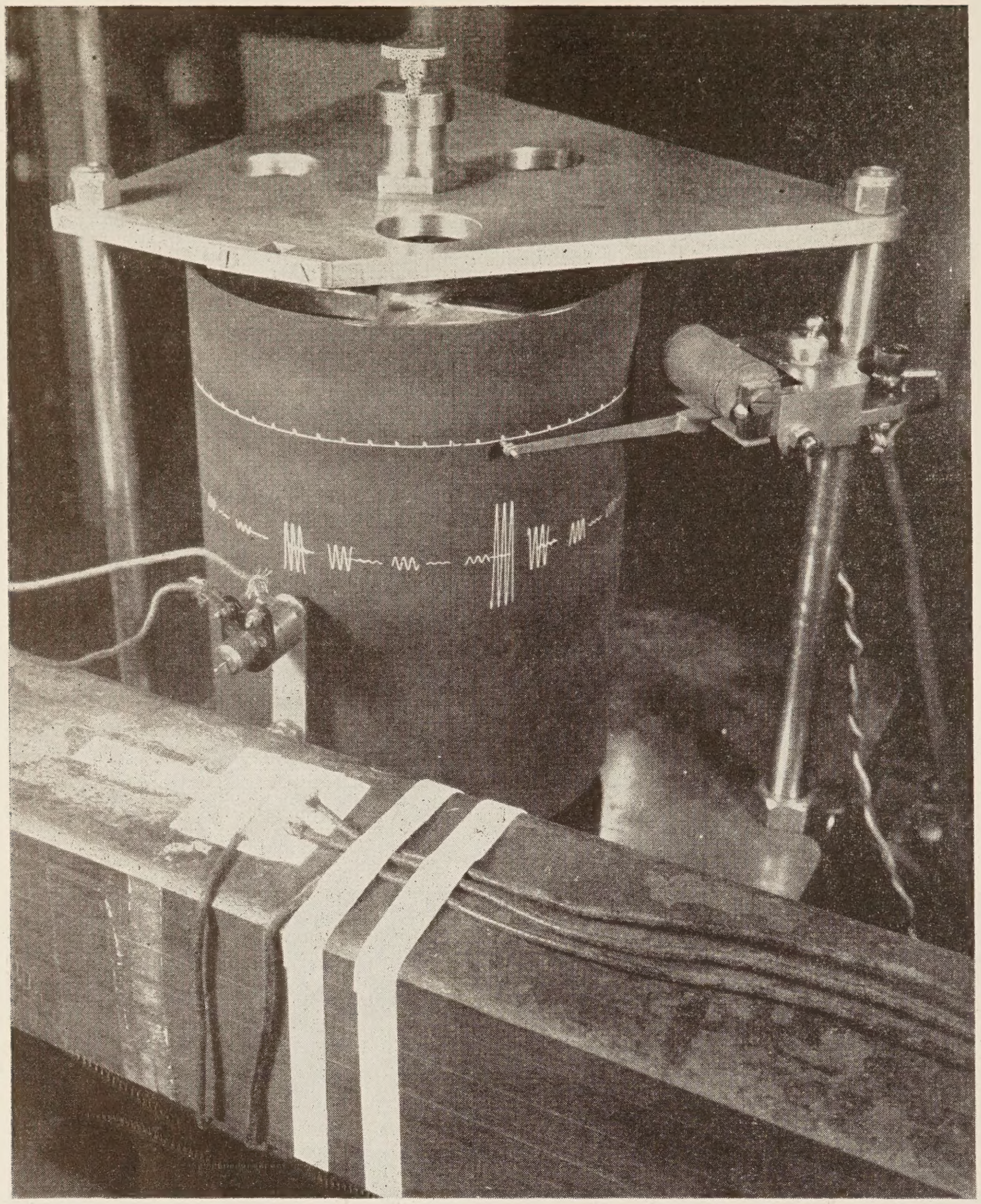


Figure 5.—The deflection-recording equipment: the solenoid-actuated styus at the left records vertical motion on the drum, while the stylus at the right records time traces. The bar specimen, with strain gage installed, appears below.

gages on the surface of the rectangular bar may be seen in figure 5 and typical strain data obtained on the **H**-section are shown in figure 7.

The relations between strain and load and between deflection and load were utilized for a number of purposes during the course of the investigation.

Some attempt was made in the early tests to determine decrement values from the rate of strain decay as recorded by an oscillograph. It was concluded that the method was feasible, but that the direct recording of deflection was perhaps a more reliable means since no electrical amplification was involved. However, in the supplemental investigation, with better instrumentation available, this question was studied more thoroughly with results that will be discussed later in the report.

The cover illustration shows the shortened truss as set up on the 28-foot, 4-inch span length for comparisons with the solid rectangular bar. The deflection measuring equipment, ball-bearing wheels at the (near) end frame of the truss, dead-load weights at the panel points, and the suspended live-load weights are to be seen in this photograph.

Chord Joints Tested

The trussed member was made up of angles, 1-inch by 1-inch by 0.065-inch in section, cold formed from a low alloy steel. Except for the lateral bracing in the plane of the upper chords, the joints of the truss as originally fabricated were drawn up with No. 10–24 commercial machine screws used as bolts. These passed through clearance holes in the gusset plates and truss members and were fitted with washers and hexagonal nuts of commercial grade. This was the type of joint fastening used in the initial tests.

A number of tests with a torque-indicating wrench showed that this screw–nut combination would withstand a tightening torque of 40 inch-pounds or more before failure occurred. On the basis of this information it was decided to test the trussed member (or truss, as it will be called) at three degrees of bolt tension, measured by tightening torques of 35, 25, and 15 inch-pounds, respectively.

The net section of a No. 10–24 machine screw is approximately one-half that of a solid rivet of the same overall diameter. This fact raised a question as to the strength of the chord splices in tension and it was decided to test such a splice to failure before beginning the program of

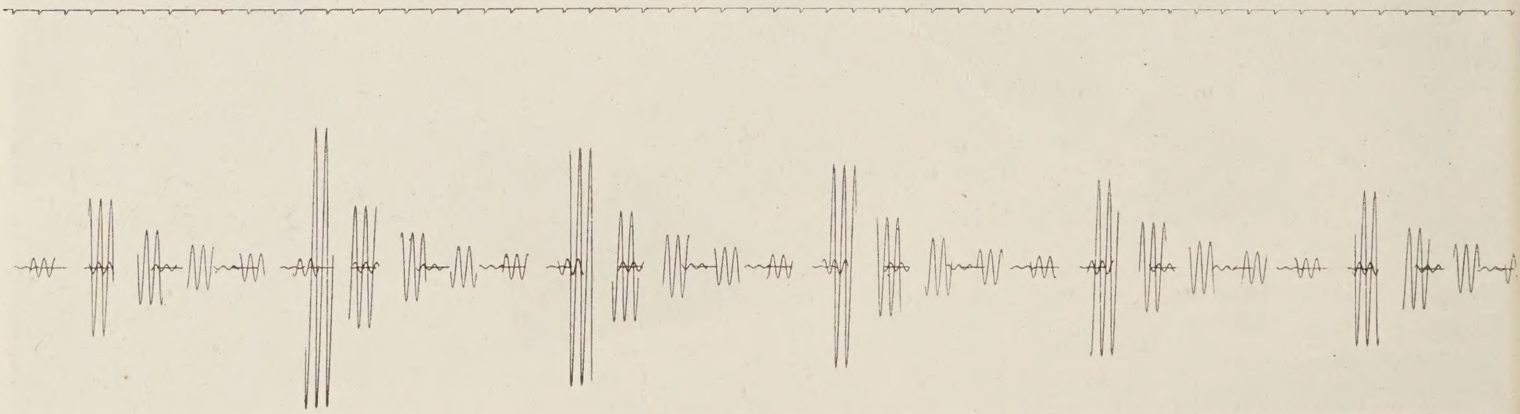


Figure 6.—Deflection record taken from the drum and laid flat. The oscillations persist during several revolutions of the drum.

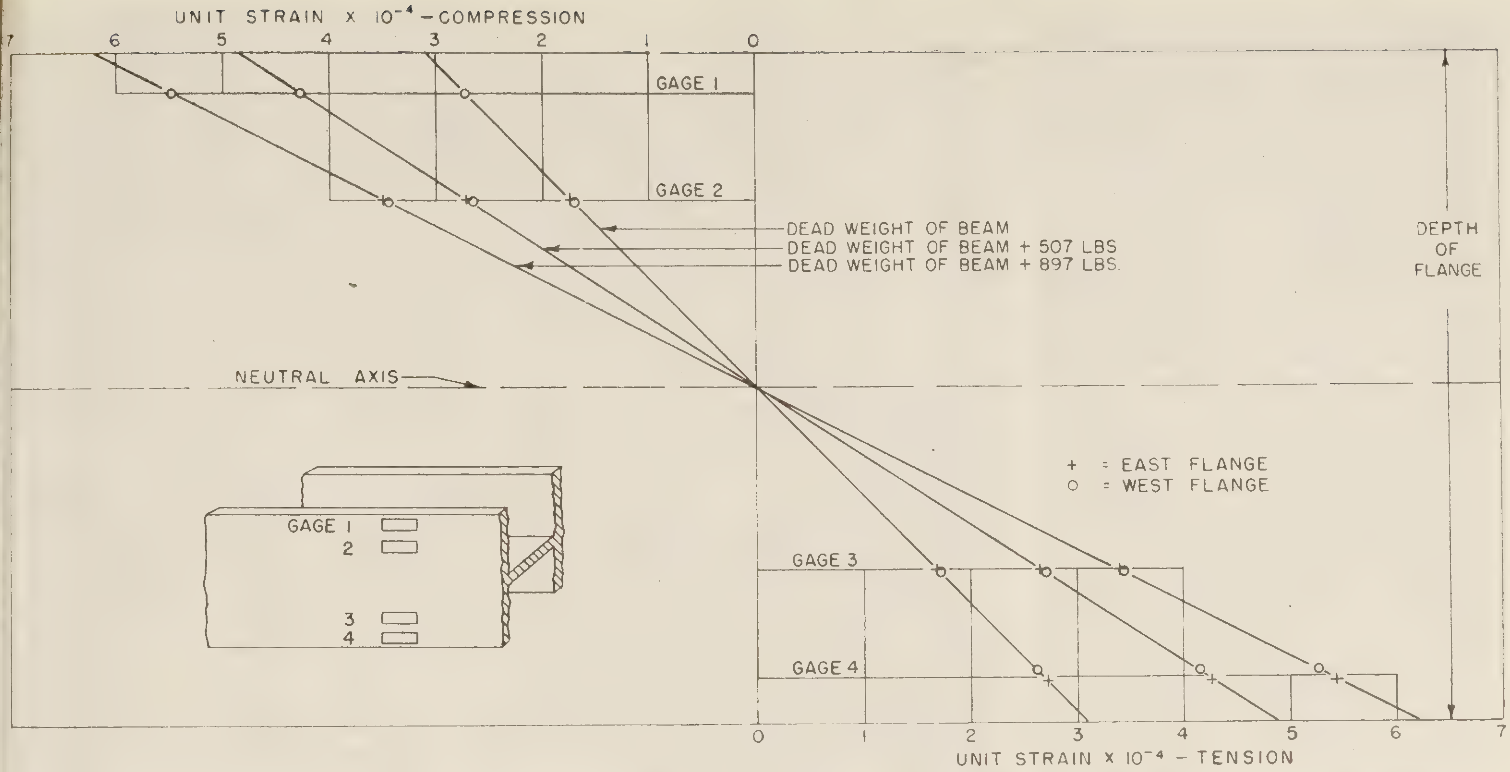


Figure 7.—Typical measured strain data on vertical faces of the H-section at midspan under various uniformly distributed loads.

load tests with the truss. The Inland Steel Company had on hand a few pieces of the angle from which the truss was fabricated and made these available. There was more than enough material for the one chord splice specimen desired for the tension test so as a matter of interest 34-inch specimens, representing a section of the upper chord between panel points, were made up and tested as columns in compression. Figure 8 shows the chord splice as set up in the testing machine for the tension test and figure 9 shows the set-up for the compression test. Restraint from bending at the ends of the compression specimen and restraint from deflecting laterally in one plane at the midpoint were provided to simulate the conditions under which the member would function. The bolts in the connections of both the tension and compression test specimens were tightened with a torque of 35 inch-pounds. From these tests the data contained in table 3 were obtained.

The tests of the chord sections in both tension and compression were considered important because of the rather high unit stresses expected in the chords under the heavier loadings (approximately 24,000 p.s.i.). On the basis of the results of these tests, as shown by the data in table 3, it was concluded that the truss would not be overstressed under any of the scheduled loadings.

Damping Characteristics of Truss and Solid Members

The truss bolted up with the No. 10–24 machine screws tightened to a value of 35 inch-pounds with a torque indicating wrench, as shown in figure 10, was compared with the **H**-section on the 36-foot, 10-inch span, the excitation being from the release of either the 19.5-pound or the 34.5-pound live-load weights. Similarly the shortened truss was compared with the rectangular bar on the 28-foot, 4-inch span, the excitation in this case being from the release of the 19.5-pound, 34.5-pound, or 51.75-pound live-load weights. Pertinent data on loads, deflections, and static-load stresses obtained in these tests are given in table 4.

From the data in this table it will be noted that under the various test conditions the initial double amplitudes at midspan varied from about 0.7 inch to about 4.1 inches and that the maximum stress in the extreme fiber at midspan ranged from about 6,350 p.s.i. to about 23,450 p.s.i.

As may be deduced from the record of oscillation decay shown in figure 6, the amplitude values decrease progressively with time as part of the energy is lost with each successive oscillation. If the energy loss is caused largely by viscous friction within the metal, as in the case of the **H**-section and the rectangular bar, the rate of decrease tends to be according to some exponential function. If, on the other hand, it is caused by external dry friction, the rate of decrease would tend to be linear. In these tests energy loss from both types of friction was present in varying degree, depending upon the particular conditions of test, as will be seen in data that will be presented.

Amplitude decay curve

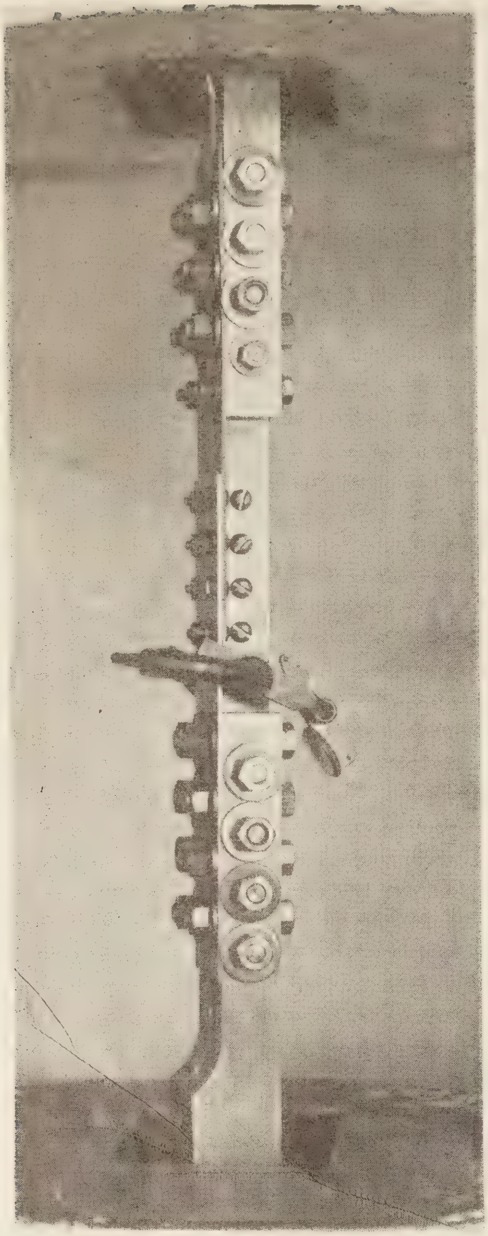
If a continuous record is made of the vertical movements of a point on the vibrating specimen and is related to a uniform horizontal time scale, and if a boundary or envelope curve is drawn through the extreme tips of the individual amplitude traces, a smooth curve will result. The shape of this envelope or amplitude decay curve is indicative of the type of friction that is causing the amplitudes to decrease, and from it values of the logarithmic decrement may be obtained. It will tend to be an exponential curve if viscous friction is the dominant cause of damping or tend toward

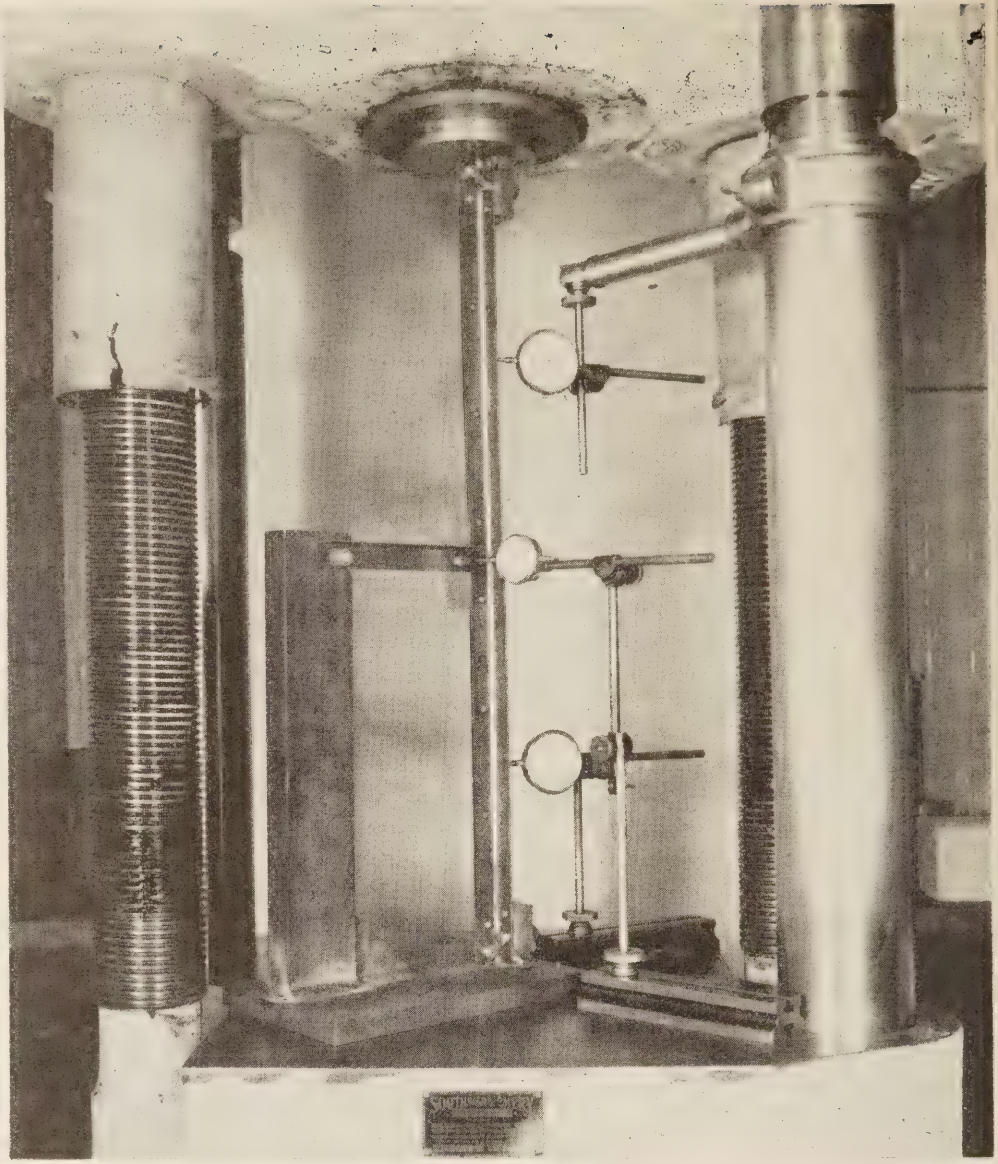
Table 3.—Tests of chord splices

	Fastenings		Load at failure	Stress in angles at failure	Type of failure
	Type	Torque applied			
		In.-lb.	*Lb.*	*P.s.i.*	
Tension tests: [1]					
Bolted splice	No. 10–24 machine screws	35	11,100	55,800	Bolts failed in shear.
Bolted splice	NAS screws	15	15,220	76,600	Angles failed at bolt holes.
Riveted splice	Rivets		13,540	68,100	Rupture in splice plates.
Compression test [2]	No. 10–24 machine screws.	35	10,700	43,300	Buckling of angles at midlength.

[1] Net section of chord angles, 0.199 sq. in.

[2] Full section of two chord angles, 0.247 sq. in.





(LEFT) *Figure 8.—Tension test on chord splice of bolted truss.*

(ABOVE) *Figure 9.—Compression test on section of upper chord of bolted truss.*

Table 4.—Loads, initial amplitudes, and static load stresses

Member	Span length	Added weights		Dead load		Live load		Total load		Initial double amplitude		Stress in extreme fiber at midspan			
													Computed stresses		Tested
		Number	Weight of each	Planned	Tested	Planned	Tested	Planned	Tested	Planned	Tested	Planned	I from measured section	I from weight-deflection data	Measured strains × 30,000,000
			Lb.	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*Lb.*	*In.*	*In.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*
Weighted truss (machine screws)	36′–10″	None	....	1,012.9	1,045.8	0	0	1,012.9	1,045.8	0	0	13,117	12,829	12,581	11,868
		26	19.5	1,012.9	1,045.8	507.0	507.4	1,519.9	1,553.2	2.06	1.836	19,682	19,053	18,685	17,505
		26	34.5	1,012.9	1,045.8	897.0	897.8	1,909.9	1,943.6	3.65	3.266	24,733	23,842	23,381	22,623
Riveted truss (for comparison)	36′–10″	None	....	1,012.9	1,040.9	0	0	1,012.9	1,040.9	0	0	13,117	12,829	12,642	12,750
		26	19.5	1,012.9	1,040.9	507.0	507.4	1,519.9	1,548.3	2.06	1.833	19,682	19,053	18,776	18,930
		26	34.5	1,012.9	1,040.9	897.0	897.8	1,909.9	1,938.7	3.65	3.267	24,733	23,842	23,495	23,670
H-section	36′–10″	None	....	1,012.9	890.0	0	0	1,012.9	890.0	0	0	8,954	8,982	9,428	9,360
		26	19.5	1,012.9	890.0	507.0	507.4	1,519.9	1,397.4	2.06	2.308	13,436	14,103	14,804	14,664
		26	34.5	1,012.9	890.0	897.0	897.8	1,909.9	1,787.8	3.65	4.082	16,884	18,042	18,939	18,729
Weighted truss (machine screws)	28′–4″	None	....	1,379.8	1,403.8	0	0	1,379.8	1,403.8	0	0	13,745	13,246	13,311	13,489
		20	19.5	1,379.8	1,403.8	390.0	390.4	1,769.8	1,794.2	0.72	0.656	17,631	16,930	17,013	17,247
		20	34.5	1,379.8	1,403.8	690.0	690.6	2,069.8	2,094.4	1.28	1.149	20,619	19,762	19,859	20,097
		20	51.75	1,379.8	1,403.8	1,035.0	1,035.4	2,414.8	2,439.2	1.92	1.738	24,056	23,016	23,129	23,462
Rectangular bar	28′–4″	None	....	1,379.8	1,377.6	0	0	1,379.8	1,377.6	0	0	6,140	6,176	6,207	6,345
		20	19.5	1,379.8	1,377.6	390.0	390.4	1,769.8	1,768.0	0.72	0.731	7,876	7,926	7,966	8,124
		20	34.5	1,379.8	1,377.6	690.0	690.6	2,069.8	2,068.2	1.28	1.277	9,211	9,272	9,318	9,480
		20	51.75	1,379.8	1,377.6	1,035.0	1,035.4	2,414.8	2,413.0	1.92	1.905	10,746	10,817	10,871	11,073

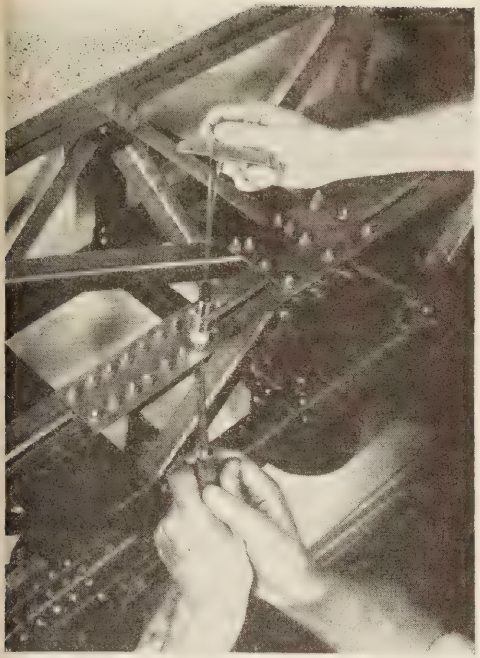


Figure 10.—Use of torque indicating wrench for setting bolt tension.

a straight line if dry friction is the dominant cause.

If the equation for the amplitude decay curve can be determined, the logarithmic decrement value at any oscillation or time value may be obtained directly from the equation. This method was used for determining logarithmic decrement values in all of the tests with the solid sections. An example of the method of analysis is illustrated in figure 11 where amplitude values resulting from experimental measurement are shown as plotted points along an exponential curve, the equation for which was derived from the experimental data. Attention is called particularly to the way in which the observed points lie along the line of the curve, representing the equation derived to fit the observed values. Below in the same figure is another curve showing the variation in logarithmic decrement values as the oscillations damp out, decreasing from an initial value of about 0.0071 to a final essentially constant value of about 0.0031. The decrement values that established this curve were computed from the equation.

In those cases where the damping results from some complex combination of influences it frequently becomes impractical to find an equation that fits the experimentally determined amplitude decay curve. This was found to be the case in a number of tests with the bolted truss. For these data logarithmic decrement values were calculated from the ratio of two successive amplitudes at each of a series of points along the amplitude decay curve.

Logarithmic Decrement Relations

The measurement of both strain and deflection at midspan made it possible to relate extreme fiber stress to midspan deflection for each specimen and from this to relate the instantaneous logarithmic decrement values to maximum fiber stress developed during the particular oscillation to which the values applied. Graphs showing the variation of logarithmic decrement with dynamic stress were particularly useful for the comparisons desired in this investigation and much of the data will be presented in that form.

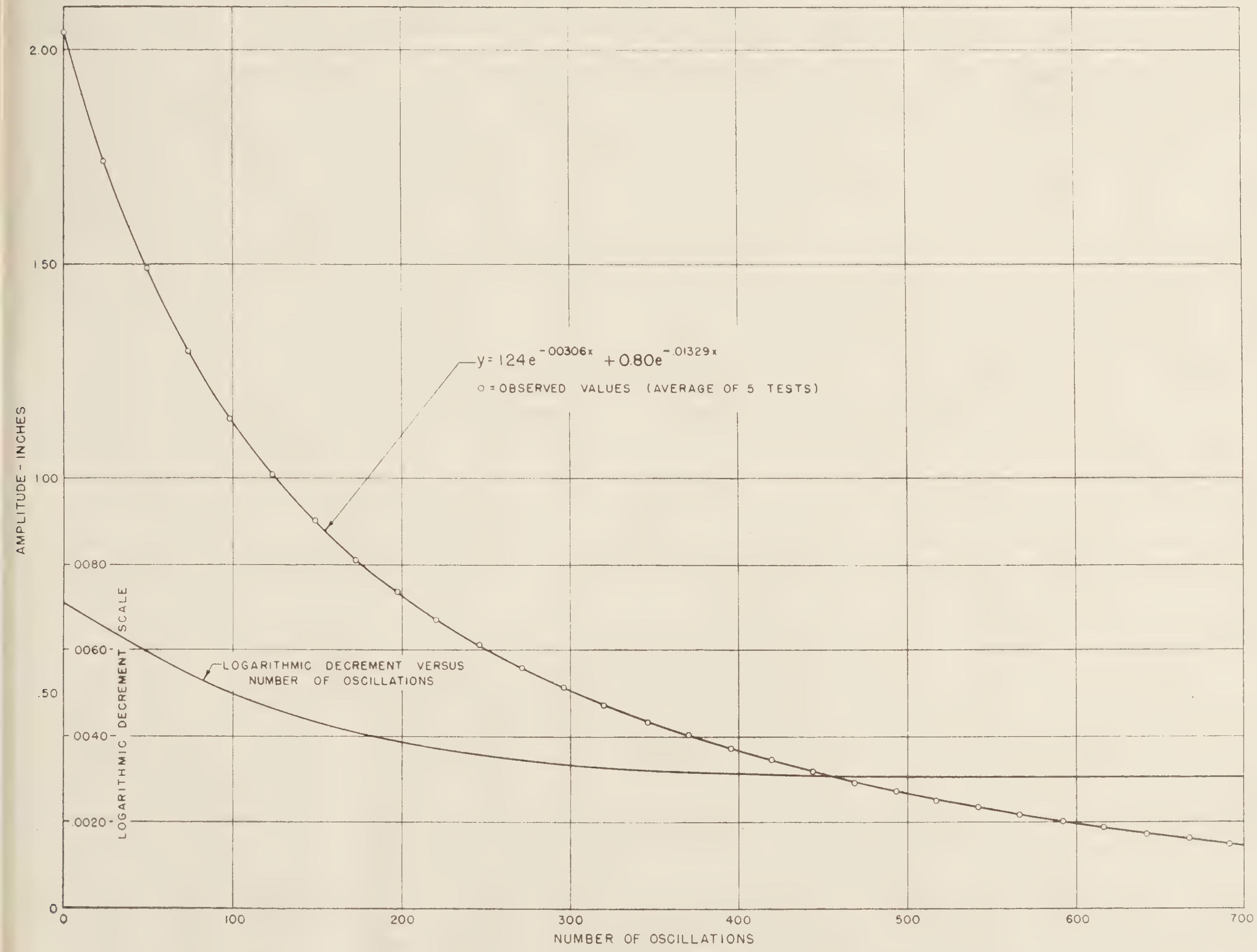


Figure 11.—Analysis of amplitude decay curve: H-section with 34.5-pound weights.

Figure 12 shows the relation between logarithmic decrement and stress for the truss and the **H**-section under identical conditions of test on the 36-foot, 10-inch span as found in the initial tests. In these particular tests the truss was bolted up with the No. 10–24 machine screws drawn up with a 35 inch-pound torque. The initial amplitudes cause the highest stresses and appear toward the right-hand side of the graph. When excited with the 34.5-pound live-load weights the truss showed an initial decrement value of 0.0511 as compared with a value of 0.0071 for the **H**-section. As the amplitudes decreased the dynamic strains decreased and the decrement values decreased also to values of the general order of 0.0048 for the truss and 0.0031 for the solid section of the **H**-beam.

Data from a similar comparison between the shortened truss and the rectangular bar when tested under identical conditions on the 28-foot, 4-inch span are shown in figure 13. Three different live-load weight values were used to excite the specimens in these tests. Even with the 51.75-pound weights the maximum dynamic stress in the bar was only about 4,700 p.s.i. At this stress level the decrement value for the truss was approximately twice that of the solid section of the rectangular bar. In this comparison, as in that between the truss and **H**-section, the maximum damping of the truss was found at the beginning of the oscillations where the amplitude of motion and the stresses were greatest. It is under these conditions that the likelihood of motion in the joints of the truss with the accompanying development of dry or Coulomb friction is greatest. It is to be noted that at low dynamic stress values the logarithmic decrement values are relatively low in all cases.

Each point on these and subsequent figures of the same type represents an average of 5 to 7 tests and may be considered quite well established since the variation for a given set of test conditions usually was quite small.

In these initial tests, with the joints in the truss fastened with the No. 10-24 machine screws, a study was made of the damping of the truss as influenced by the degree of tension in the bolts with which the joints were drawn up. In this study the truss was tested on both the 36-foot, 10-inch span and the 28-foot, 4-inch span and in both cases the oscillations were caused by the release of the 34.5-pound live-load weights. Three degrees of bolt tension, determined by tightening torque values of 15, 25, and 35 inch-pounds, respectively, were used and each of the 1,700 bolts in the truss was adjusted to the value required by the particular test. The relation between logarithmic decrement and dynamic stress for each of the several test conditions is shown in figure 14. From these data it is apparent that the more tightly the joints are

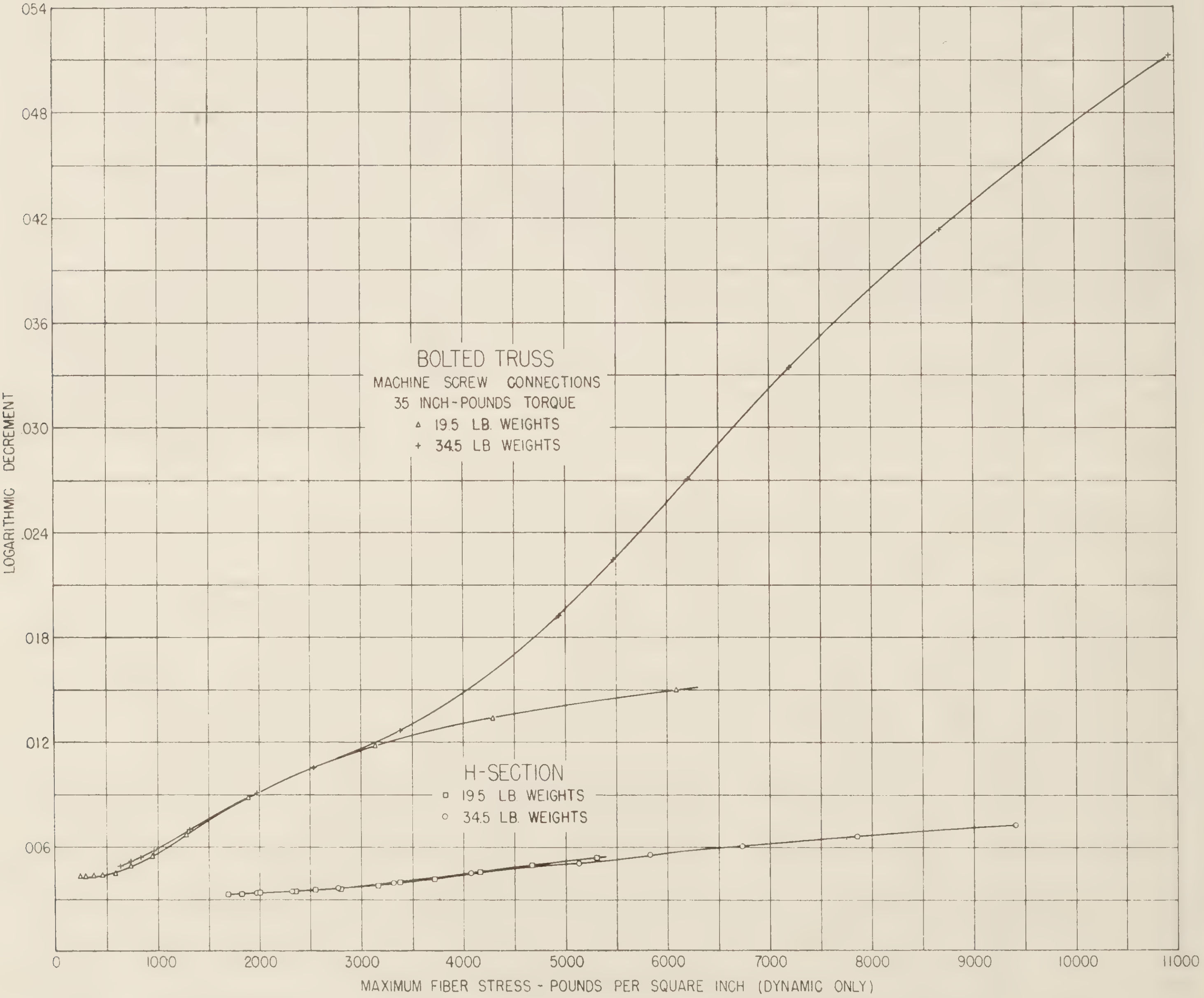


Figure 12.—Variation of logarithmic decrement with stress: Bolted truss and H-section, 36-foot, 10-inch span.

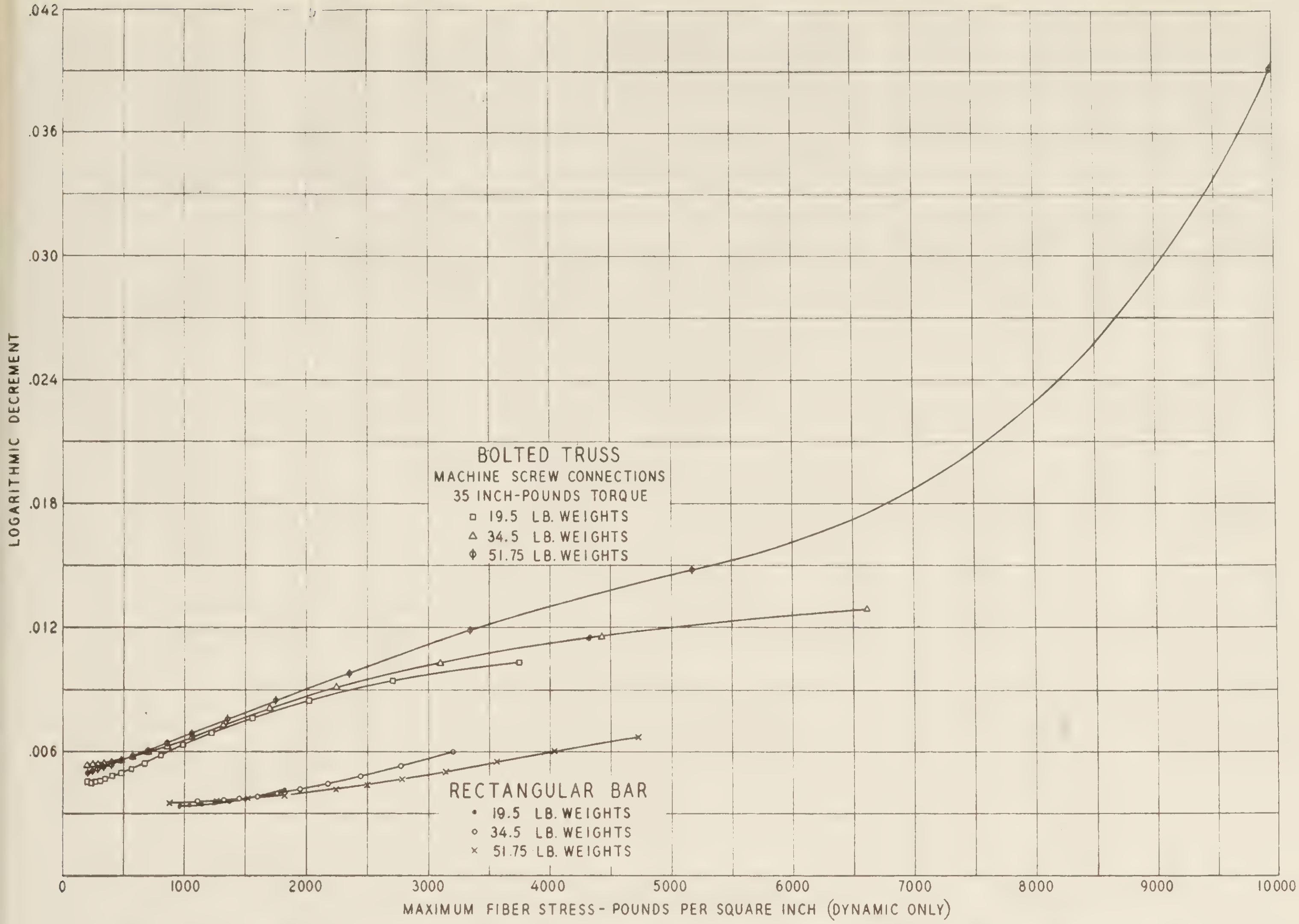


Figure 13.—Variation of logarithmic decrement with stress: Bolted truss and rectangular bar, 28-foot, 4-inch span.

drawn up, the less the damping, particularly at the higher stresses.

Examination of some of the joints near the middle of the truss showed plainly that there had been relative motion between the bolted members and that in some cases the threads along the body of the bolts had been deformed considerably by it. This raised the question as to what might be the damping characteristics of the trussed member if the bolts more nearly filled the holes.

Truss Fastenings Studied

The Advisory Board authorized further tests with bolts that had a solid or unthreaded body where the bolt passed through the angles and gusset plates and that fitted closely in the hole through these members. After some investigation it was found that certain screws available in the aircraft industry had suitable characteristics. These were of high strength steel, manufactured to close tolerances, with well formed threads in the fine series (32 threads per inch). Also, they were obtainable with solid or unthreaded bodies of various lengths. They are known as NAS (National Aircraft Standard) screws and will be referred to as such in this report. The average diameter of those obtained for these tests was found to be 0.186 inch. A special reamer was made with a diameter of 0.187 inch and all holes in splices and other connections of the truss were reamed to this size.

The nuts selected for use with these high strength NAS screws were a commercial product known as the "Elastic Stop Nut." Each nut contains an integral fiber washer which tends to prevent the nut from working loose. Tests with a torque-indicating wrench showed that, as used in these tests, the torque required to turn these nuts on the NAS screws was of the order of 1 to 2 inch-pounds.

Tightening of the NAS screw and Elastic Stop Nut combination showed that failure occurred by yielding of the bolt body in tension at a tightening torque of about 90 inch-pounds, as compared with about 45 inch-pounds for the commercial machine screws used in the original assembly of the truss. In other words, these fasteners were about twice as strong as the screw–nut combination used in the initial tests with the truss.

For the tests of the truss with the NAS screw fastenings, tightening torque values of 15, 25, and 45 inch-pounds were selected. The first two gave direct comparisons with data obtained when the No. 10–24 machine screws were used, while the 45-inch-pound value was chosen because tests showed that it corresponded to a direct tensile stress of about 60,000 p.s.i. in the bolt body. This seemed to be a reasonable upper limit for working stress in structural bolting.

A chord splice made up with the NAS screws tightened with a torque of 15 inch-pounds was tested in tension. As shown in table 3, it failed at a load of 15,220 pounds by rupture of the metal in the angles, the screws being undamaged. In a comparative test with the No. 10–24 machine screws the splice failed at 12,240 pounds by shear in the bolts. The computed stress in the chord angles, based on net section, was about 76,600 p.s.i. in the test with the NAS screws and about 61,500 p.s.i. in that with the commercial machine screws. The appearance of the failed chord section tested with the NAS screws is shown in figure 15.

After all the holes had been reamed and the NAS screws had been installed, tests were made with the truss on the 36-foot, 10-inch span with the 34.5-pound live-load weights, using tightening torques of 15, 25, and 45 inch-pounds, respectively.

The data obtained in these tests are shown in figure 16 and are comparable with those obtained with the truss when fastened with the machine screws as shown in figure 14. It will be observed that with the highest bolt tension, represented by a tightening torque of 35 inch-pounds for the machine screws and 45 inch-pounds for the NAS screws, the relations between logarithmic decrement and dynamic stress are essentially the same.

From this comparison it would appear that insofar as the self-damping characteristics of the truss are concerned the tightness with which the connections are bolted up is of more importance than is the fit of the bolts in the bolt holes.

Tightening procedure examined

At the low tension, represented by a tightening torque of 15 inch-pounds, the truss with the NAS screws showed more damping at the higher stress values than had been found in the comparable tests with the machine screws. This was rather surprising and, in searching for an explanation, it was suspected that variations of this sort, particularly where lower bolt tensions were involved, might be the result of variations in the tightening procedure itself—such as, for example, whether or not a given level of bolt tension had been preceded by a higher or a lower bolt tension value. It was recognized that the relation between bolt tension and tightening torque is susceptible to variation, and throughout the tests great care was used to follow a uniform procedure to control this variation as much as possible.

To obtain information on this point, tests were made with the truss on the 36-foot, 10-inch span excited with the 34.5-pound live-load weights. In one series, three bolt tensions were applied in ascending order; in a second series, the same tension values were applied in descending order. The data obtained are shown in figure 17.

It is apparent from these data that the sequence of bolt tightening operations could have a measurable effect on the damping characteristics of the truss, the effect being least at the higher bolt tensions. It is indicated that the more tightly the joints are drawn up, the less sensitive they are to the variations inherent in the tightening procedure. This seems quite reasonable.

It will be recalled, however, that when the chord splices were tested to failure in tension the bolts were brought into bearing and at these high stresses the effect of bolt type and fit in the holes on the ultimate strength of the splice was quite marked.

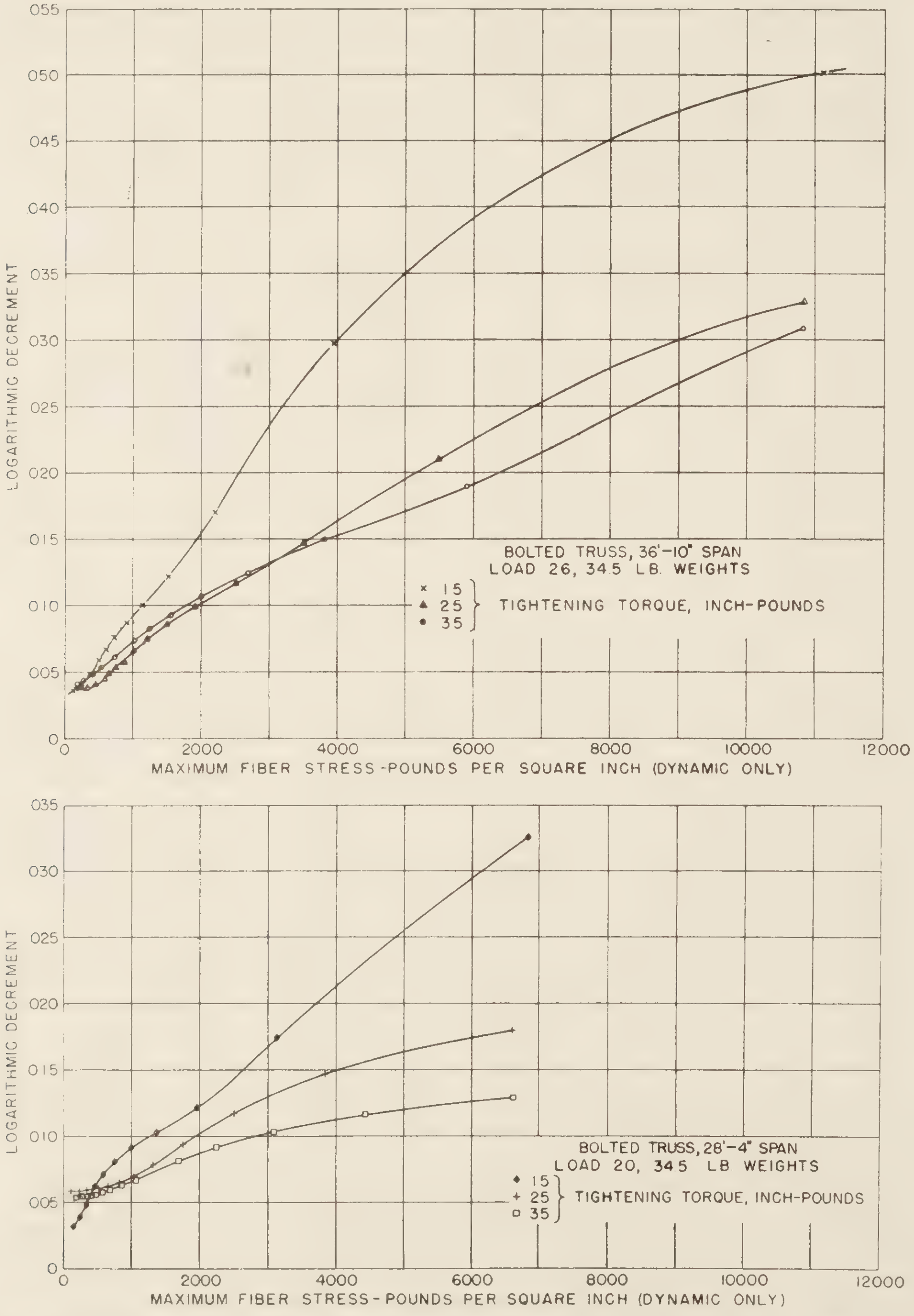


Figure 14.—Variation of logarithmic decrement with fiber stress: Truss (both span lengths) bolted with machine screws with three degrees of bolt tension.

Effect of Variation in Dead Load

One of the questions raised in the discussion of the damping tests by the Advisory Board had to do with possible effects of changes in dead load on the damping characteristics of the truss. It was particularly desired to learn what might be the effect of an increase in dead load. Because of the relatively high combined stresses developed in the chord members by the dynamic tests, there was a practical limit to the amount by which the dead load could be increased. In order to obtain a relatively wide spread in dead-load values without developing an excessively high combined dead- and live-load stress in the chord members, the dead load of the truss was first reduced from its normal value of 1,059.6 pounds (with NAS screws and Elastic Stop Nuts) to 843.5 pounds by decreasing the dead-load weights attached to the lower chord panel points. After tests had been made with this reduced dead load, using both the 19.5- and the 34.5-pound live-load weights, dead load was added to the truss until it weighed 1,278.2 pounds. The tests were then repeated. Amplitude decay curves for each of the four test conditions are shown in figure 18. The data indicate that increasing the dead load of the truss by 51.5 percent caused no significant change in its damping characteristics.

In the original discussion of the damping test program an item was included that re-

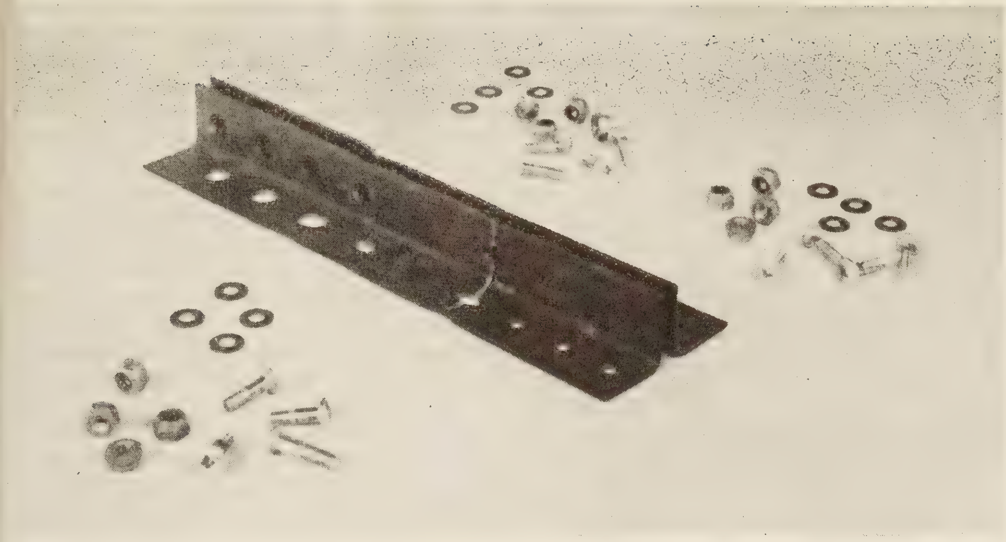


Figure 15.—NAS screws and Elastic Stop Nuts used in truss connections, and chord test section which failed in tension when these screws were used.

lated to the manner of excitation of the specimens. Specifically, the **H**-section was to be excited by the release of live-load weights arranged in two different patterns and varied in amount so as to produce equal deflections of the beam at midspan. One pattern was that used in the tests that have been described—that is, 26 weights, each of 34.5 pounds, uniformly distributed at 17-inch intervals throughout the span length. The other pattern consisted of a series of weights arranged symmetrically about the midpoint of the span length, but not spread uniformly from one reaction to the other.

Use was made of the 51.75-pound weights available from the tests with the rectangular bar. By trial it was found that 12 of these weights would develop the required deflection. The details of the two load arrangements, together with the relations between logarithmic decrement and number of oscillations (or time) as found in each test, are shown in figure 19. From this comparison it may be concluded that insofar as these particular load arrangements are concerned no significant effect on damping characteristics was found.

To summarize: the data obtained in the comparisons of the internal damping characteristics of trussed and solid steel members show that there is a marked difference between the two at the higher vibration amplitudes and higher stress ranges, the damping of the truss being greater than that of the solid section in all tests. At lower vibration amplitudes the differences are less marked and the damping, as measured by the logarithmic decrement values, is relatively quite small with both types of structural members.

Augmented Damping of Truss

The data obtained in the tests that have been described so far led to a discussion in the Advisory Board of the probable behavior of the truss if it were provided with a simulated deck having sliding bearings to support the deck sections—that is, if the trussed member were made to conform more nearly to the deck structure of a suspension bridge. As a result of the discussion it was decided to extend the program to include some study of the effects of augmenting the dry friction within the truss with dry friction developed by mechanical brakes, by sliding bearings at the ends of sections of a simulated floor system, and by sliding bearings at the truss support. These studies will be discussed in the order named.

Tests with Mechanical Brakes

It was considered desirable as a part of the program in which the damping of the truss was augmented by dry or Coulomb friction, applied externally, to have some system by which the amount of the frictional force could be controlled within close limits.

For this purpose a mechanical brake designed to develop known frictional forces

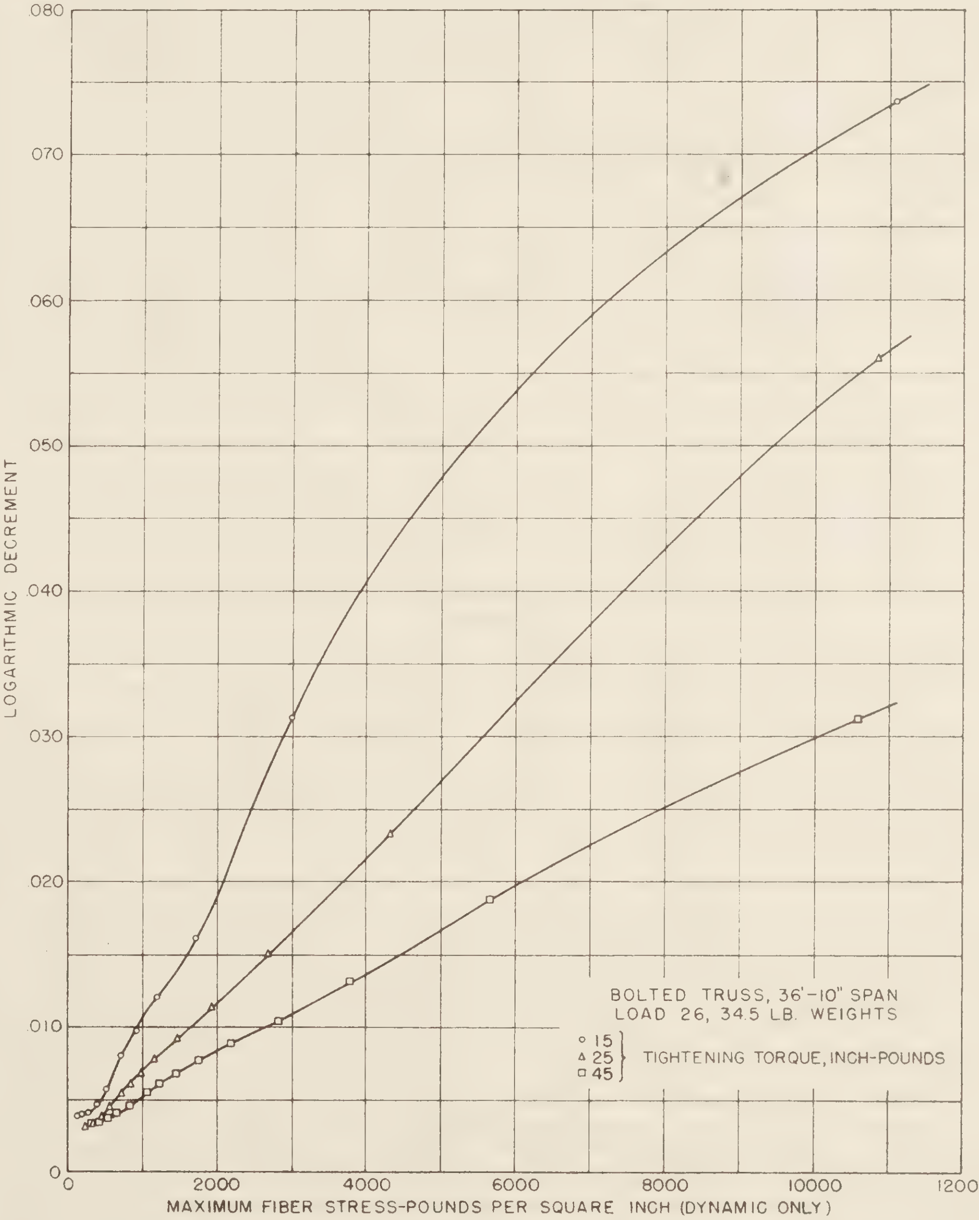


Figure 16.—Variation of logarithmic decrement with fiber stress: Truss bolted with NAS screws with three degrees of bolt tension.

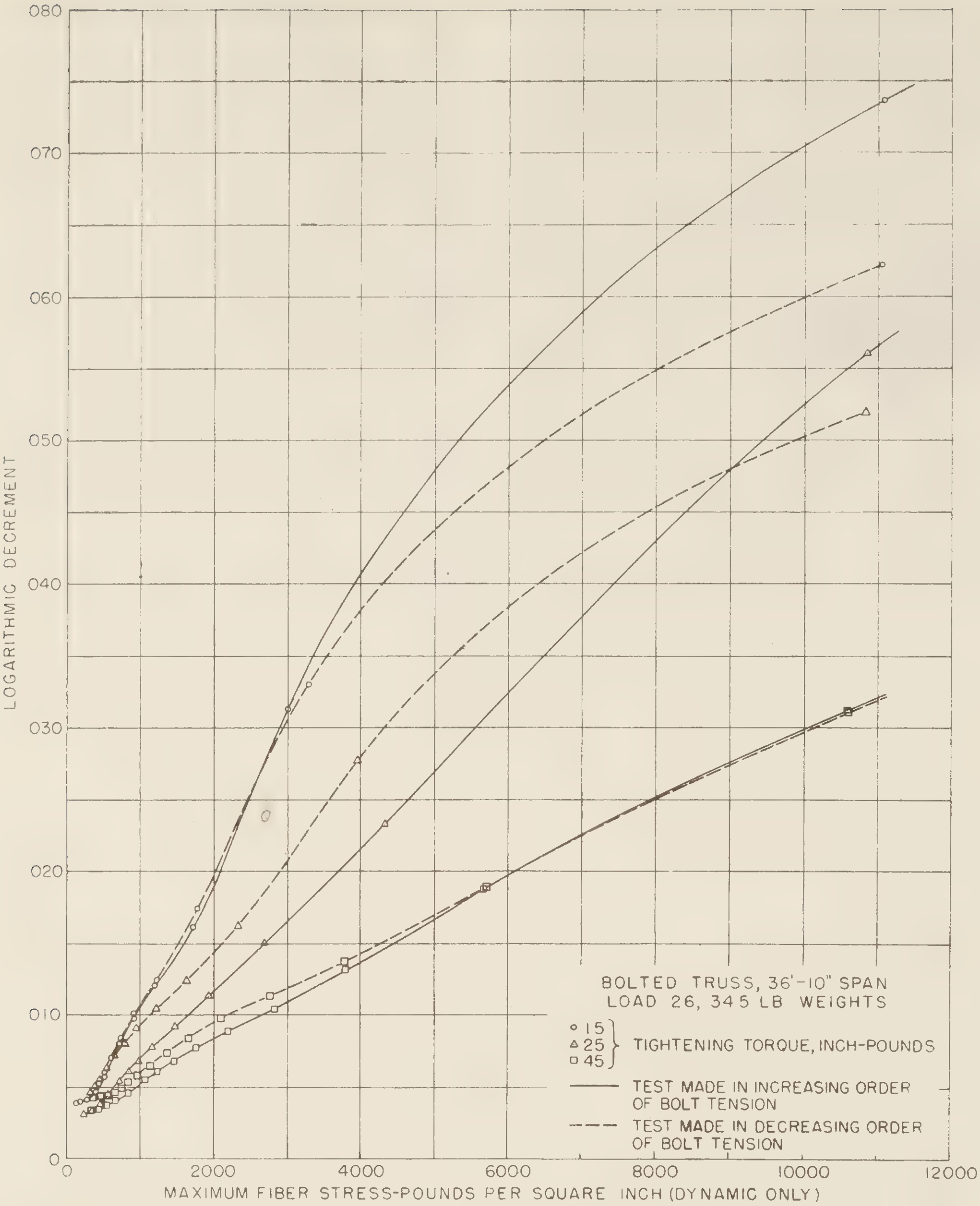


Figure 17.—Effect of bolt tightening sequence on logarithmic decrement–fiber stress relations.

at the ends of the truss was constructed. The principle of the brake is quite simple and its operation may be readily understood by reference to figure 20. To the inner face of the concrete pedestal that carried the end bearings of the truss a steel support or post was bolted. This post extended upward through the truss and provided a ball-bearing fulcrum for a horizontal lever that extended outward longitudinally over the end frame of the truss. At the outer end of the lever there was suspended on knife edges a pendant platform on which cast-iron weights could be applied to develop a known downward force on friction surfaces located beneath the lever and at a point near the fulcrum. These surfaces were of several forms and materials and will be described presently. The upper surface was attached to the lever while the lower surface was carried on a plate bolted transversely across the truss in the plane of the upper chord and directly over the end frame. The downward reaction at the friction surfaces was, therefore, directly over the end bearing of the truss.

As the truss oscillated in the vertical plane the end frame went through a rotational motion, causing a horizontal sliding motion at the plane of contact of the friction surfaces. With the three weights used on the platform of the brake, vertical reactions of 70, 140, and 210 pounds were developed on the braking surfaces. One of these brakes was installed at each end of the truss and both were operative in all of the tests in which brakes were used.

Friction surfaces varied

In the initial tests with the brakes, both of the friction surfaces were of cold rolled steel—the upper surface being a cylindrical segment of 6-inch radius, the lower surface being plane. These were the surfaces in use when the photograph of figure 20 was taken. To insure dry friction the rubbing surfaces were carefully cleaned before each test.

It was at once evident that the rubbing of a cylindrical surface of cold rolled steel on a plane surface of the same material in the absence of a lubricant was causing a surface scoring or "galling" which resulted in erratic test results and was, therefore, not satisfactory for comparative testing. The condition was present in tests at relatively low pressures on the friction surfaces, but was more severe at the higher pressures.

To increase the areas of contact of the friction surfaces and thus decrease the pressure intensity, circular plane surfaces of 1.0- and 2.0-square-inch area, respectively, were made up as replacements for the upper cylindrical surface used in the initial tests. These also were of cold rolled steel, finely finished. They were conical in form and were fitted with a ball seat at the top to insure that the plane friction surfaces would remain in uniform bearing as motion occurred. Even with the greatly reduced pressure intensities obtained by this modification the scoring continued as long as the opposed surfaces were of cold rolled steel and were without lubrication.

The character of the material used for the lower friction surface was next changed. Inserts of bronze or of hardened steel were fastened in the plate that was bolted across the truss. The bronze insert was made of some bridge bearing material left over from an earlier research program and met the requirements of A.S.T.M. Designation B-22-21, Class C. The steel insert was of flat drill-rod stock hardened to Rockwell C 57.

These various friction surfaces are shown in figure 21. In the bottom row from left to right are the 2-square-inch circular plane surface, the bronze insert, the hardened steel insert, and the 2-square-inch circular plane surface in its normal position with the ball in place to bear against the lower surface of the lever arm. In the upper row of the group are two views of the cylindrical steel surface used in the initial tests with the brake and of the 1-square-inch circular plane surface of cold rolled steel used later.

Damping effect of brakes

With the friction brakes in operation, the oscillations of the truss damped out much more rapidly than did those obtained under identical test conditions without this externally applied frictional force. This is as would be expected. Because of this rapid rate of amplitude decay it was no longer feasible to determine the logarithmic decrement from the intermittent records of movement obtained with the stylus at midspan and recourse was had to a magnetic type pickup with oscillograph recording, as mentioned earlier. This type of recording was used in all of the tests in which external friction was applied to the truss. Typical records obtained with this recording system are shown in figure 22. These records are of interest because they indicate very clearly the strong damping developed by the brakes, particularly as the braking force F_n is increased, and also because they show the difference in shape of the envelope curve where the damping is principally caused by dry or Coulomb friction.

Amplitude decay curves obtained with the mechanical brakes in operation are shown in figures 23 and 24 in comparison with that for the truss when no external friction was present. Figure 23 contains data obtained with the bronze lower friction surface in contact with cold rolled steel upper friction surfaces of each of the three types and for three pressure intensities. Figure 24 contains data for comparable test conditions except that the lower friction surface was of hardened steel.

In these figures and some that appear later the amplitude values are as measured with the pickup unit near the end of the truss. They are, therefore, only about 10 percent of the corresponding amplitude values at midspan.

It is apparent that where the bronze and steel plates were used as opposing friction surfaces (fig. 23) the braking action was smooth and consistent, the damping increased progressively with the increase in force applied normally to the surface (F_n), and the area of the friction surfaces had little influence. In other words, the action conformed to the basic principles of dry friction.

In contrast, where the opposing friction surfaces were of steel, even though one was much harder than the other, abrasion and scoring were prevalent. The result, as will be seen from figure 24, is that although the damping action was at times greater than with the bronze-steel combination, the action was neither consistent nor dependable. Although the damping does increase with increases in the force applied normally to the friction surfaces, the relation is not particularly consistent. It is apparent also that with the greater pressure intensities obtained with the smaller contact areas the frictional resistance was greater than with the larger areas, indicating that smooth sliding friction did not obtain.

It is of particular interest that the observed behavior of these friction surfaces was quite similar to that observed in a series of friction tests on sliding bearings made by the Bureau of Public Roads a number of

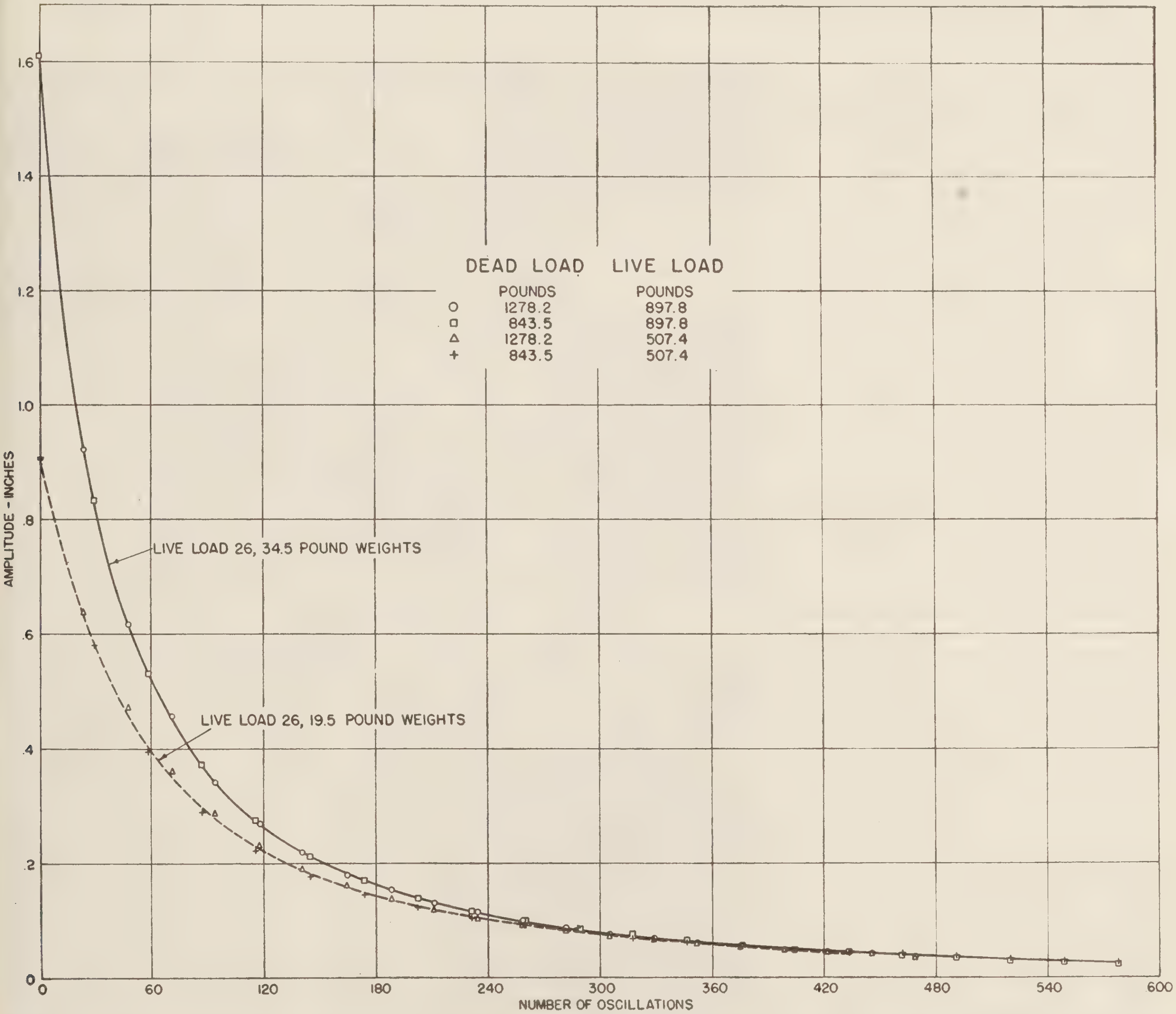
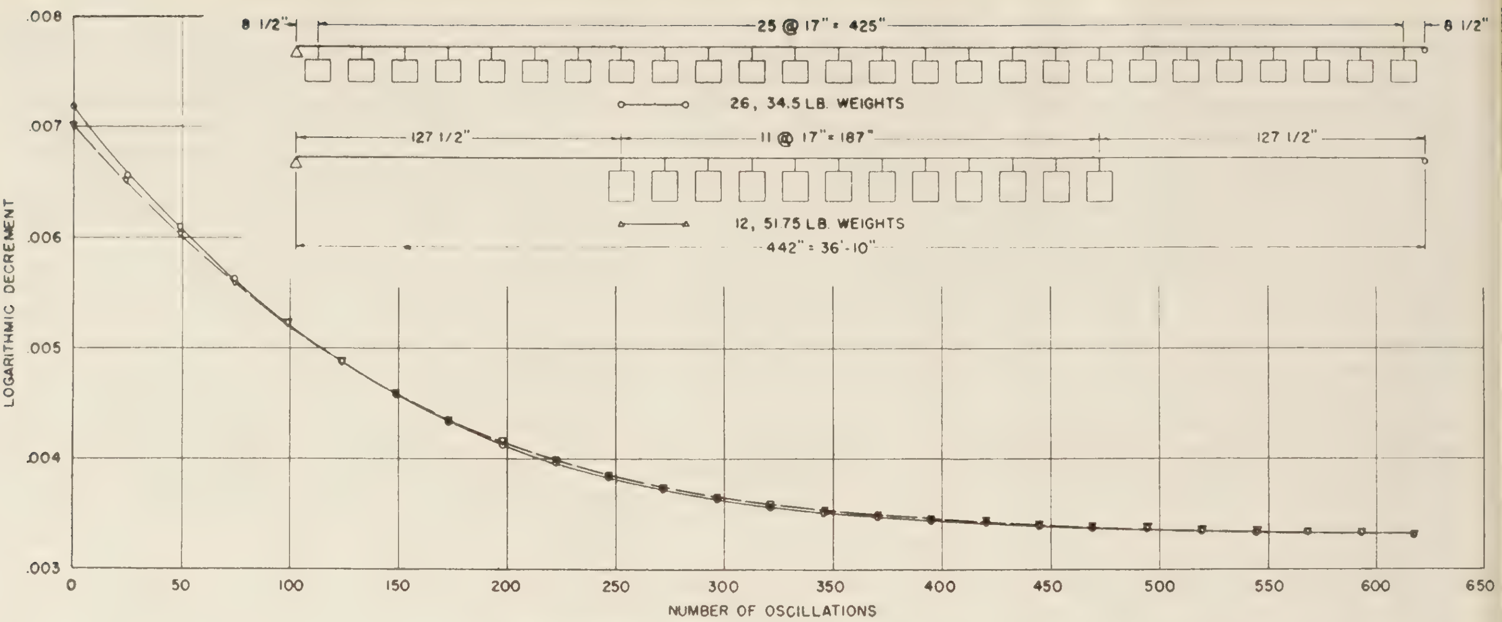
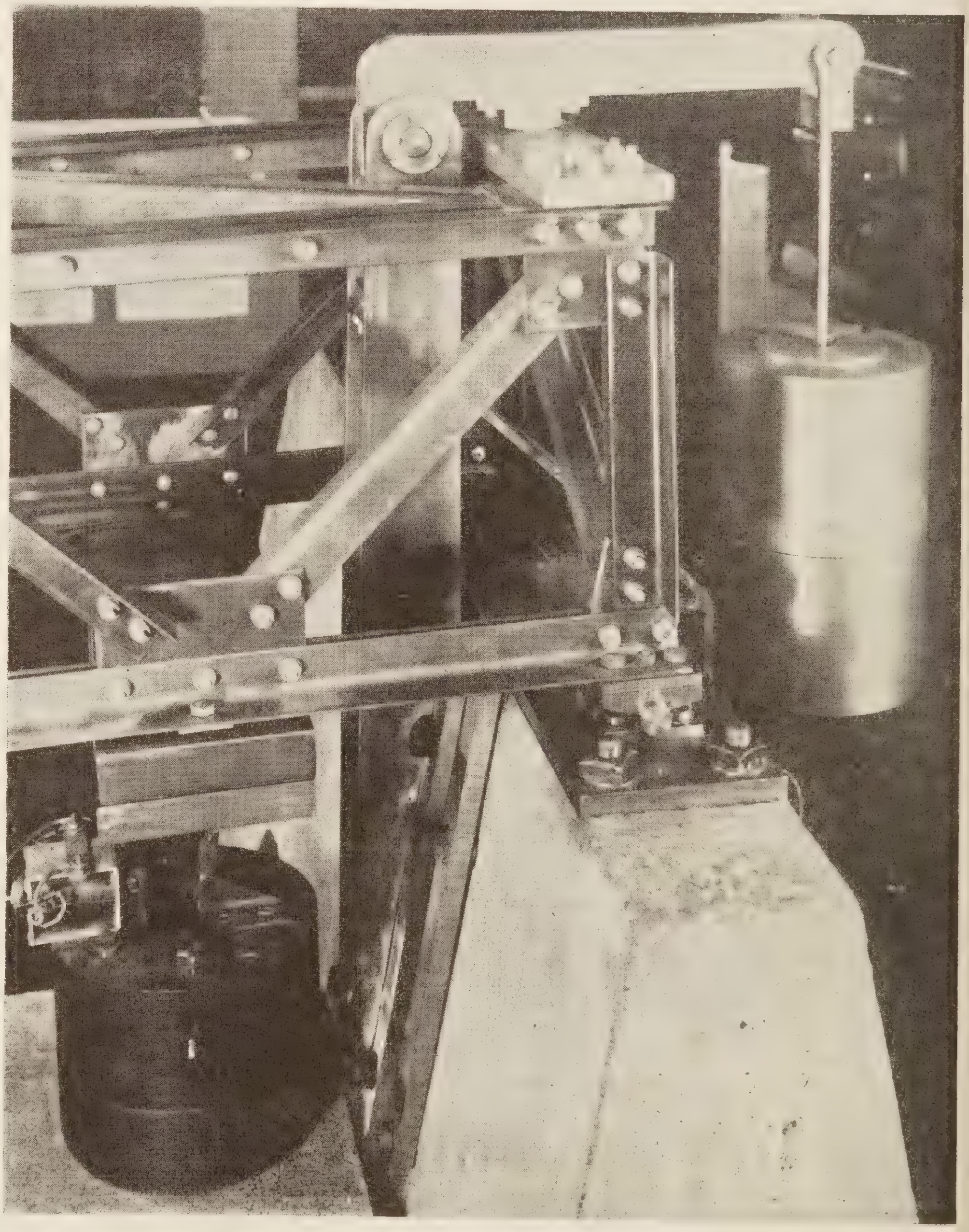


Figure 18.—Effect of dead load variations on amplitude decay: 36-foot, 10-inch span truss bolted with NAS screws with 45 inch-pounds tightening torque.





(ABOVE) ***Figure 19.—Comparative effects of uniform loading and of symmetrical but non-uniform loading on the damping of the H-section (midspan deflection the same in both cases).***

(RIGHT) ***Figure 20.—Friction brake, with cylindrical surface on brake lever in contact with plane surface on truss.***

years ago.[4] It was concluded from these earlier tests that combinations of like or unlike ferrous metals gave the highest coefficients of friction and that ferrous metals in contact with bronzes gave the lowest. Also, where the opposing plates were of ferrous metals, either like or unlike, seizure and scoring almost always occurred.

For the comparative tests required in this program it seemed clear that a combination of steel and bronze must be used for the friction surfaces if the data were to be concordant and susceptible of analysis, even though the frictional forces developed were somewhat smaller.

With the mechanical brakes acting, it is evident from the data in figure 23 that the oscillation amplitudes decrease very rapidly to values of the order of 0.01 inch or less, as measured at the deflection gage position near the end of the truss (which corresponds roughly to amplitudes of 0.1 inch or less at midspan). Also it is apparent that the shape of the envelope or amplitude decay curve tends to become linear as the braking force is increased. This is as would be expected, since the Coulomb damping supplied by the braking system tends to become the dominant component as this force is increased.

In figure 25 are shown logarithmic decrement values computed from the amplitude decay curves of figure 23 for the 2-square-inch friction plate area and for four values

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[4] *Determination of coefficients of friction of sliding bearings for bridges*, by G. W. Davis. PUBLIC ROADS, vol. 17, No. 10, Dec. 1936.

of the braking force as measured by the normal component F_n. The complex nature of the overall damping with the brakes in operation made it expedient to compute decrement values directly from successive measured amplitudes at frequent intervals, as described earlier. This accounts for the slight scatter of the points for the three upper curves in figure 25.

In the case of Coulomb damping the logarithmic decrement is inversely proportional to amplitude. It can be shown that such a hyperbolic relation exists in the data from the tests in which the maximum braking force was used, that is, $F_n = 210$ pounds, which indicates that with the highest braking force active, the damping is almost entirely from the braking action, hence follows the laws of dry or Coulomb damping.

At lesser values of F_n the action is not so completely dominated by the dry friction developed by the brakes and the damping relations are more complex.

Simulated Floor System

The second group of experiments involving the development of additional Coulomb damping were those in which a simulated floor system, with sliding bearings at intervals, was placed on the top of the trussed member.

This deck was designed as a series of steel plates 7¾ inches wide by $\frac{3}{16}$ inch thick, arranged end to end over the full length of the truss. Except for one section 34 inches in length at the center of the span, the deck sections were each 8 feet, 6 inches in length. At alternate panel points of the upper chord small plates of cold rolled steel were bolted transversely on the truss and on these the steel-plate deck sections were supported. At one end of each individual deck section (except the 34-inch section in the center) two short vertical legs were fastened. This pair of legs was attached to one of the transverse plates by a hinge or knuckle connection that was resistant to horizontal or to vertical motion, but not to rotation. At each of the other support points, the deck section was fitted with a similar pair of legs except that these were tipped with bronze shoes at the lower end to create sliding friction bearings for the horizontal movements that occurred at these points as the truss oscillated in the vertical plane.

A deck load of about 500 pounds was considered desirable for the purposes of the tests. To develop this and at the same time to maintain the total dead-load weight that had been used in the majority of the tests with the truss, the dead-load weight attached to the truss at the lower panel points was reduced from 768.9 pounds to 274.3 pounds, a difference of 494.6 pounds. Ballast weights attached to the deck sections were used to increase the weight of the simulated floor system by an amount which equaled approximately that removed from the lower panel points. The steel

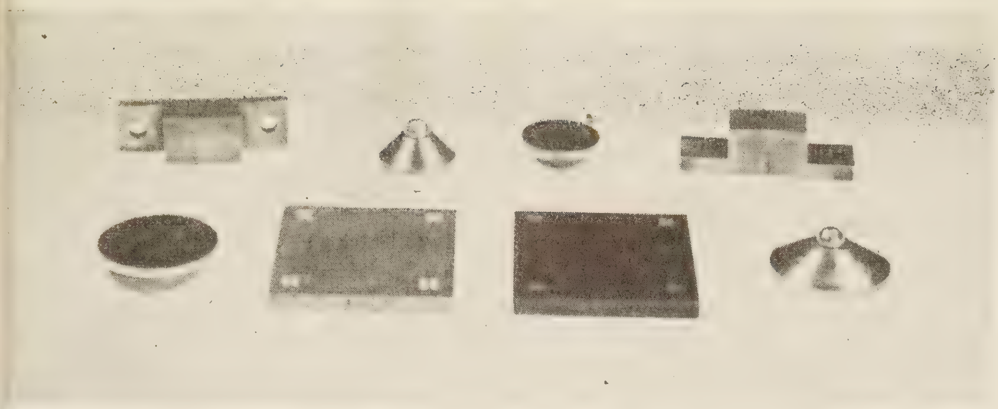

Figure 21.—Various bearing surfaces used in the friction brakes.

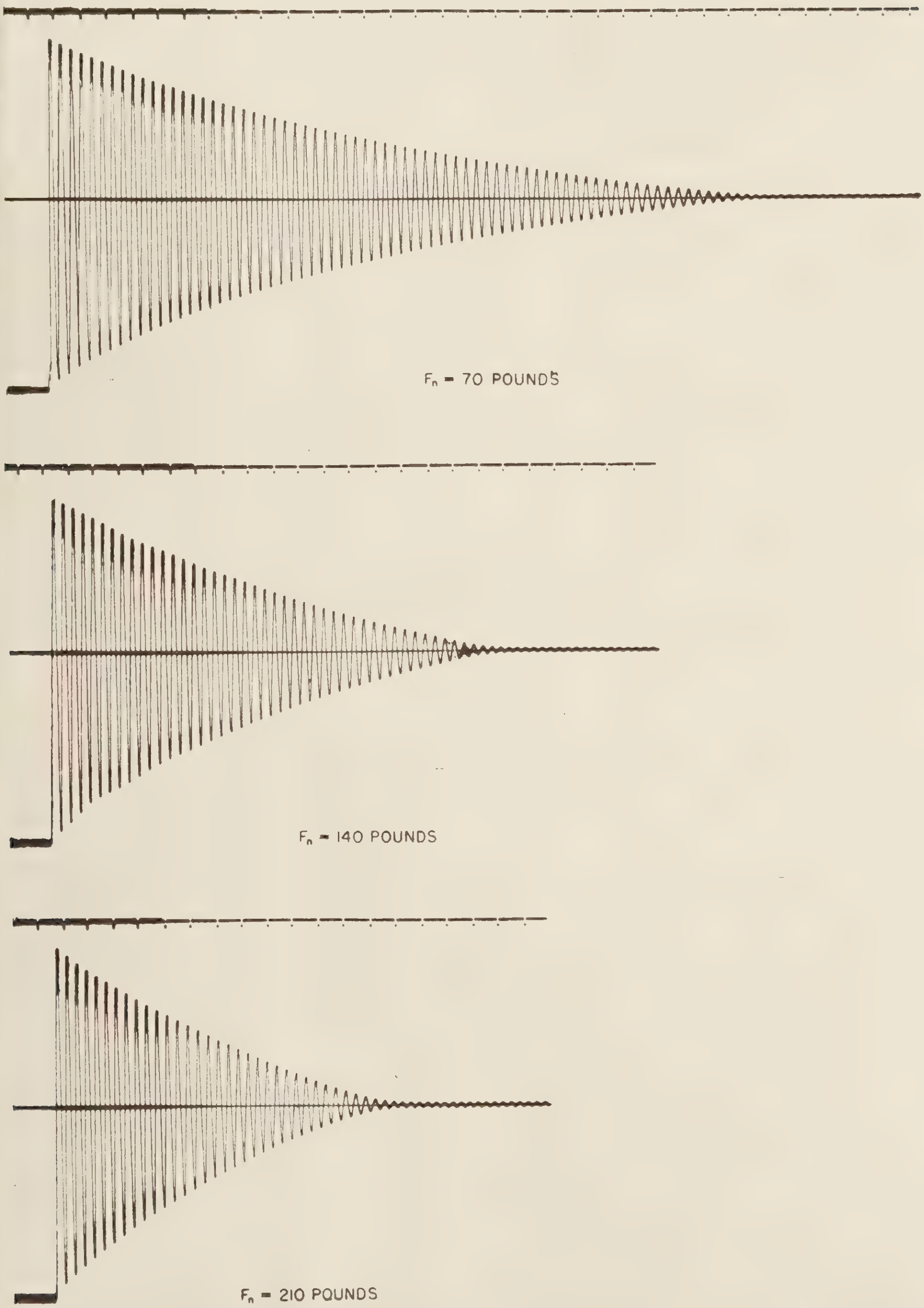

Figure 22.—Typical amplitude decay records of friction brake tests, with 1-square-inch plane contact area.

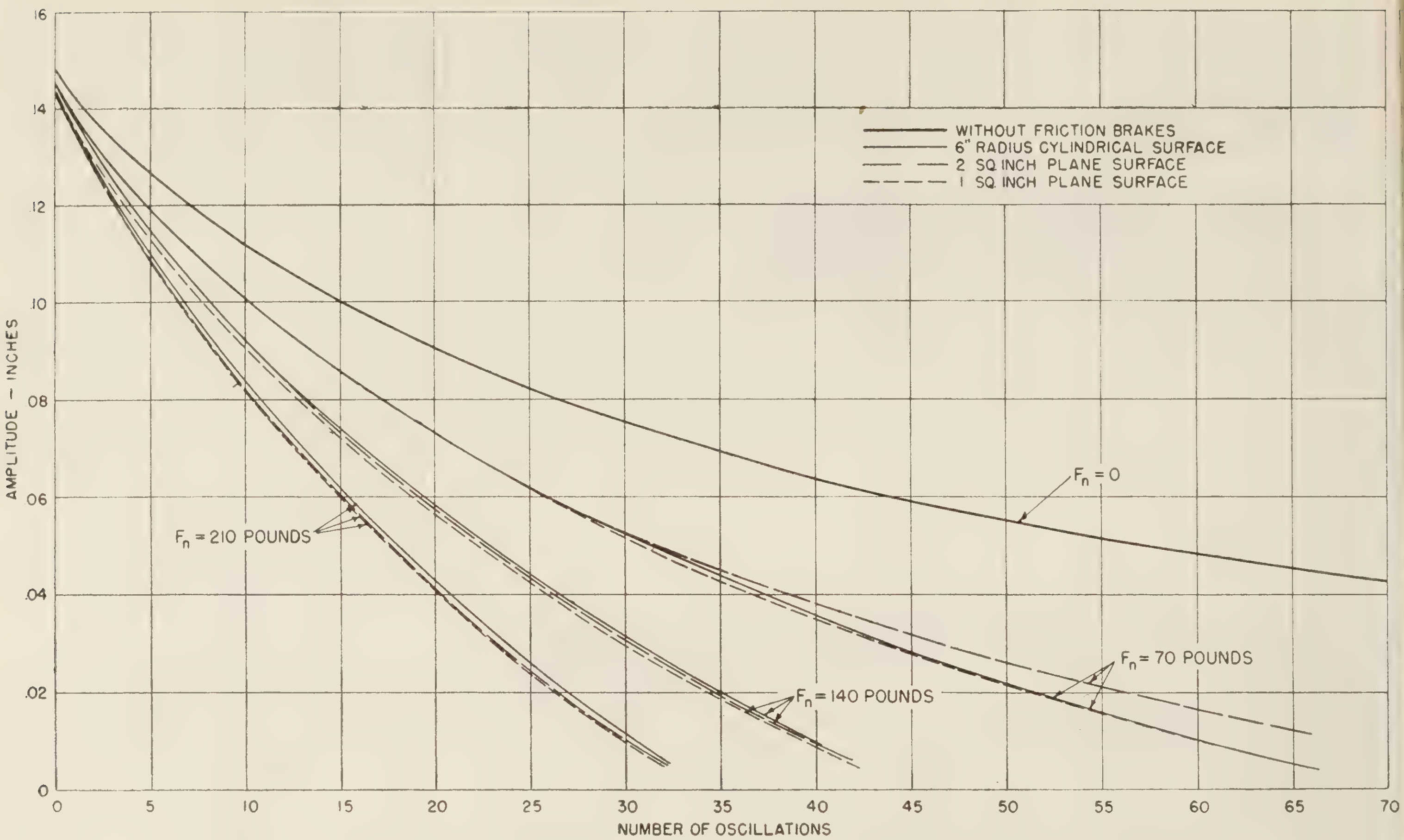

Figure 23.—Effect of various degrees of dry friction on amplitude decay: steel against bronze.

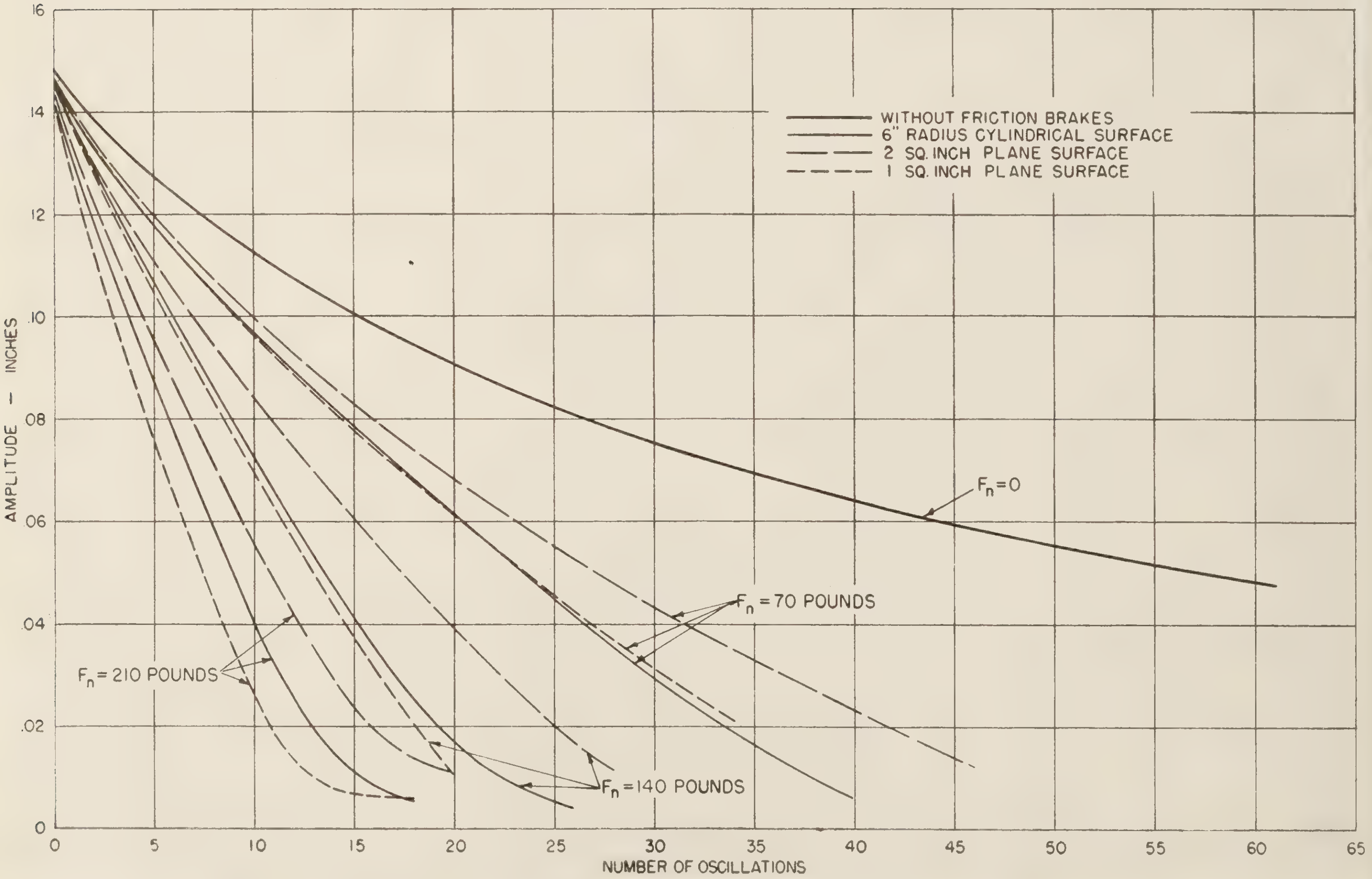

Figure 24.—Effect of various degrees of dry friction on amplitude decay: steel against steel.

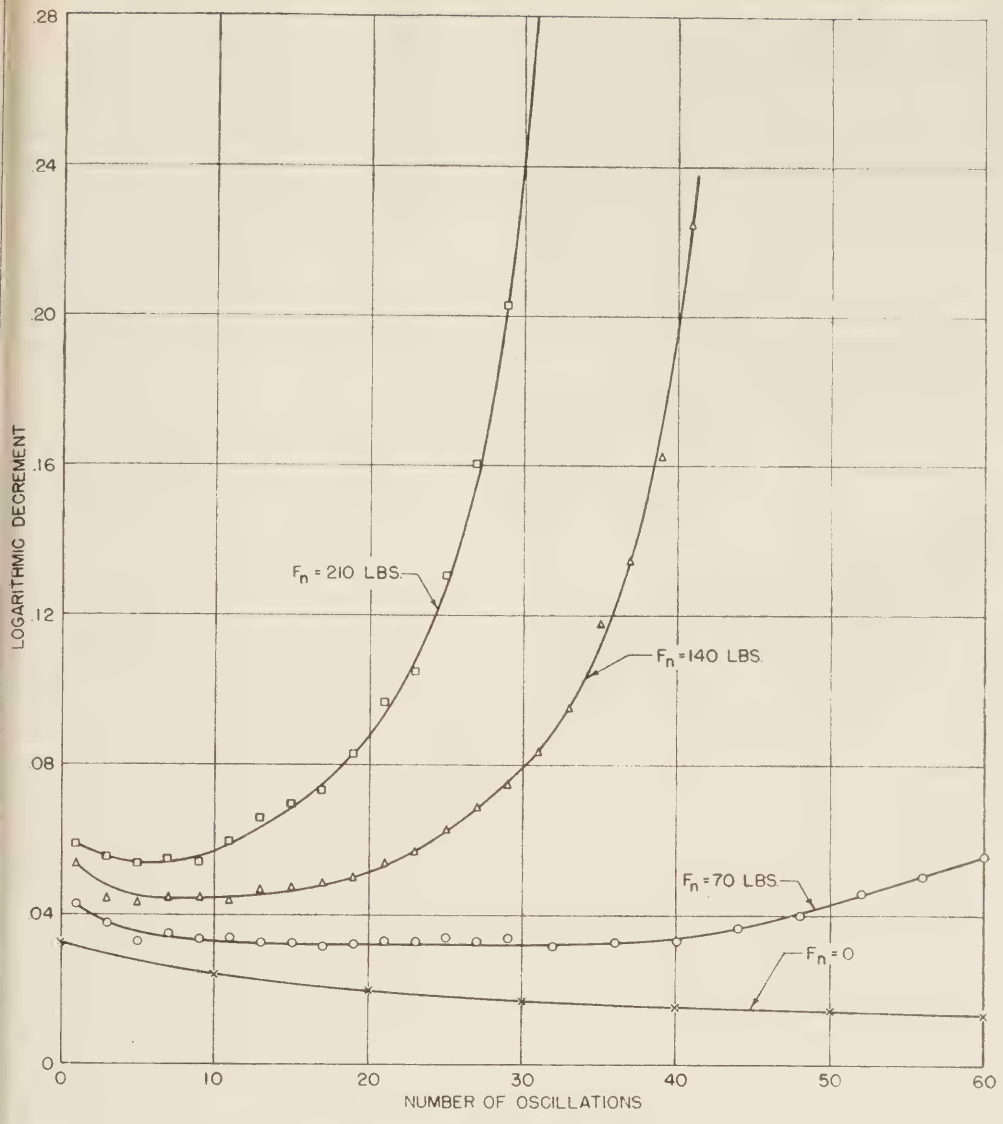

Figure 25.—Effect of various degrees of dry friction on logarithmic decrement values (36-foot, 10-inch truss loaded with 26 weights, each of 34.5 pounds, and bolted with NAS screws at 45 inch-pounds tightening torque; brakes steel against bronze, 2-square-inch plane areas).

deck, supports, and ballast weighed 497.7 pounds, making the total weight of the specimen 1,062.6 pounds as compared with 1,059.6 pounds before the deck was added.

Figure 1 (p. 203) shows the general appearance of the truss with the deck sections in place. In the foreground may be seen the electromagnetic pickup device used for recording oscillation amplitudes in this part of the program. In figure 26 are shown the details of the end connection of one deck section, the sliding bearing at the end of the adjacent section, and the manner in which the ballast weight was applied to the plates over the support points so that there would be no tendency for a secondary period of vibration to develop in the deck sections as the truss oscillated. The bronze tipped legs supporting the deck sections rested in shallow flat-bottomed grooves machined in the plates that were bolted to the truss. These also are shown in figure 26.

The 34-inch section in the center of the span was equipped with friction shoes at both ends rather than being fastened to the truss at one end as were the other sections.

Joint openings of ⅛ inch between sections were provided to insure freedom for longitudinal movement.

Air damping studied

It was recognized from the beginning that in all of the tests a certain amount of air damping was present. However, there was evidence that it contributed only in a small degree to the overall damping for which the logarithmic decrement was being determined.

With the addition of a relatively large horizontal area such as was represented by the plates of the simulated deck, there was reason to suspect that the air damping might become a significant component of the overall damping and some experiments were made to determine how important this influence might be.

A series of plates of ¼-inch plywood were attached to the truss as a replacement for the steel plates of the deck system. Each plywood plate was attached to the truss at the midlength of the plate and the plates were separated slightly so that no stiffening effect was introduced. The total area of plywood plates was the same as that of the steel deck. The total weight of the plywood was 16.75 pounds. A wooden strip was used at the center of each section to support it and to raise it clear of the steel of the truss.

There was noticeable fanning of the air when the truss oscillated, particularly where the amplitudes were large. By generating chemical smoke underneath the truss, the puffs of air expelled at the edges of the plates were made quite apparent.

Amplitude decay curves for the truss with and without the plywood plates attached are compared in figure 27 with a similar relation obtained from tests of the truss with the steel deck sections in place. It is apparent that the additional air resistance created by the application of the plywood plates and the consequent addition of approximately 24 square feet to the frontal area did increase the overall damping to a degree that could be measured, although the effect was relatively small. This tends to support the assumption that, in the case of the truss without a deck, air resistance was not an important contributing component to the damping.

Damping effect of deck

With the steel deck sections added and Coulomb friction active at the sliding deck support bearings, the increase in damping was relatively large (fig. 27), being quite similar to the effect observed with the brakes acting at the ends of the truss, the magnitude corresponding approximately to that observed with a braking force $F_n = 70$ pounds.

The variation of logarithmic decrement value with dynamic fiber stress for three deck conditions (no deck, plywood plates, and steel deck with deck support friction) is shown in figure 28. As in other graphs of the same type, the high stress values measured at the beginning of the test are at the right-hand side of the graph. The decrement values were computed from measured values of successive amplitudes in the manner previously described, and again the slight scatter of the points on the upper curve is attributed to the difficulty in determining decrement values precisely by this method where the damping rate is high.

In figure 29 are shown logarithmic decrement values plotted against the number of oscillations (or time) for the three deck conditions and for two live-load weight values used in the tests. This figure is similar to figure 25 except for the extent of the horizontal scale.

It is interesting to note that the increase in the value of the logarithmic decrement with decrease in vibration amplitude that was observed in the tests with the friction brake is present also in these data from the tests with the steel deck in place. The upward trend of the decrement values reaches a maximum after about 45 oscillations with the smaller live load and after about 65 oscillations with the larger live

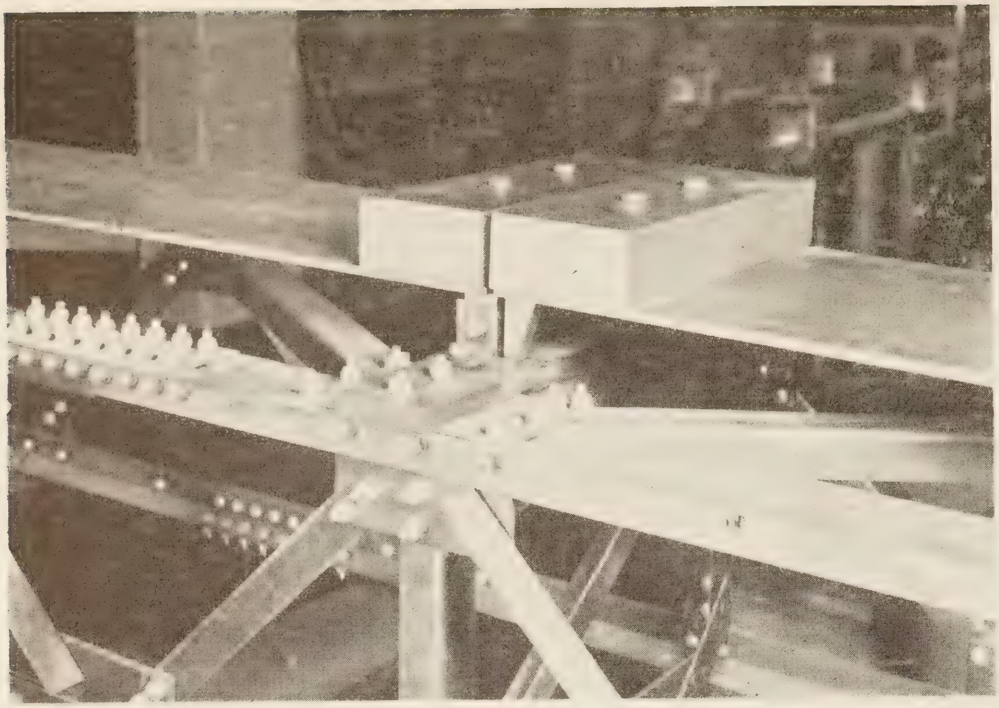

Figure 26.—Fixed and sliding bearings at ends of steel plates of simulated deck placed on top of the truss.

load, after which the decrement values decrease very rapidly. These peak values are significant. It will be noted from figure 27 that after 65 oscillations the amplitude of vibration is quite small (approximately 0.1 inch at midspan). When the amplitude decreases to this value, sliding of the friction bearings of the floor system ceases and from that point on damping is controlled by the conditions of static friction.

As was to be expected, the frequency of oscillation of the truss changed slightly after the steel deck sections were installed. Also, it was found that the change in frequency was not constant but tended to increase slightly as the amplitude became smaller. For example, from seven tests with the larger live load (26 weights of 34.5 pounds each), the average frequency during the first 150 oscillations was found to be 2.5913 vibrations per second while the average for the remaining portion of the records was 2.6275 vibrations per second. Using these values to evaluate the effect of the deck on truss stiffness, it was found that the apparent moment of inertia ranged from 20.99 inches^4 (average for the first 150 oscillations) to 21.58 inches^4 (average for the remaining oscillations). The value of the moment of inertia of the truss without the deck, as given in table 1, is 20.7 inches^4. From these comparisons it can be concluded that the effect of the steel deck and the forces developed at the sliding shoes of the deck sections was to add slightly but measurably to the stiffness of the truss.

Sliding End Bearings

The third method used in these studies for developing external Coulomb friction was the substitution of sliding bearings for wheel bearings at one end of the specimen. This method was applied both to the bolted truss and to the **H**-section. To make the desired comparisons, sliding shoes were designed that would mount on the same cross shaft that normally carried the ball-bearing wheels. The shoe body was of steel and served as a housing for a self-alining ball bearing that slipped over the cross shaft. The lower edge of this steel body was faced with a bronze shoe plate splined to it. This shoe plate, 3.0 inches long and 0.6 inch wide, served as the moving friction surface. It rested on a finely

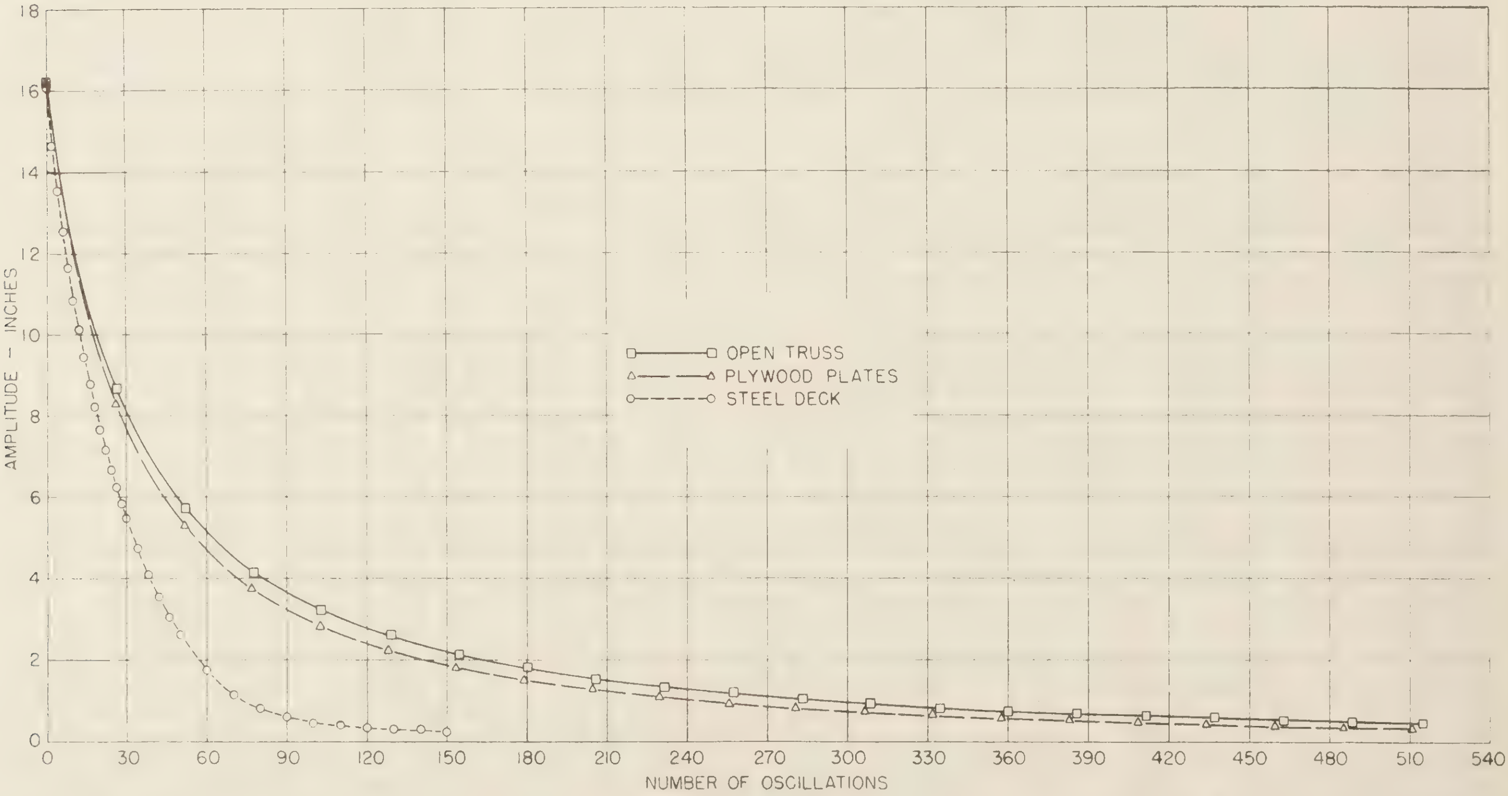

Figure 27.—Effect of variations in deck condition on amplitude decay (36-foot, 10-inch truss loaded with 26 weights, each of 34.5 pounds, and bolted with NAS screws at 45 inch-pounds tightening torque).

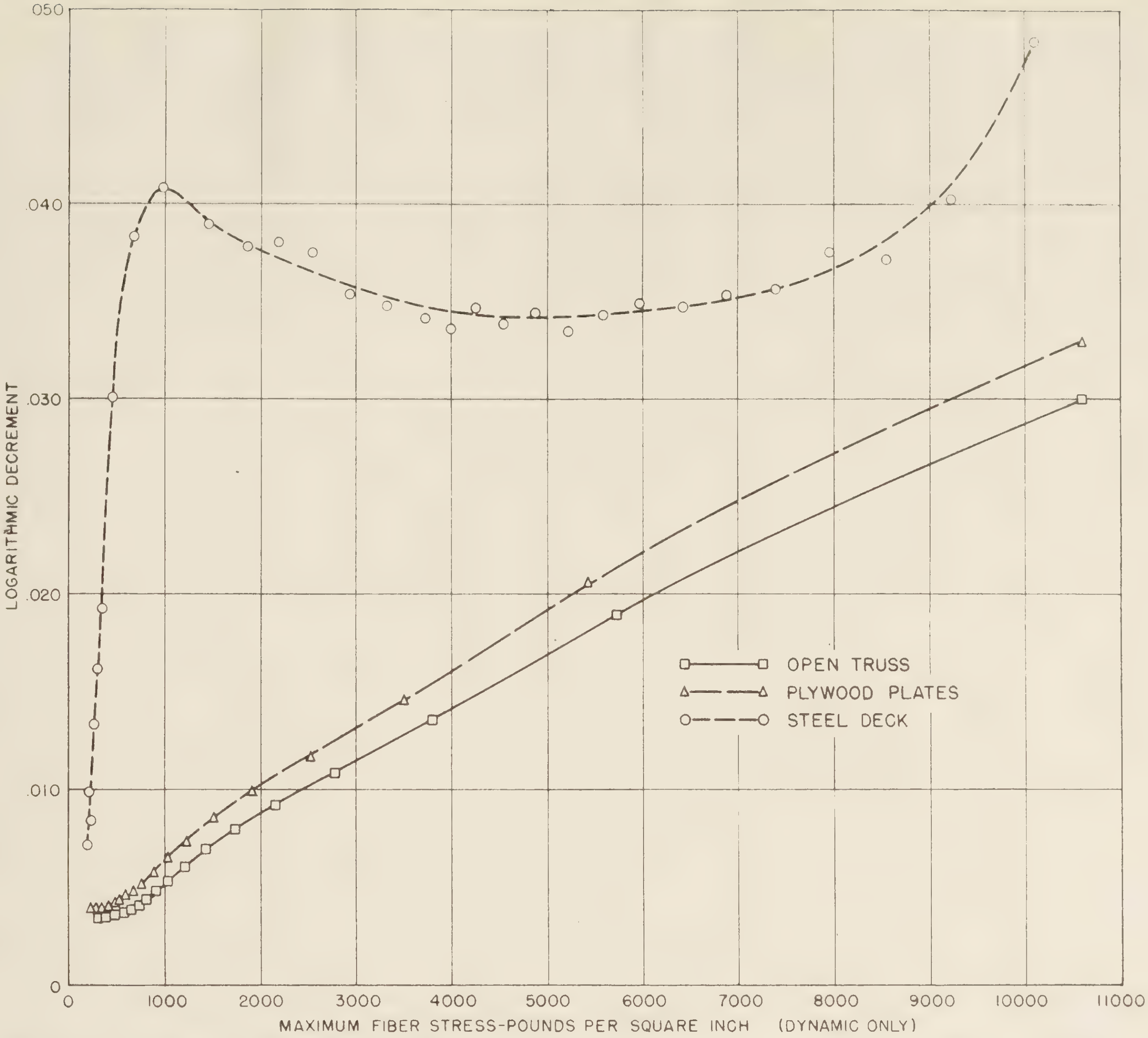

Figure 28.—Variation of logarithmic decrement with fiber stress for three different deck conditions (36-foot, 10-inch truss loaded with 26 weights, each of 34.5 pounds, and bolted with NAS screws at 45 inch-pounds tightening torque).

finished steel plate bolted to the top of the concrete support pedestal. Figure 30 shows a pair of these shoes mounted on the **H**-section. The self-alining bearings made it possible for the sliding plates to remain in flat bearing with the mating surfaces at all times, regardless of any angular motion that might develop in the cross shaft.

A number of tests were made with both types of end bearing with both the truss and **H**-section. For these tests both the 19.5-pound and the 34.5-pound live-load weights were used. Amplitude decay data were obtained and from these logarithmic decrement values were calculated. The data from tests with the 34.5-pound live-load weights are compared with data for other test conditions in figures 31 and 32. In figure 32 the two lower curves show how logarithmic decrement values decreased where the specimens were mounted on ball-bearing wheels and the end bearing friction is small. In contrast, where end bearings of the sliding type are used (without lubrication) and a strong damping force is developed by dry friction, the damping increases with amplitude decrease, rising to a maximum at the 25th oscillation in the case of the truss and at the 30th oscillation in the case of the **H**-beam, after which it decreased very rapidly to a value well below that which obtained at the time of the first oscillation. As in the case of the other tests with external Coulomb friction, these maxima occurred at midspan vibration amplitudes of the order of 0.1 inch at the point where sliding motion of the friction surfaces ceased.

It is of interest to compare the effect on damping of the friction forces developed by the mechanical brakes with those developed by the sliding end bearings. For this purpose the dash line was added to the other data in figure 32. The similarity of the effects of the external resistance derived from dry friction in the two cases is apparent.

Forces Developed at the Sliding Bearings

A study was made of the friction forces developed at the sliding contact of the bronze and steel plates used in most of the friction tests. Information on the character and magnitude of these forces was needed, particularly for the correlation of observed behavior with theory.[5]

To obtain this information an apparatus was designed that would reproduce as closely as possible the conditions present in the friction brake used at the end frame of the truss, and at the same time would provide means for measuring the horizontal forces required to produce sliding of the

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[5] See reference, footnote 1, p. 203.

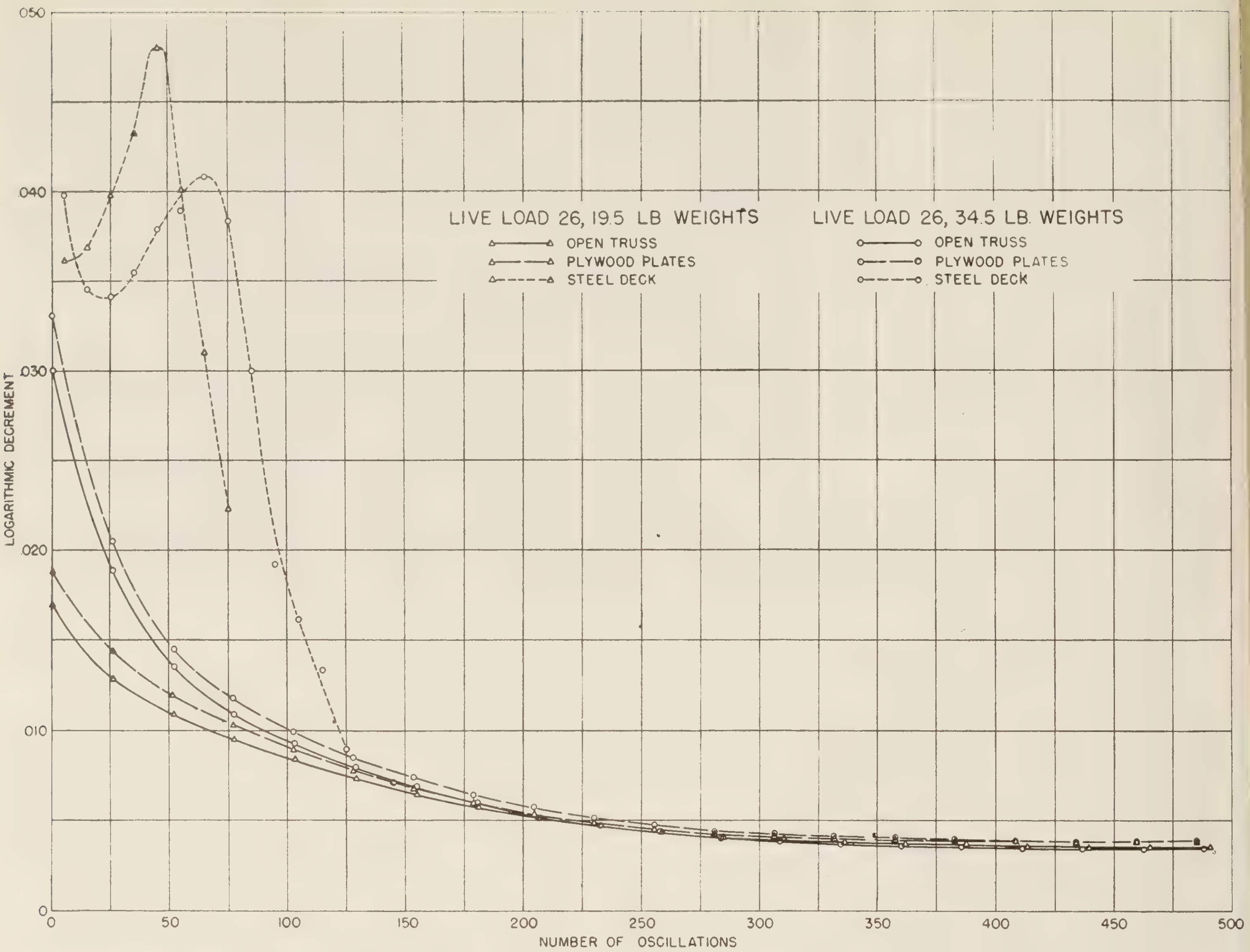

Figure 29.—Effect of variations in deck condition on logarithmic decrement values (36-foot, 10-inch truss bolted with NAS screws at 45 inch-pounds tightening torque).

one friction surface on the other. The apparatus is shown in figure 33. It consists of a motor-driven mechanism that produces a horizontal translatory motion closely approximating in stroke and frequency that of the friction plates in the brake on the truss. This motion is imparted to a small horizontal plate or carriage mounted on small ball-bearing wheels. Included in the linkage is a strain gage dynamometer component to measure continuously the horizontal resisting force created by the friction plates. On the carriage mentioned above the bronze friction plate was fastened, with the steel friction plate superimposed. Vertical pressure between the two was developed by the same lever and weights used in the friction brake on the truss. An oscillograph recorded the entire elastic strain cycle as the dynamometer responded to the resisting forces developed between the two friction plates in the reciprocating motion to which they were subjected.

With this apparatus it was possible also

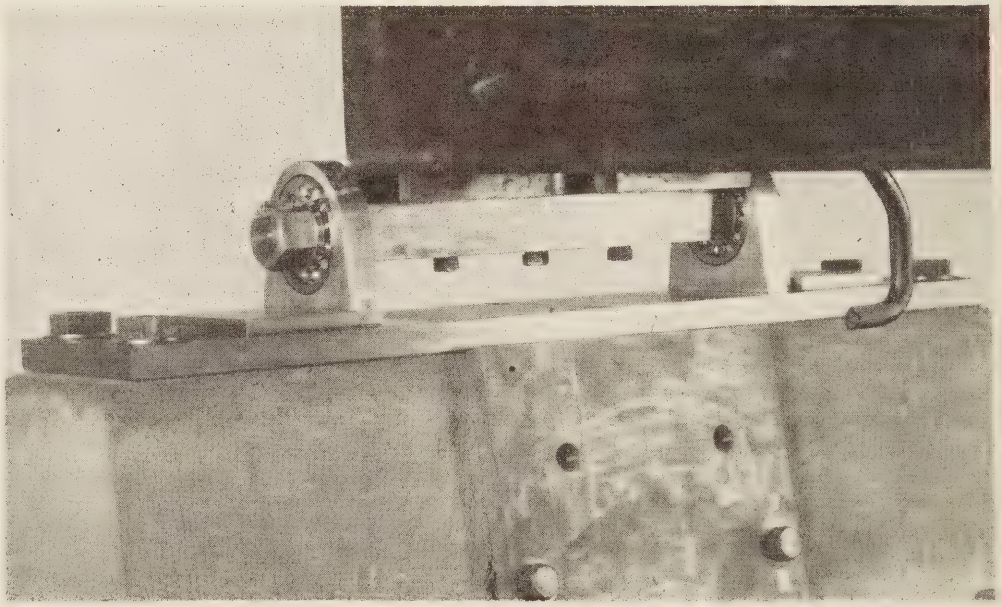

Figure 30.—Sliding end bearings substituted for wheel bearings, mounted on the H-section.

to determine the resistance to horizontal motion offered by the ball-bearing wheels used to support one end of the truss, **H**-section, and rectangular bar in most of the tests. A reproduction of an oscillographic record of tests with the bronze and steel plate combination in an unlubricated condition and with the ball-bearing wheels is shown in figure 34.

From a series of tests with this device it was found that:

1. The force required to cause the steel plate to slide over the bronze plate with the reciprocating motion that has been described varied with time essentially in the form of a square wave, as shown in the lower part of figure 34.
2. Once sliding began, the resistance to motion (or the coefficient of sliding friction) did not vary with the velocity of the motion.
3. The average coefficient of sliding friction for the 2-square-inch steel plate on the bronze plate in an unlubricated condition was found to be 0.131. That with the ball-bearing wheels was too small to measure accurately.

Tests with Riveted Truss

It appeared desirable before concluding the investigation to make some tests with the truss connections riveted, as a supplement to the tests of the authorized program, in order to afford comparisons between the damping obtained with riveted joints and that found with the several conditions of bolted connections.

The satisfactory riveting of the many connections in the trussed member presented a practical problem of some difficulty. A considerable amount of shop experimentation was necessary before a technique was developed that produced tight rivets, with well formed heads, without distorting the thin metal of the truss members. The rivets used were of soft iron, had an average clearance in the reamed holes of about 0.001 inch before driving, and were driven cold with a small air hammer operating at about 40 p.s.i. pressure. Special tools were made to form the round heads and the length required for the various connections was found by trial. The appearance of typical connections is shown in figure 35 and the overall appearance of the trussed member on its supports is shown in figure 36. The truss was given a spray coat of flat white paint after riveting, with the thought that this might aid in detecting movement in the joints during subsequent testing. The movements proved to be too small to be detected visually, however.

The structural testing activities of the Bureau of Public Roads were moved to a new building in Fairfax County, Va., in 1951. Moving of the testing activities to the new location involved the casting of one new end pedestal, the dismantling and re-setting of the end bearings, and other operations that conceivably might cause changes in the conditions of the tests. Since it was desired to make comparisons between data obtained with the riveted truss at the new location and data obtained with the bolted truss at the old location, it was considered desirable to repeat certain tests made with the **H**-section in the early part of the program, to establish the magnitude of any effects that might have developed as a result of moving the test set-up.

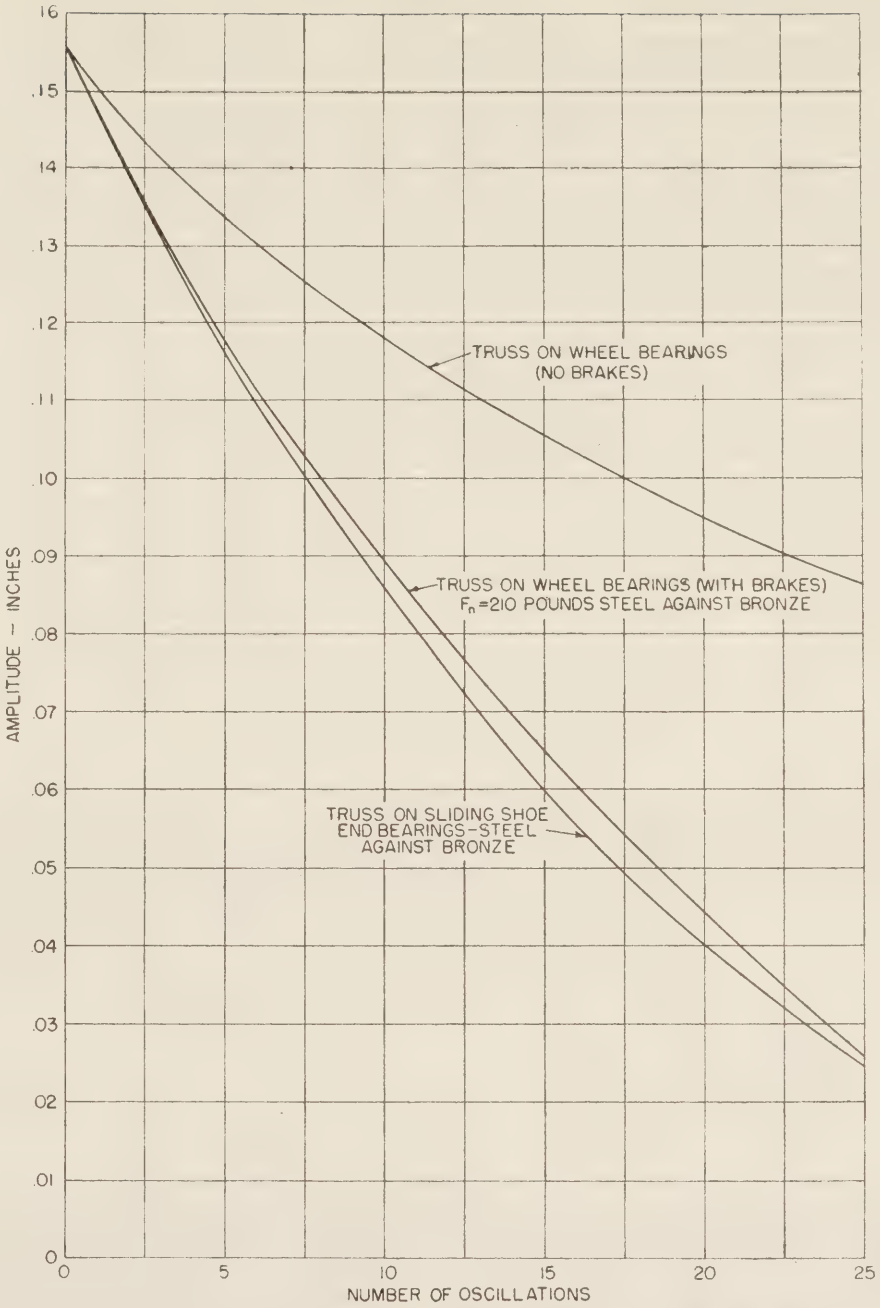

Figure 31.—Comparative effect of brake friction and sliding end bearing friction on amplitude decay.

For the comparison, tests were made with both the 19.5-pound and the 34.5-pound live-load weights. All details of the original test procedure were repeated as nearly as was possible. Figure 37 shows amplitude decay curves for tests with the 34.5-pound live-load weights at each location, with equations derived to fit each set of experimental data. It will be observed that although the initial amplitudes and those after 500 oscillations are identical there is a slight but definite difference between the shapes of the envelope curves between these points. The equations reflect this difference. Whether the slightly reduced rate of decay at intermediate amplitudes shown in the data obtained in the recent tests is due to reduced friction at the end bearings is not known but it seems probable. These bearings were cleaned and re-alined when the new installation was made. It is significant that, whatever the cause, exactly the same effect was found in the tests with the 19.5-pound live-load weights.

The self-damping of the **H**-section has proved to be relatively small in all of the tests and it is to be expected that the slight

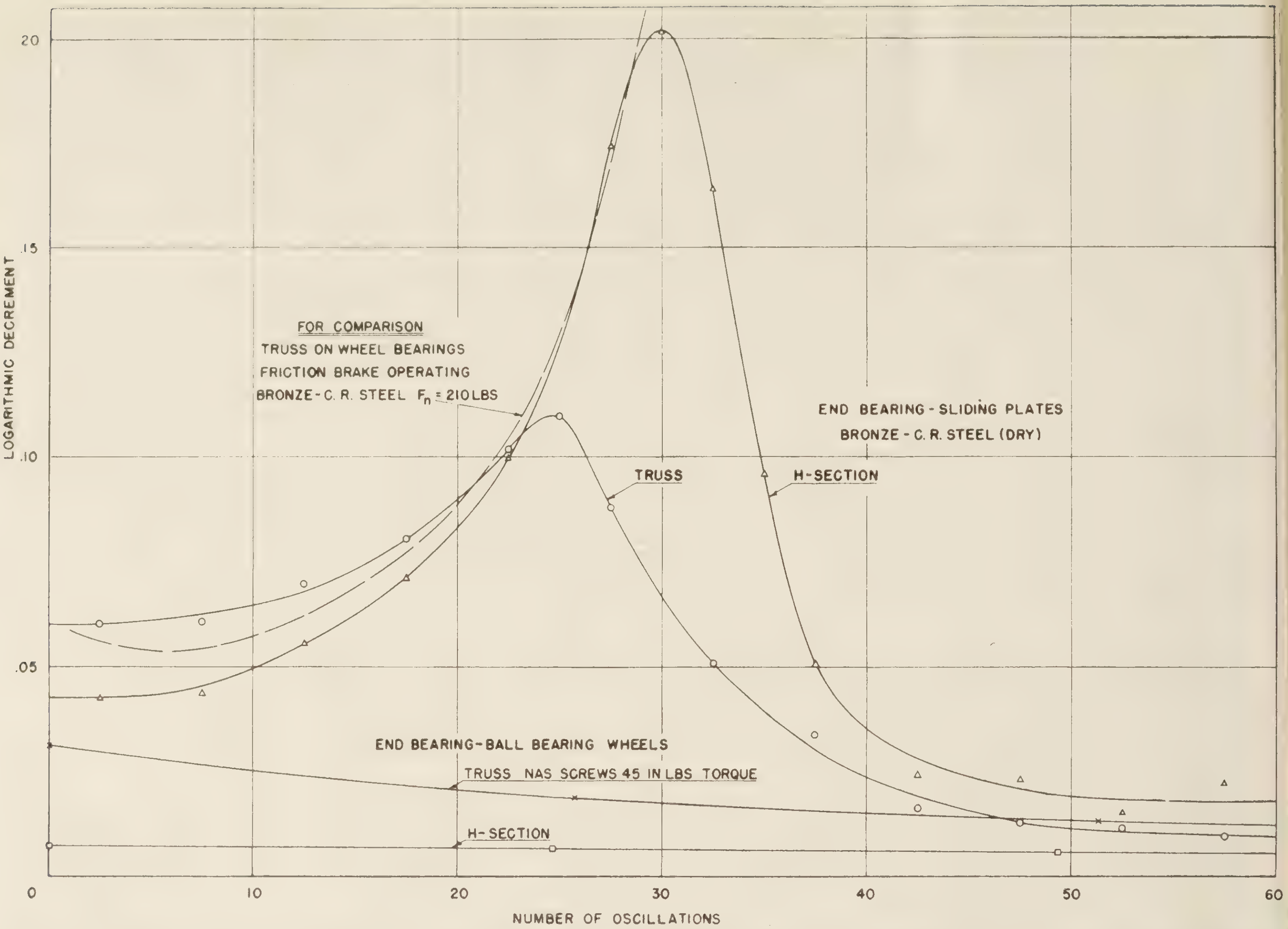

Figure 32.—Effect of type of end bearing on damping of truss and H-section, excited with 26 weights, each of 34.5 pounds. (Damping of truss with friction brake included for comparison.)

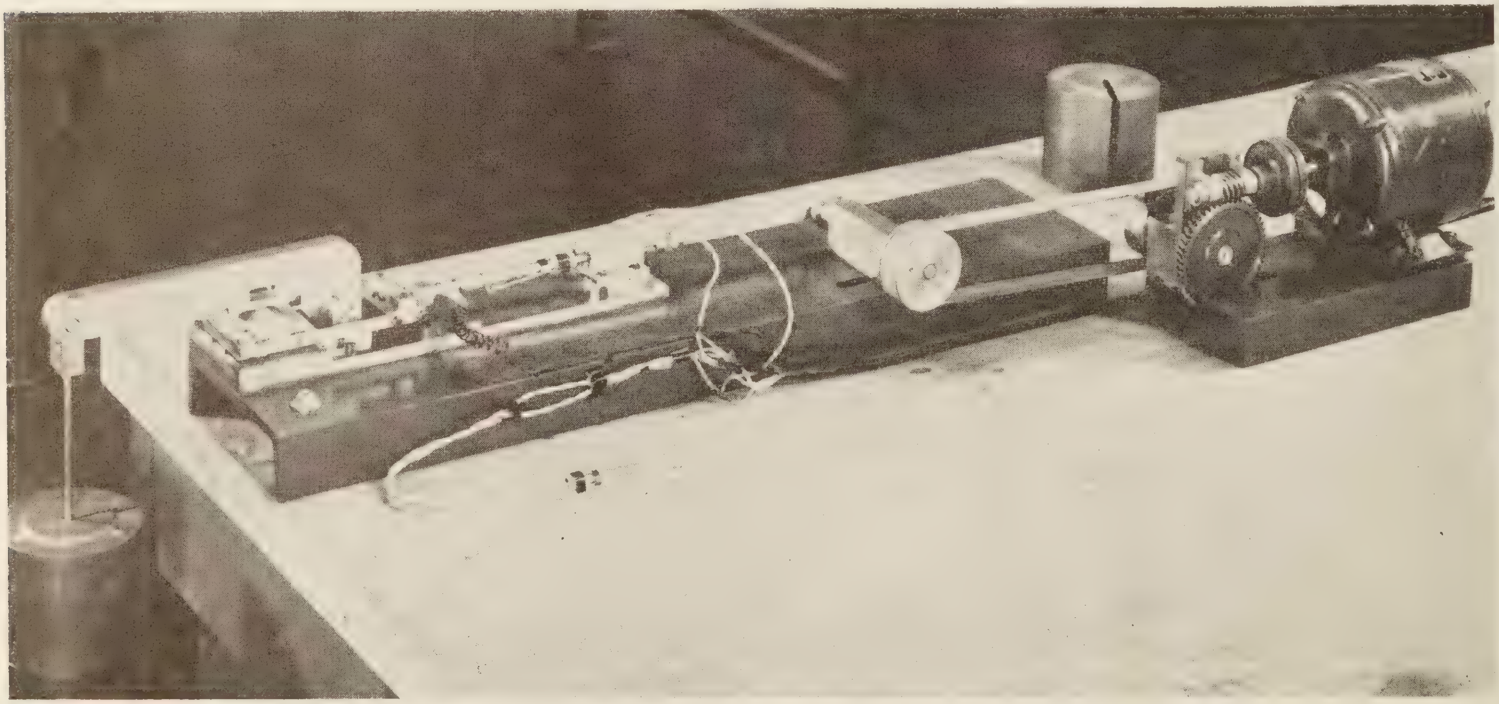

Figure 33.—Apparatus used to evaluate coefficient of friction of surfaces used in brake tests.

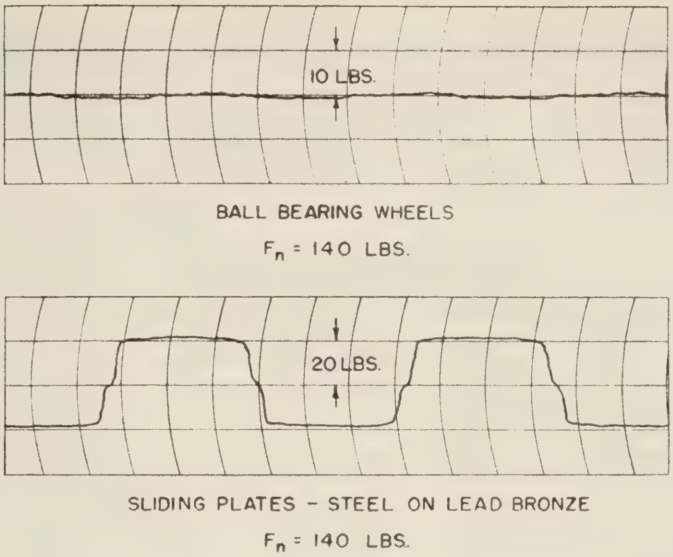

Figure 34.—Relative frictional resistance of ball-bearing wheels and sliding plate during cycles of horizontal motion.

difference in the shape of the two amplitude decay curves of figure 37 would be reflected in a noticeable difference in the logarithmic decrement values at the intermediate and higher amplitudes. That such a difference exists is shown by the decrement-stress relations for the two series of tests as shown in figure 38. It is well to keep in mind the generally low order of magnitude of the decrement values for the **H**-section. Differences such as are shown in figure 38 are of relatively small significance when comparing data from tests with the truss in either the bolted or the riveted condition.

Comparison of test data

Following the tests with the **H**-section, the riveted truss was set up on the 36-foot, 10-inch span and tested with both the 19.5-pound and the 34.5-pound live-load weights, using exactly the same testing procedure that had been employed in the earlier tests with the bolted truss. Since the tests with the 19.5-pound weights developed no information that was not shown by the tests with the 34.5-pound weights, only the data from the latter will be included in this report.

It was found in the early tests with the truss bolted with machine screws at 35 inch-pounds of torque that a permanent sag developed in the member as a result of slight movements in the many joints. For the bolted truss the magnitude of this sag at midspan was 1.09 inches. Measurements made during the testing of the riveted truss showed the sag at midspan after testing to be 0.04 inch or about 4 percent that of the bolted truss. Moment of inertia values computed from the measured load-deflection characteristics of the truss were 20.7 inches^4 when bolted and 20.6 inches^4 when riveted. These data indicate less movement in the joints of the riveted truss but little or no change in its stiffness.

Logarithmic decrement values computed from amplitude decay data for the riveted truss are shown in figure 39, plotted against dynamic stress values obtained by means of strain measurements. Similar curves for the truss bolted up with both the No. 10–24 machine screws and the NAS screws, as well as that from tests with the **H**-section, are shown in the same figure for comparison.

It is indicated by the comparisons available in this figure that while reduced movements in the joints of the riveted truss did lower appreciably the self-damping of the member below that of the bolted truss, particularly at higher amplitudes (and stresses), it still showed much greater self-damping at all amplitudes than was found for the comparable solid member (**H**-section).

A test of a riveted chord splice in tension failed by rupture of both of the splice plates in the grip. No failure occurred in the riveted splice although the computed unit stress in the chord angles was about 68,100 p.s.i. It will be recalled that the tension test of a chord splice drawn up with the NAS screws at 15 inch-pounds torque developed failure by rupture of the chord angles through the first bolt hole at a computed stress in the angles of about 76,600 p.s.i. Data from the test of the riveted splice are included in table 3.

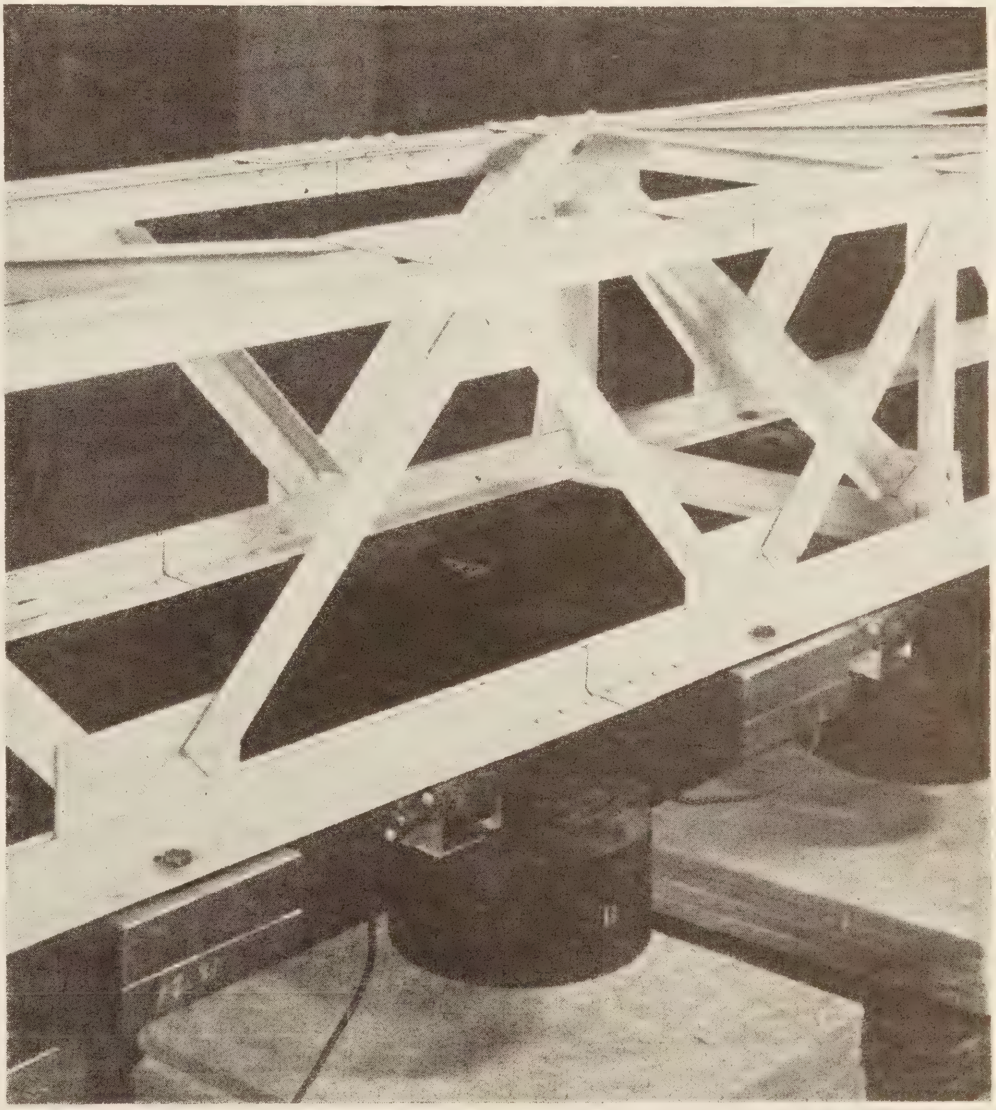

Figure 35.—Appearance of riveted connections after applying spray coat of flat white paint.

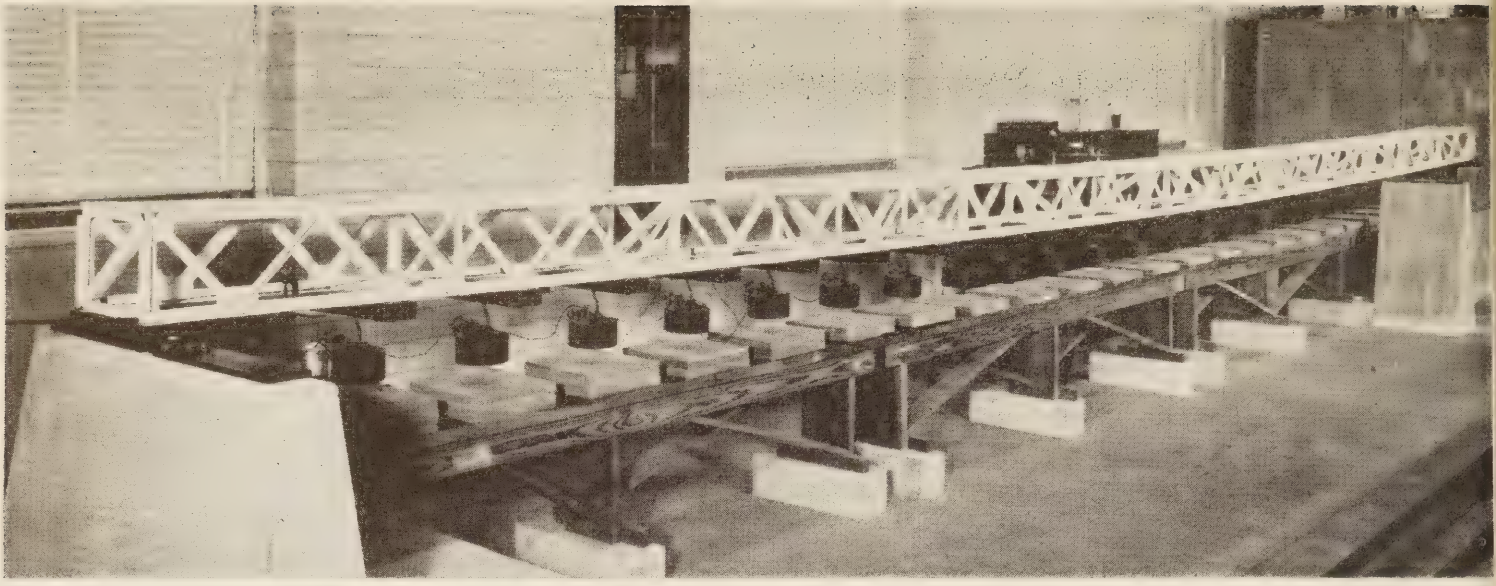

Figure 36.—General appearance of riveted truss at new test site.

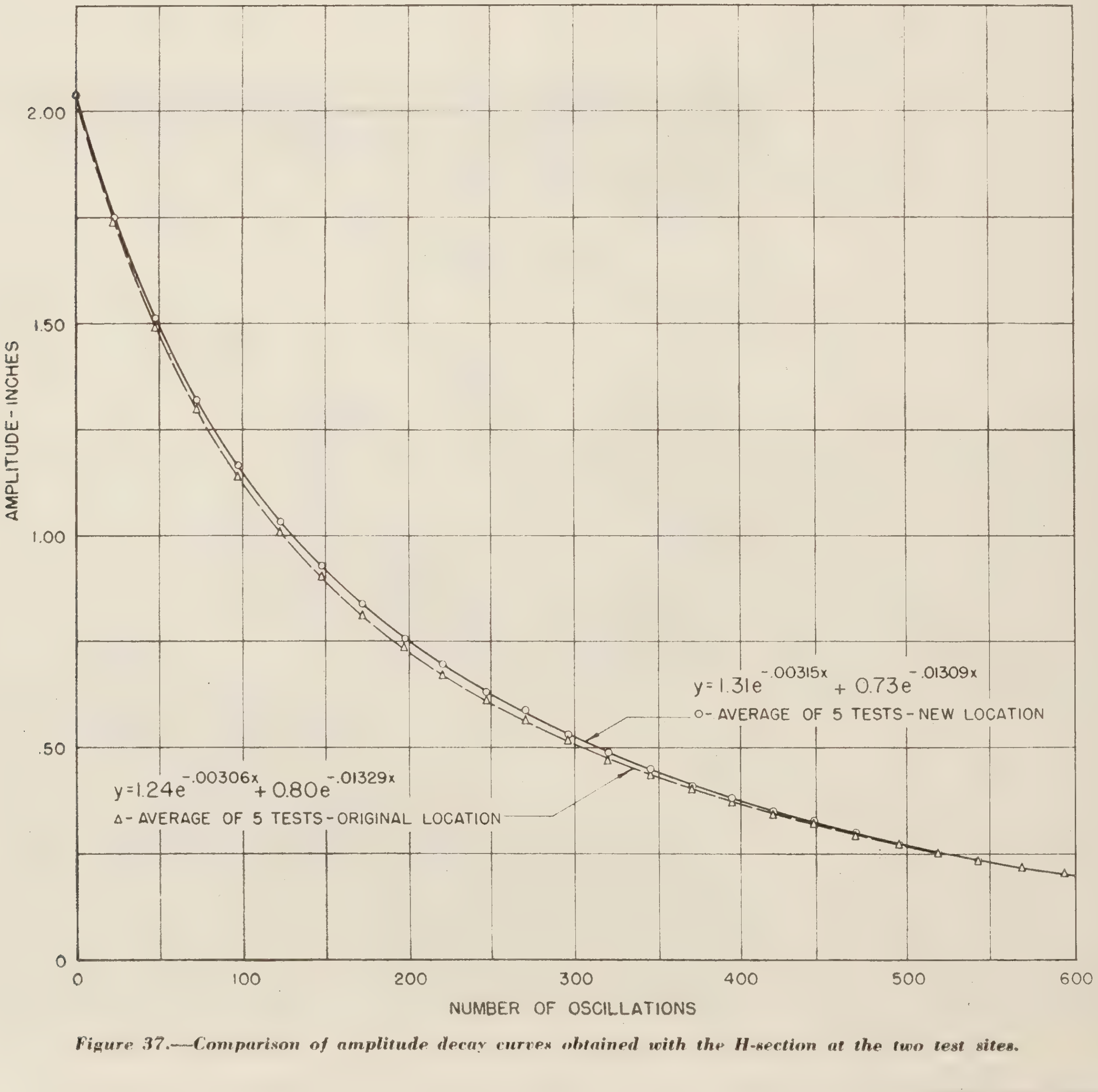

Figure 37.—Comparison of amplitude decay curves obtained with the H-section at the two test sites.

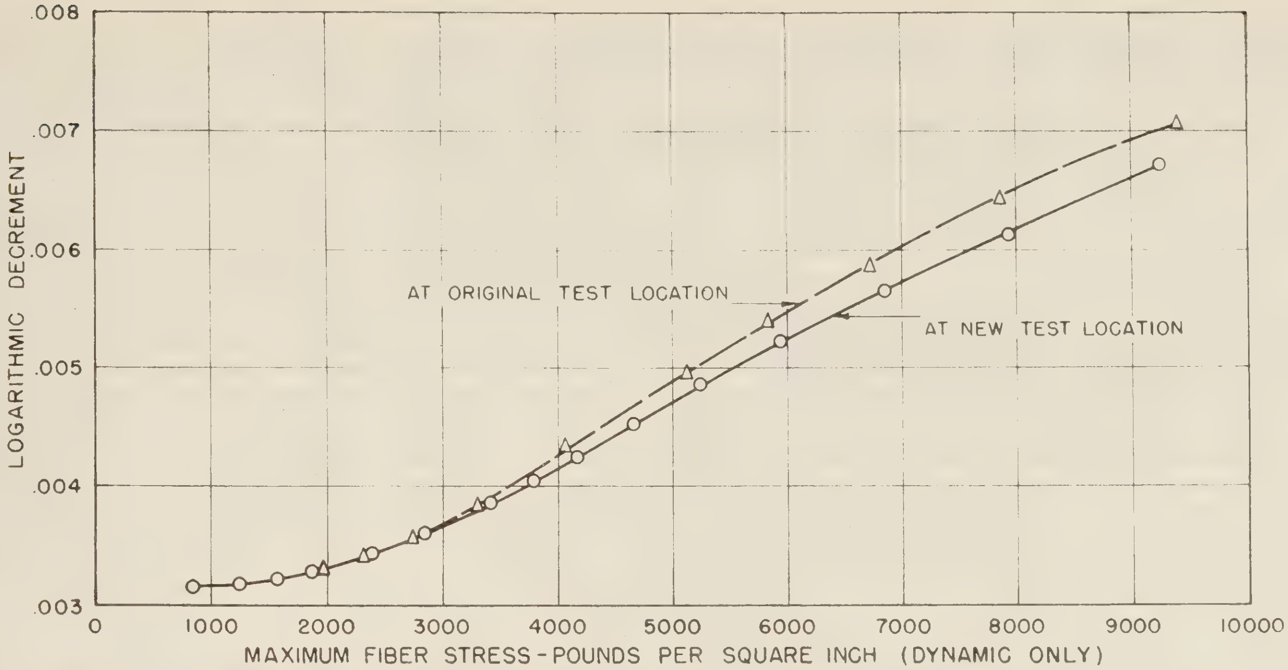

Figure 38.—Comparative logarithmic decrement data obtained with the H-section at the two test sites.

Comparative Measurements of Damping

It was discovered at the time of the first tests of the original program that the vertical oscillation of the test specimens was responsive to very small amounts of friction in the recording apparatus at midspan, so care was taken to reduce the friction of the stylus in the drum recording equipment to a minimum. The use of a method that yielded direct recordings of amplitude at midspan had considerable appeal since there could be no doubt of the extent of the motion that it was desired to measure. However, it was realized that some stylus friction was always present and the effect of this could not be readily evaluated.

Later, when equipment became available that permitted measurements of oscillation amplitude without physical contact with the specimen, it was felt that this might be a better method for obtaining amplitude decay data. As stated earlier, the magnetic reluctance pickup, having been designed for another purpose, had an effective range of motion that was too small for measurements at midspan so it was necessary to install it near one reaction and to establish by test the proportionality of vertical amplitudes there with those at midspan. This was done by simultaneous measurements at midspan with the smoked paper on the drum and measurements near the rocker reaction with the magnetic cell. A good general proportionality was found to exist. Because of the amplification required for recordings with the magnetic cell, the element of instrumental performance was present in these data. The installation of this unit at the new test site is shown in figure 40.

The question of determining damping characteristics through the analysis of continuous recordings of strain was discussed early in the program. At that time suitable equipment was not available and experiments made with the equipment at hand, while encouraging, showed the need for better instrumentation if the subject were to be investigated.

Such equipment, acquired for other purposes, was available at the time of the tests with the riveted truss and for this reason some comparative tests were made, both with the **H**-section and with the riveted truss. In these tests simultaneous measurements were made of midspan deflection with smoked drum recording, midspan strain with amplification and oscillograph recording, and of deflection amplitudes at a point about 14 inches from one end reaction using a magnetic reluctance pickup and oscillograph recording. From each of these records amplitude decay curves were obtained and logarithmic decrement values computed. The computed logarithmic decrement values plotted against a number-of-oscillation (or time) scale are shown for both specimens and for the three types of recorded data in figure 41. Considering the variables that are involved in the recording and reducing of the data obtained in this study, it is considered that a rather good correlation was obtained. Curiously, the lowest decrement values were consistently those derived from data obtained with the direct recording by means of the stylus on the smoked drum. This suggests the possibility that characteristics of the electrical amplification circuits employed in the other two recording systems may have been responsible for such dispersion as is shown.

Some Comparisons of Experimental Data with Theory

In the paper published previously[6] there was a discussion of the motions which occurred at the friction surfaces where the self-damping of the truss was augmented by dry friction externally applied. This discussion was a part of the theoretical development preliminary to obtaining comparisons between theoretical and observed relations of vibration amplitude versus damping capacity as measured by values of logarithmic decrement. Subsequent work done, as one of the supplemental investigations previously mentioned, yielded information of value regarding this relation.[7]

Measurements were made of the translatory and rotational movements at the two ends of the **H**-section as caused by the release of the 26 weights of 34.5 pounds each, symmetrically arranged at uniform spacing. Under the conditions of these tests the tendency for translatory movement at the end supports is the result of two separate deformations, both of which vary as the beam vibrates. In the first place, the deflection of a beam that is simply supported is accompanied by a shortening of its upper fibers under compression and a lengthening of its lower fibers under tension. This is reflected in a rotational motion of the transverse sections immediately over the supports. In the present case the beam had considerable depth and the supports were below the neutral axis so that the rotation

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[6] See footnote 1, p. 203.

[7] Joseph H. Appleton, Assistant Structural Engineer, participated in the conduct of this portion of the program of supplementary tests. His assistance is gratefully acknowledged.

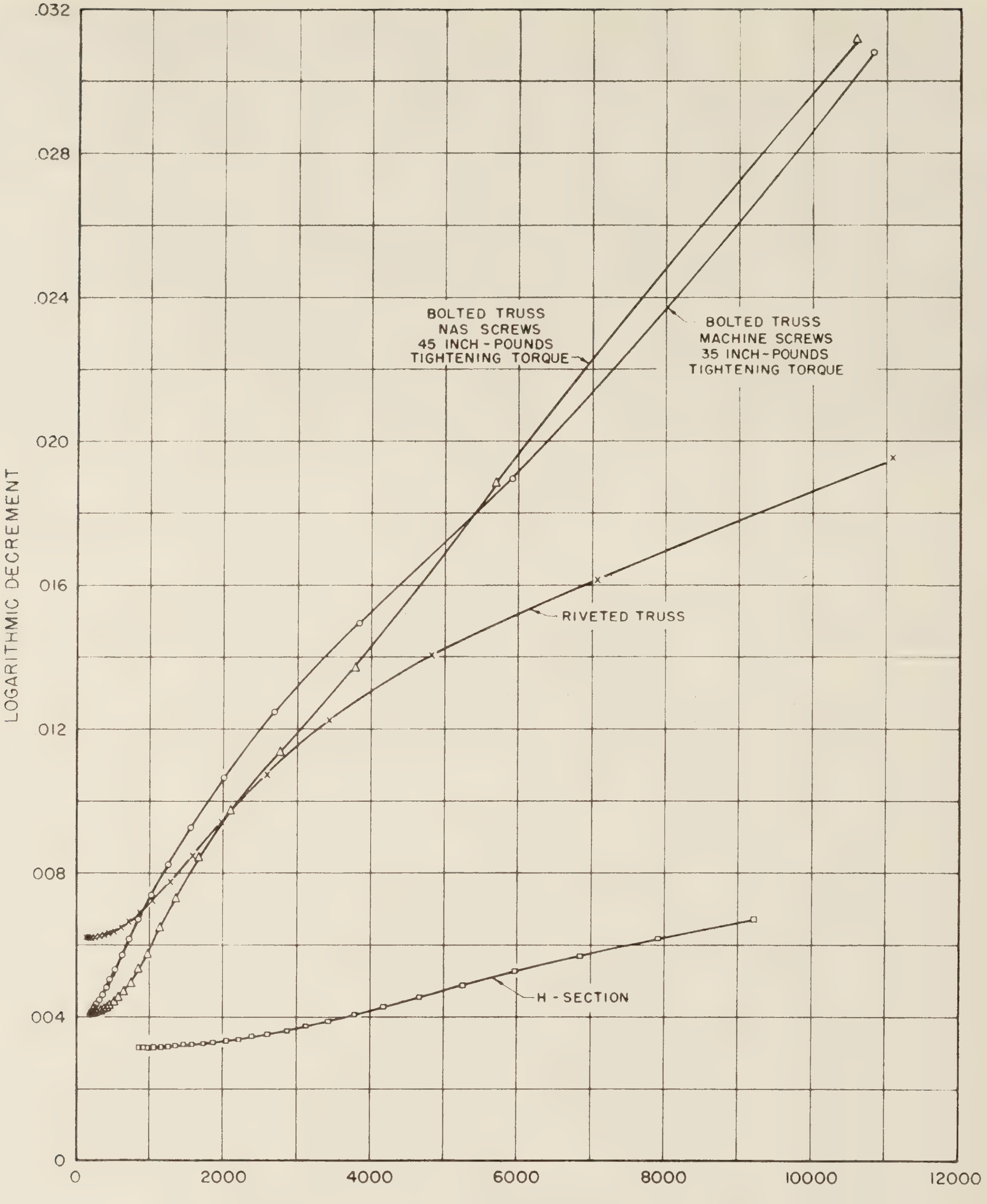

Figure 39.—Variation of logarithmic decrement with fiber stress for the truss and H-section (36-foot, 10-inch span with 26 weights, each of 34.5 pounds).

of the end sections developed a tendency for translatory motion at the end supports. Secondly, any change in the vertical deflection of the beam is accompanied by a change in the length of the chord between the two ends of the neutral axis. This also causes a tendency for translation at the end supports. Since at the rocker bearing there was restraint against longitudinal motion, all of the translatory motion at the supports had to take place at the wheel bearing end of the beam.

The theoretical movements, both rotational and translatory, were computed for the particular conditions of these tests and were compared with motions as measured with dial micrometers. The comparison is shown in table 5.

Having obtained a satisfactory correlation for the **H**-section, a study was made of the movements that would occur at the ends of the bolted truss, particularly at the position of the friction surfaces used in the tests with the friction brakes. Since the damping capacity depends directly upon the extent of the movement at these surfaces, it was desirable that a rather precise comparison be made. This led to a study of the effect of the sag of the truss, which has been mentioned before, on the motions that would occur if the sag were not present. The magnitudes of the movements were computed, both with and without a correction for sag, and from these logarithmic decrement values for various amplitudes were obtained, as shown in figure 42. The results are compared with a similar relation obtained from measured amplitude and logarithmic decrement values.

It is apparent that the sag present in the bolted truss was sufficient to have a measurable effect on the computed value of damping capacity. It is indicated also that when a correction for sag is introduced there is somewhat better agreement between the computed and observed data shown in this graph. Furthermore, this figure shows a good correlation between the observed behavior of the truss with strong Coulomb damping and that predicted by theory for the same conditions.

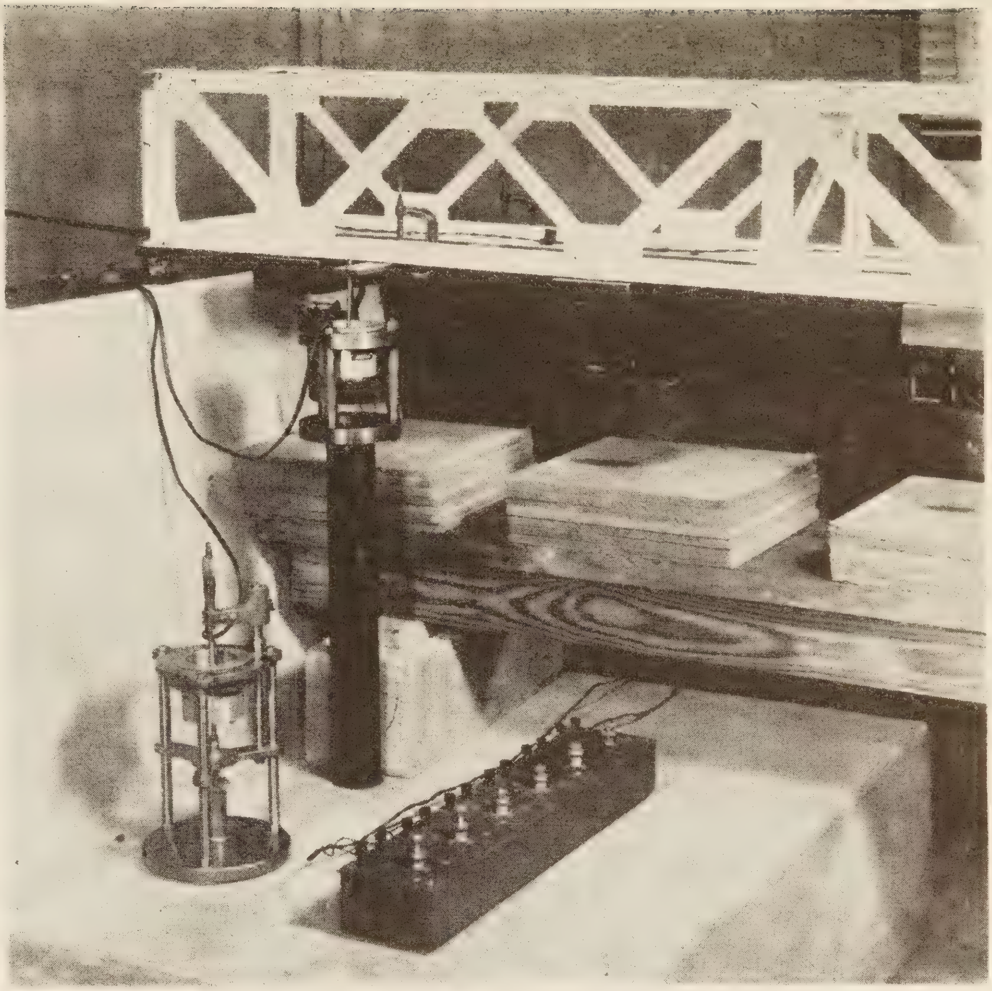

Figure 40.—Magnetic reluctance pickup device located about 14 inches from the rocker end bearing on the riveted truss.

Table 5.—Comparison of computed and observed rotational and translatory movements at end supports

	Computed movement	Observed movement
End rotation:		
Rocker end ....radians..	0.0149	0.0147
Wheel-bearing end ....do....	0.0149	0.0148
Translation, resultant outward, at axis of wheel bearing ....inch..	0.053	0.054
Translation, resultant inward, at end of neutral axis:		
Rocker end ....do....	0.061	0.061
Wheel-bearing end ....do....	0.008	0.007

(Figs. 41 and 42 are on the following pages.)

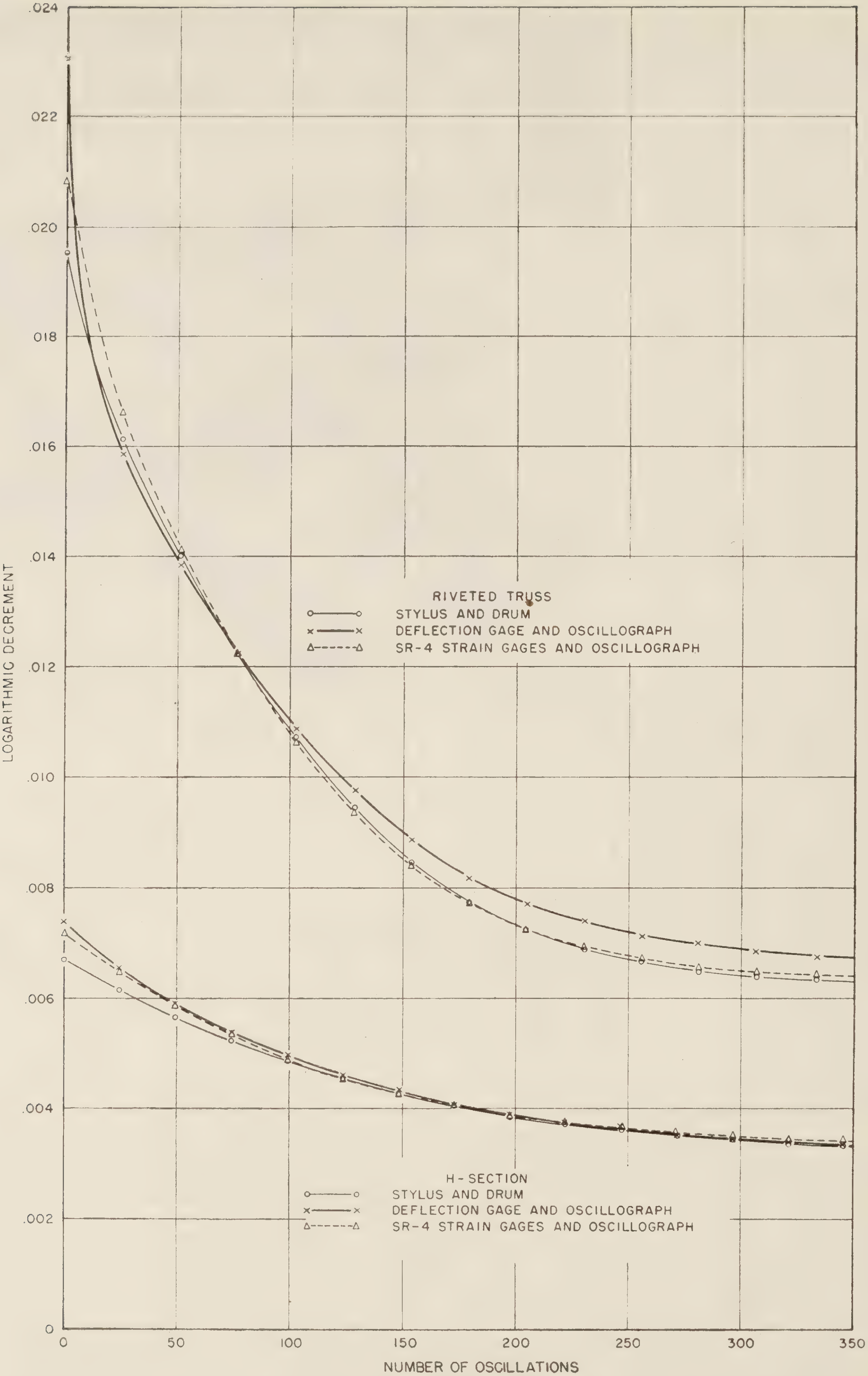

Figure 41.—Comparative logarithmic decrement values obtained with three methods of measurement.

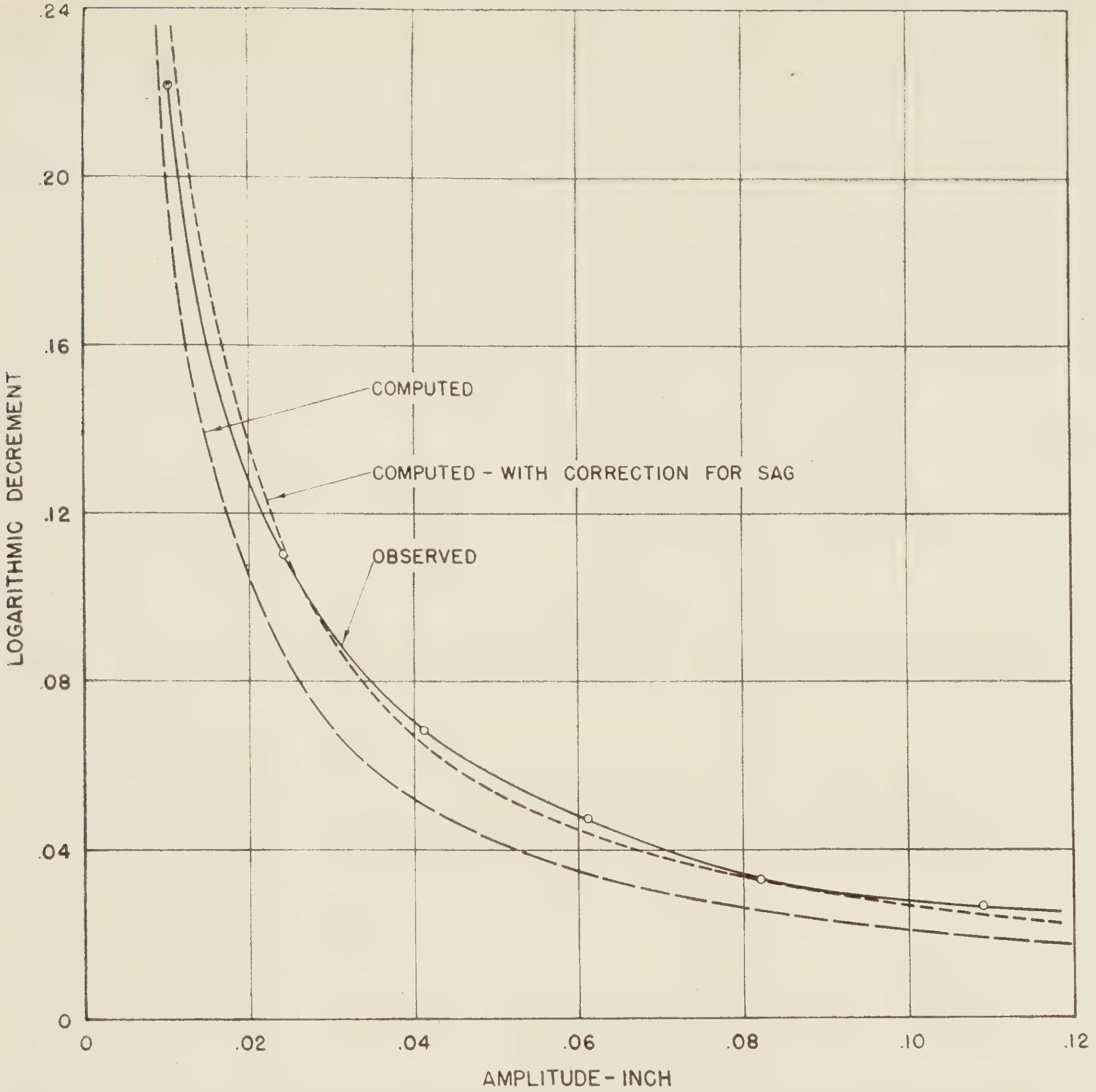

Figure 42.—Effect of correction for sag of bolted truss on the correlation between observed and computed logarithmic decrement-amplitude relations (friction brake tests, $F_D = 210$ *pounds).*

Results of Physical Tests of Road-Building Aggregate: a new bulletin

The Bureau of Public Roads has recently published a new bulletin, *Results of Physical Tests of Road-Building Aggregate,* which reports the results of tests performed by the Bureau's laboratory on more than 9,700 samples of ledge rock, crushed stone, gravel, and blast-furnace or smelter slag, and more than 3,400 samples of natural or manufactured fine aggregate, received from sources all over the United States. The bulletin is available from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., at $1.00 a copy.

Since the value of material for use as aggregate in road construction depends largely on the extent to which it will resist the destructive forces of traffic and weather, and on its ability to exist in harmony with other materials with which it is used, the test data reported in this bulletin serve, to some extent, as measures of these qualities. Thus, for engineers and contractors, the bulletin will be a useful guide on the availability and suitability for highway construction of local coarse and fine aggregates.

A brief introductory text in the bulletin reports the nature of the tests performed and describes the rocks and minerals mentioned in the tables. Results of tests on coarse and fine aggregates are tabulated separately, and are arranged in alphabetical order by State, county, and nearest town. The type of source is indicated as commercial, local, or prospective.

For both coarse and fine aggregates, the bulletin reports the name or lithological composition of the material, and results of tests of bulk gravity, absorption, and soundness. In addition, for coarse aggregate, test results of abrasive loss, crushing strength, hardness, toughness, and weight of compacted aggregate are reported; for fine aggregate, test results of grading, fineness modulus organic matter content, and mortar strength are shown. All tests were not performed on all samples, however.

The tests reported in *Results of Physical Tests of Road-Building Aggregate* cover the work of the Bureau of Public Roads in this field over the 56-year period from 1895 to January 1, 1951. The bulletin supersedes and supplements U. S. Department of Agriculture Miscellaneous Publication No. 76, *The Results of Physical Tests of Road-Building Rock,* published in 1930 and long out of print.

A list of the more important articles in PUBLIC ROADS may be obtained upon request addressed to Bureau of Public Roads, Washington 25, D. C.

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1941, 15 cents. 1948, 20 cents.
1942, 10 cents. 1949, 25 cents.
Public Roads Administration Annual Reports:
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Annual Reports of the Bureau of Public Roads:
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Act V.—Uniform Act Regulating Traffic on Highways. 20 cents. (revised 1952)

Model Traffic Ordinance. 20 cents. (revised 1952)

MAPS

State Transportation Map series (available for 39 States). Uniform sheets 26 by 36 inches, scale 1 inch equals 4 miles. Shows in colors Federal-aid and State highways with surface types, principal connecting roads, railroads, airports, waterways, National and State forests, parks, and other reservations. Prices and number of sheets for each State vary—see Superintendent of Documents price list 53.

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1947, 45 cents. 1951, 60 cents.
Highway Statistics, Summary to 1945. 40 cents.
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Manual on Uniform Traffic Control Devices for Streets and Highways (1948). 75 cents.
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Results of Physical Tests of Road-Building Aggregate (1953). $1.00.
Roadside Improvement, No. 191MP (1934). 10 cents.
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Taxation of Motor Vehicles in 1932. 35 cents.
Tire Wear and Tire Failures on Various Road Surfaces (1943). 10 cents.
Transition Curves for Highways (1940). $1.50.

Single copies of the following publications are available to highway engineers and administrators for official use, and may be obtained by those so qualified upon request addressed to the Bureau of Public Roads. They are not sold by the Superintendent of Documents.

Bibliography on Automobile Parking in the United States (1946).
Bibliography on Highway Lighting (1937).
Bibliography on Highway Safety (1938).
Bibliography on Land Acquisition for Public Roads (1947).
Bibliography on Roadside Control (1949).
Express Highways in the United States: a Bibliography (1945).
Indexes to PUBLIC ROADS, volumes 17–19 and 23.
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STATUS OF FEDERAL-AID HIGHWAY PROGRAM

AS OF AUGUST 31, 1953

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM											
		PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$5,550	$19,288	$9,895	305.6	$11,062	$5,511	204.2	$37,922	$19,468	474.8	$68,272	$34,874	984.6
Arizona	1,273	3,404	2,379	76.6	1,322	918	29.7	6,367	4,529	89.0	11,093	7,826	195.3
Arkansas	4,073	12,889	6,765	363.5	3,177	1,592	105.6	11,579	5,714	284.1	27,645	14,071	753.2
California	2,938	12,975	4,729	64.8	6,834	3,674	48.1	105,084	52,207	317.3	124,893	60,610	430.2
Colorado	2,442	6,431	3,642	150.7	3,633	2,052	63.8	16,796	9,086	170.0	26,860	14,780	384.5
Connecticut	6,959	1,902	1,003	3.6	475	235	.3	12,504	6,150	35.5	14,881	7,388	39.4
Delaware	2,810	605	305	.8	1,179	589	7.6	3,547	1,766	14.5	5,331	2,660	22.9
Florida	4,682	16,459	8,359	255.2	7,035	3,809	127.6	17,639	8,894	239.5	41,133	21,062	622.3
Georgia	7,462	17,137	8,800	440.2	8,483	4,018	152.0	33,997	16,259	487.5	59,617	29,077	1,079.7
Idaho	2,834	9,584	6,003	169.4	3,343	2,097	66.5	11,833	7,513	242.5	24,760	15,613	478.4
Illinois	9,006	30,775	16,570	144.0	19,704	10,534	117.4	70,029	36,210	594.7	120,508	63,314	856.1
Indiana	10,514	36,255	18,882	161.6	6,427	3,221	50.0	27,253	14,350	148.8	69,935	36,453	360.4
Iowa	2,779	14,778	8,105	368.5	6,651	4,138	272.7	18,024	9,076	827.7	39,453	21,319	1,468.9
Kansas	4,445	9,315	4,654	845.2	7,350	3,693	396.7	17,993	8,654	794.5	34,658	17,001	2,036.4
Kentucky	3,813	11,968	6,188	133.4	5,218	2,609	101.4	23,112	12,010	300.6	40,298	20,807	535.4
Louisiana	1,735	21,097	10,577	139.6	3,446	1,721	17.7	26,524	12,829	137.6	51,067	25,127	294.9
Maine	958	7,834	3,931	60.5	2,591	1,278	27.6	13,300	6,434	81.2	23,725	11,643	169.3
Maryland	8,210	8,117	4,232	70.5	3,743	1,717	27.3	6,168	3,567	35.4	18,028	9,516	133.2
Massachusetts	3,268	16,293	8,241	24.6	3,074	1,525	4.1	40,143	19,133	34.6	59,510	28,899	63.3
Michigan	6,746	23,418	12,299	415.2	12,068	6,060	261.0	53,131	22,903	294.4	88,617	41,262	970.6
Minnesota	4,155	11,981	6,469	920.4	3,691	2,065	280.3	21,268	11,338	706.8	36,940	19,872	1,907.5
Mississippi	1,251	15,941	8,064	443.2	3,863	1,822	161.6	22,009	11,242	637.5	41,813	21,128	1,242.3
Missouri	8,952	15,850	8,193	705.5	4,099	2,058	111.2	56,415	27,863	528.6	76,364	38,114	1,345.3
Montana	7,564	10,935	6,732	196.2	4,545	2,809	98.2	16,340	9,943	279.3	31,820	19,484	573.7
Nebraska	13,147	13,110	7,008	541.4	2,183	1,346	47.7	11,810	6,545	257.7	27,103	14,899	846.8
Nevada	4,899	3,877	3,246	71.2	438	367	7.8	4,752	3,940	104.2	9,067	7,553	183.2
New Hampshire	2,592	2,627	1,307	13.1	721	360	5.5	6,236	3,237	36.4	9,584	4,904	55.0
New Jersey	3,332	7,782	3,891	61.6	7,819	3,722	8.6	26,506	12,686	25.0	42,107	20,299	95.2
New Mexico	1,132	2,760	1,727	54.1	3,610	2,288	93.0	6,828	4,329	153.4	13,198	8,344	300.5
New York	23,536	79,128	40,598	114.2	28,798	14,681	125.4	148,271	68,438	435.9	256,197	123,717	675.5
North Carolina	6,254	19,405	9,422	365.9	5,764	2,726	122.1	28,359	13,587	497.6	53,528	25,735	985.6
North Dakota	2,532	4,908	2,468	823.9	2,470	1,235	352.2	10,920	5,638	781.6	18,298	9,341	1,957.7
Ohio	7,686	17,161	7,899	116.6	9,816	4,995	36.2	95,299	47,120	149.6	122,276	60,014	302.4
Oklahoma	8,791	11,197	6,263	156.9	4,200	2,216	91.0	16,479	8,665	204.0	31,876	17,144	451.9
Oregon	3,288	809	433	16.2	1,141	677	46.8	14,112	8,541	202.9	16,062	9,651	265.9
Pennsylvania	5,168	34,211	15,578	32.2	28,884	13,770	66.8	91,052	45,289	236.3	154,147	74,637	335.3
Rhode Island	1,944	3,277	1,638	31.9	161	80		9,831	4,912	22.2	13,269	6,630	54.1
South Carolina	2,881	11,504	6,310	307.8	2,313	1,162	120.7	16,613	8,415	318.7	30,430	15,887	747.2
South Dakota	688	8,279	4,784	497.6	4,024	2,250	227.8	8,316	4,901	429.4	20,619	11,935	1,154.8
Tennessee	4,455	10,643	5,301	363.4	10,633	6,007	323.6	32,201	14,151	238.9	53,477	25,459	925.9
Texas	11,800	6,607	3,509	125.7	12,785	6,746	385.9	59,893	33,306	820.9	79,285	43,561	1,332.5
Utah	492	3,026	2,314	47.1	2,513	1,870	50.0	13,268	10,051	174.1	18,807	14,235	271.2
Vermont	614	4,081	2,160	41.8	418	286	1.6	9,083	4,522	62.4	13,582	6,968	105.8
Virginia	965	14,018	5,990	202.8	9,009	4,360	101.9	32,876	15,960	241.6	55,903	26,310	546.3
Washington	1,047	9,937	5,146	130.3	3,017	1,545	86.7	17,203	9,206	135.6	30,157	15,897	352.6
West Virginia	3,872	8,400	4,227	44.0	4,815	2,431	29.2	15,649	7,841	112.8	28,864	14,499	186.0
Wisconsin	3,469	11,674	6,268	190.1	4,383	2,341	119.4	36,792	18,677	415.3	52,849	27,286	724.8
Wyoming	694	1,960	1,242	48.0	1,725	1,116	59.9	8,636	5,696	167.6	12,321	8,054	275.5
Hawaii	1,027	3,248	1,590	7.8	161	81	.6	11,667	5,625	18.5	15,076	7,296	26.9
District of Columbia	738	7,788	3,654	6.0	4,653	2,131	.2	10,094	4,742	3.5	22,535	10,527	9.7
Puerto Rico	3,693	10,385	4,761	51.2	1,429	700	6.7	14,755	7,045	47.9	26,569	12,506	105.8
TOTAL	235,155	647,033	333,751	10,921.6	290,896	151,234	5,249.9	1,426,478	720,203	14,050.4	2,364,407	1,205,188	30,221.9

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