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AN INVESTIGATION OF RIGID FRAME BRIDGES
PART III

TESTS OF STRUCTURAL HINGES OF REINFORCED CONCRETE

A REPORT OF AN INVESTIGATION
CONDUCTED BY
THE ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
IN COOPERATION WITH
THE PORTLAND CEMENT ASSOCIATION

BY
RALPH W. KLUGE

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CONTENTS

LIST OF FIGURES

LIST OF TABLES

AN INVESTIGATION OF RIGID FRAME BRIDGES

PART III

TESTS OF STRUCTURAL HINGES OF REINFORCED CONCRETE

I. INTRODUCTION

1. *Object and Scope of Investigation.*—In many cases it is highly desirable to introduce some form of articulation at the bases of the vertical members of concrete rigid frame bridges, particularly in long spans, where high deformation stresses would otherwise occur, due to temperature changes and shrinkage of the concrete. What constitutes a satisfactory hinge for such a structure can be determined only by laboratory tests and field experience. The purpose, therefore, of this investigation was to obtain information relative to the structural behavior of various types of hinges adaptable to concrete rigid frame bridges.

Previous tests of hinges for concrete structures have been limited to a type, similar to type 4 of this report, developed by the late Augustin Mesnager, a French engineer. Mesnager constructed two of his hinges and tested them to failure under vertical load combined with a forced rotation.* D. E. Parsons and A. H. Stang,† as well as G. C. Ernst,‡ made series of tests on the same type of hinge. Their work included axial and oblique load tests, as well as combined load and rotation tests, on specimens with and without concrete covering over the reinforcing bars at the center of rotation. A valuable discussion of the use of Mesnager hinges and the procedure to be followed in their design was presented in 1935 by B. Moreell.¶

A properly designed hinge, besides being sufficiently flexible to permit a given angular rotation, should be capable of withstanding compressive forces as well as shearing forces, be economical to construct, and require a minimum of maintenance. Seven types of hinges which it was thought might meet these requirements were selected for testing. The specimens were tested to determine their elastic and ultimate strength under vertical loads and under inclined loads such as occur at the hinges of a rigid frame bridge. Their

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*"Experiences sur une semi-articulation pour routes en Beton Arme," M. Mesnager, Annales des Ponts et Chaussees, 1907.

†"Tests of Mesnager Hinges," D. E. Parsons and A. H. Stang, Journal of the American Concrete Institute, Jan.-Feb. 1935.

‡"Tests of Reinforced Concrete Hinges of the Mesnager Type," G. C. Ernst, Highway Research Board, Vol. 17, 1937.

¶"Articulations for Concrete Structures—the Mesnager Hinge," B. Moreell, Proc. A.C.I., Vol. 31, or Journal A.C.I., Vol. 6, pp. 368-381, 1935.

resistance to angular rotation was measured, and some were subjected to repeated rotation and then tested to failure under a vertical load combined with a forced rotation. Those specimens in which angular deformation occurred in the concrete during rotation of the hinge were tested to determine the effect of plastic flow on their resistance to rotation.

2. *Acknowledgments.*—The tests reported in this bulletin were a part of the investigation of rigid frame bridges conducted in the Arthur Newell Talbot Laboratory by the Engineering Experiment Station, University of Illinois, in cooperation with the Portland Cement Association. The work was under the administrative direction of DEAN M. L. ENGER, Director of the Station, PROFESSOR W. C. HUNTINGTON, Head of the Department of Civil Engineering, and W. M. WILSON, Research Professor of Structural Engineering. The Association was represented by an Advisory Committee consisting of FRANK T. SHEETS, President, and A. J. BOASE, Manager of the Structural and Technical Bureau. The laboratory testing was under the general direction of F. E. RICHART, Research Professor of Engineering Materials, to whom the author is indebted for helpful criticism and advice. The author is especially grateful to Professor Wilson for his careful examination of the manuscript and his suggestions for its improvement.

3. *Outline of Tests.*—Preliminary studies of rigid frame bridges indicated that the slope of the line of maximum thrust was in general about 1 vertical to 2 horizontal, and that an angular rotation as large as 0.004 radian could be expected at the bases of long span rigid frames freely hinged at these points. The tests were therefore planned on the basis of this information.

The testing program was divided into four series of tests, two series of load tests, a series of load and rotation tests, and a series of time-yield tests. All tests were made in duplicate. They are briefly described as follows:

Series V consisted of tests to failure under a vertical load passing through the axis of the hinge.

Series D consisted of oblique load tests to failure, in which the load was applied along a line inclined 26½ deg. to the vertical axis of the hinge.

Series R consisted of several different tests made on the same specimen. It included tests to determine the resistance of the hinge to an angular rotation of 0.004 radian, repeated rotation tests to the extent of 10 000 repetitions of angular movement, and, finally,

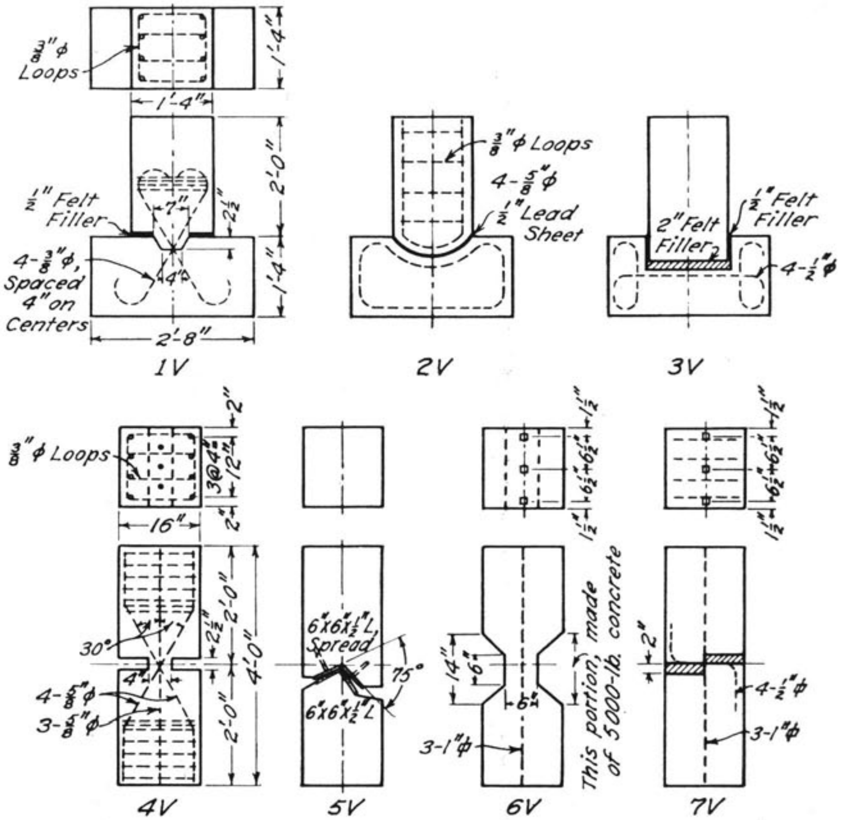

FIG. 1. VERTICAL LOAD SPECIMENS

tests to destruction, in which the hinge specimens were subjected to a vertical load and a forced rotation of 0.004 radian.

Series T consisted of time-yield tests to determine the effect of plastic yielding on the change in moment necessary to maintain a constant angular rotation over a period of time. Only those hinges in which the concrete participated in the action of the hinge were tested in this series.

II. DESCRIPTION OF SPECIMENS AND APPARATUS

4. *General Description of Test Specimens.*—The test specimens, and the details of the various types of hinges tested, are shown in Figs. 1, 2, and 3. The specimens shown in Fig. 1 were subjected to a vertical load passing through the axis of the hinge, those in Fig. 2 were subjected to an inclined load passing through the axis of hinge,

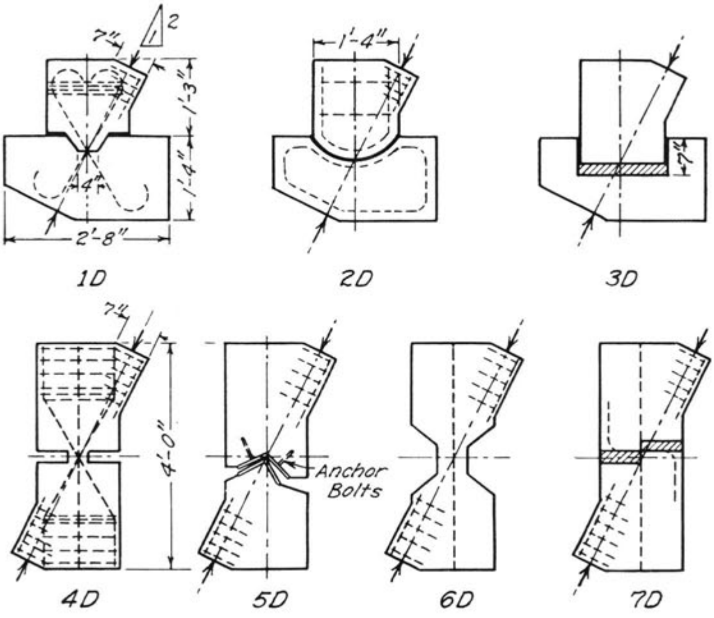

FIG. 2. OBLIQUE LOAD SPECIMENS

and those shown in Fig. 3 were subjected to a rotation. The various types of hinges are described briefly in the following paragraphs.

Type 1 is a conventional tongue-and-groove joint with ½ inch of impregnated felt filler placed between the vertical leg and the base on each side of the joint. Three-quarter-inch round deformed bars are crossed in pairs, and the pairs are spaced 4 inches apart.

Type 2 consists of a lead sheet between cylindrical surfaces of concrete.

Type 3 is another tongue-and-groove joint with a 2-inch impregnated felt filler underneath the vertical leg and ½ inch of felt along the sides.

Type 4 is a modified Mesnager hinge. It differs from the true Mesnager hinge in that it contains vertical bars in addition to the crossed bars. The bars are crossed in pairs and spaced 4 inches apart with a vertical bar between each crossed pair. This hinge was constructed and tested with and without concrete covering over the bars. The two variations were therefore designated as 4-c and 4-b, respectively.

Type 5 is a simple pivot consisting of two 6-in. x 6-in. x ½-in. structural steel angles anchored to the concrete, the corner of one

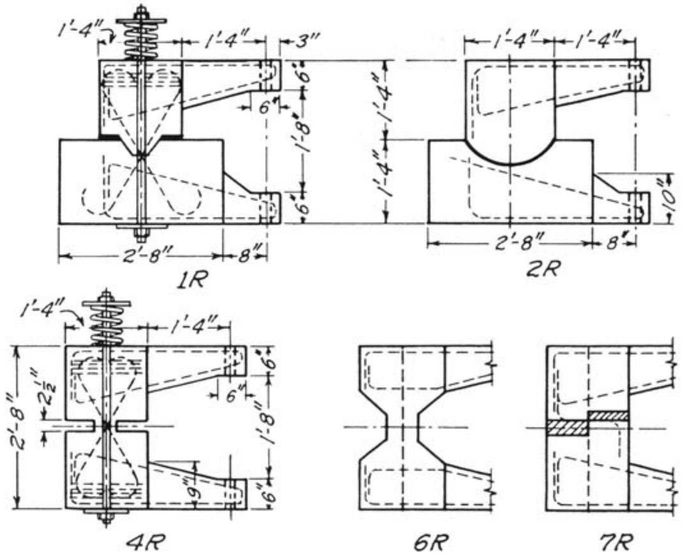

Fig. 3. Rotation and Time Load Specimens

bearing on the fillet of the other angle, which is spread slightly to provide clearance.

Type 6 represents a structural member having a deliberately reduced section of high strength concrete, reinforced at the center with 1-inch square vertical bars spaced 6½ inches apart.

Type 7 is a flexure fulcrum type of hinge in which 1-inch square vertical bars, spaced 6½ inches apart and protected by impregnated felt filler, are the flexure members, and ½-inch square horizontal bars resist shearing forces.

5. *Construction of Test Specimens.*—All of the test pieces were made from concrete designed to have a strength of 3500 lb. per sq. in. at 28 days, except the central portion of hinge 6, which was made from 5000 lb. concrete. The materials used were a standard portland cement, Wabash River torpedo sand, and gravel. The latter was graded from ¼ to 1 inch in particle size. The proportions of cement, sand, and gravel in the concrete used were 1:3¼:4, by weight, with a 1.1 water-cement ratio. This made a rather wet mix that was easily worked about the reinforcing bars. The average strength of the concrete in each specimen as determined from control cylinders is given in Table 2, page 11.

Steel forms were used except for some of the special details.

TABLE 1
AVERAGE PHYSICAL PROPERTIES OF REINFORCING STEEL

Specimen	Yield Point lb. per sq. in.	Ultimate Strength lb. per sq. in.	Elongation per cent	Reduction in Area per cent	Remarks
1-in. square	45 160	74 680	25.2	44.7	Deformed bar
¾-in. round	48 990	83 440	22.6	44.8	Deformed bar
⅝-in. round	44 530	76 830	21.4	55.0	Plain bar
½-in. square	47 120	75 380	21.7	44.0	Deformed bar
⅜-in. round	49 300	76 800	20.8	58.0	Plain bar

After 24 hours the forms were stripped, the specimens were wrapped in wet burlap and were cured in this moist condition for 7 days; they were then allowed to dry out in the laboratory air for a period of 21 days before testing. Three control cylinders were obtained (usually one from each batch) for each test specimen. They were cured in the same manner as the test specimen and tested dry when 28 days old.

The reinforcing steel was of intermediate grade, plain and deformed, having the physical properties listed in Table 1. Those hinges containing crossed bars were reinforced at and above the bends with ⅜-inch bars in the form of rectangular loops closely spaced and securely wired to the hinge steel.

Several of the hinges, types 1, 2, 3 and 5, because of the nature of their construction were poured in two operations, the lower half being poured one day and the upper half the next day. Most of the hinges involved no unusual construction difficulties; some difficulty, however, was experienced in constructing the type 5 hinges, and this perhaps warrants special comment on the method employed. In order to construct type 5 in its normal vertical position the lower half of the specimen was formed to the proper shape to support the pivot angle in its correct position; then, after the concrete had set up, the angle was grouted in place with a neat cement mortar. The bearing angle in the upper half was then supported on the pivot angle and held in position with wedges and form stops while the upper half was poured.

6. *Description of Rotation Apparatus.*—The rotation machine used for the service tests of hinges is shown in Fig. 4. It contained an adjustable eccentric cam operated by a variable-speed motor. One of the lever arms of the hinge specimen was clamped rigidly to the

TABLE 2
SUMMARY OF LOAD TESTS

Specimen	Vertical Axial Load lb.		Oblique Load lb.		Ratio	Load-Rotation lb.		Ratio
Type No.	Ultimate Load	Cylinder Strength	Ultimate Load	Cylinder Strength	Obliq. Ult./Vert. Ult.	Ultimate Load	Cylinder Strength	L-R Ult./Vert. Ult.
1 — 1	598 000	3250	443 000	4080	0.76	589 000	3505	0.89
2	653 000	3810	515 000	4330		530 000	4490	
Average	625 500	3530	479 000	4205		559 500	4000	
2 — 1	778 000	3330	416 000	3560	0.46	646 000	4353	0.75
2	950 000	3790	390 000	3530		645 000	4400	
Average	864 000	3560	403 000	3545		645 500	4375	
4-c— 1*	366 000	3660	220 000	4040	0.53	382 000	4570	0.90
2	423 000	4310	200 000	4100		326 000	3720	
Average	394 500	3985	210 000	4070		354 000	4145	
4-b— 1*	155 400	3950	119 000	4340	0.71	134 000	4140	0.82
2	173 000	4360	115 000	4420		135 000	4240	
Average	164 200	4155	117 000	4380		134 500	4190	
5 — 1	260 000	3700	180 000	3960	0.68	(†)		
2	291 000	4760	195 000	3800		(†)		
Average	275 500	4230	187 500	3880				
6 — 1	585 000	3950–5150	220 000	3670–4500	0.39	545 000	3470–5280	1.05
2	500 000	3310–5080	207 000	3780–4840		594 000	–5455	
Average	542 500	3630–5115	213 500	3725–4670		570 500	3470–5365	
7 — 1	224 000	4050	91 500	4440	0.39	250 000	4365	1.05
2	237 500	3800	90 000	4110		233 000	4385	
Average	230 750	3925	90 750	4275		241 500	4375	

*c indicates bars covered with concrete, b indicates bars bare.
†No tests for this method of loading.

base of the machine, while the other end was supported on 2-inch rollers and connected by means of a 1-inch bolt passing through a pair of calibrated car springs, one on each side of the lever arm, to a horizontal motion bar which was operated by the eccentric cam. The car springs were adjusted so that they were always in compression and operated in constant opposition to each other. This arrangement permitted a gradual angular movement of the hinge from 0 to a maximum of 0.004 radian in one direction to 0.004 radian in the other direction, and also provided a method of measuring the force required to rotate the hinge.

III. DESCRIPTION OF TESTS

7. *Vertical Load Tests.*—The hinge specimens were tested in a Southwark-Emery 3 000 000-lb. testing machine. Load was applied through a spherical block, fastened to the head of the testing machine,

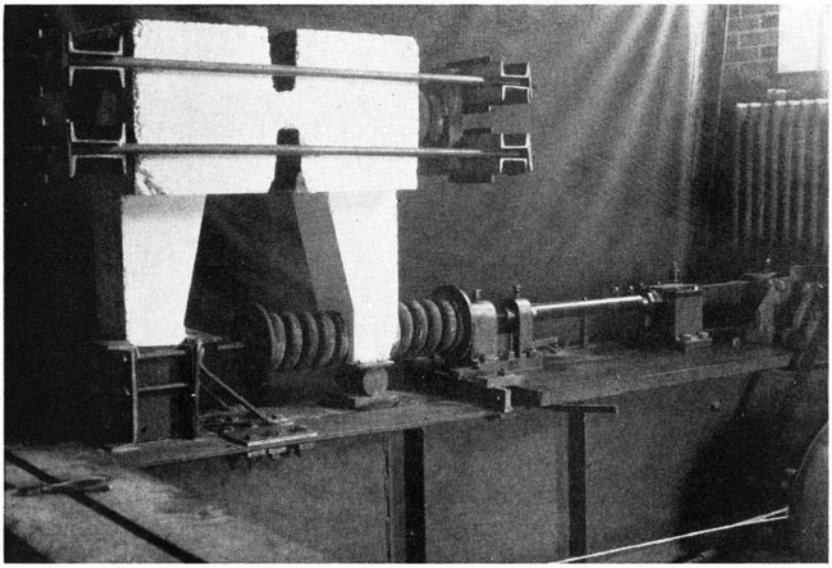

FIG. 4. VIEW OF REPEATED ROTATION APPARATUS WITH HINGE SPECIMEN IN PLACE

as shown in Fig. 5. A 1¼-inch machined plate was used to cap the specimen. Deformation of the entire length of the specimen was measured by four compressometers, one at each corner, held in place by steel bars clamped to the base and top of the specimen. Steel strains across the center of the hinge were measured on reinforcing bars that were close to the surface of the concrete, by means of a 10-inch Berry strain gage.

In order to center the specimen in the machine a small load was applied and the compression at each corner of the specimen was noted. If the deformation was not uniform the specimen was shifted until the eccentricity was eliminated, and then the spherical loading block was wedged in position.

Load was applied in increments of 20 000 and 25 000 lb. and a complete set of readings was obtained after each increment. The load was increased until failure seemed imminent, then all instruments were removed, and loading continued until complete failure of the specimen occurred.

8. *Oblique Load Tests.*—The oblique-load tests were conducted in much the same manner as the vertical-load tests, except that the specimen was inclined so that load was applied through the loading

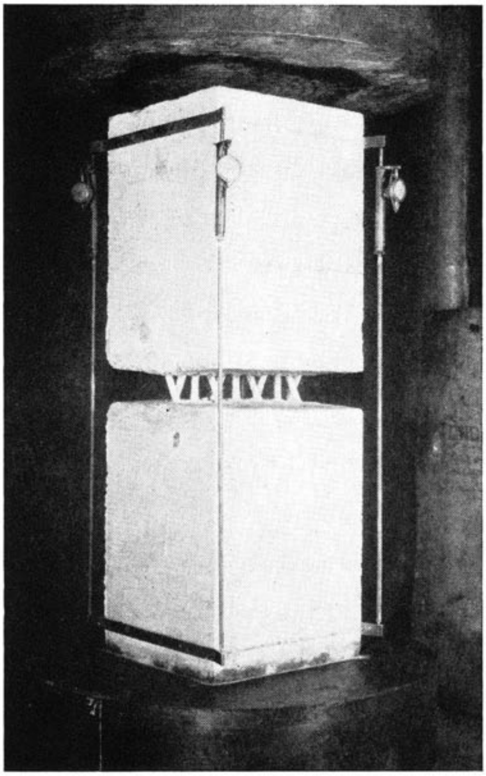

FIG. 5. VERTICAL LOAD SPECIMEN IN TESTING MACHINE

shelves, as shown in Fig. 6. Deformations were measured directly across the hinge between the points *ab* and *a'b'*, indicated in Fig. 6, and diagonally across the hinge between points *ab'* and *a'b* to obtain a measure of the relative lateral movement of the upper and lower halves of the specimen. Steel strains were obtained in the same way as in the vertical-load tests. The specimens were centered in the testing machine by noting the compression at each corner, as indicated by the four extensometers shown in Fig. 6, and adjustments were made when necessary to eliminate any eccentricity.

9. *Rotation Tests.*—In this series of tests the resistance of the hinges to angular rotation was first measured; they were then given a service test consisting of about 10 000 cycles of reversed rotation through an angle of ±0.004 radian, and finally they were tested to failure under a combined vertical load and a rotation of 0.004 radian.

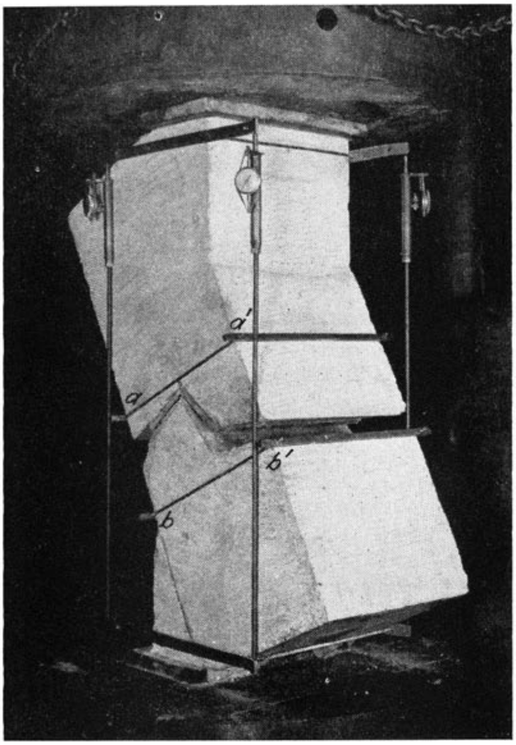

FIG. 6. OBLIQUE LOAD SPECIMEN IN TESTING MACHINE

A specimen was first loaded axially with calibrated car springs, the load being applied through steel bearing plates by means of an adjustable yoke, as shown in Fig. 7. Considerable care was exercised in applying the load so that it was absolutely central. Its position was carefully checked by the deformation dials at each corner of the specimen. The magnitude of this load was about one-third of the ultimate strength of the hinge, loaded in this manner, as estimated from the vertical load tests on similar specimens. This was considered a normal working load. The hinge was actuated by pulling the lever arms of the specimen together with a long 1-inch bolt passing through the lever arms and a calibrated spring. Compression of the spring was measured for various degrees of rotation until a maximum of 0.004 radian was produced. Knowing the force required to produce a given rotation, and the length of the lever arm, the moment resistance of the hinge was calculated. For hinges of type 2 this test was a matter of determining the moment necessary

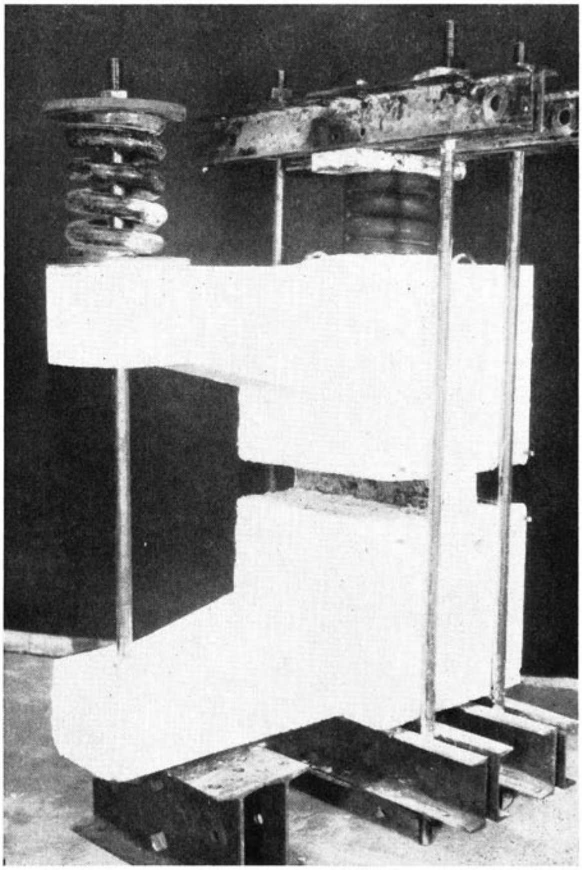

FIG. 7. ROTATION SPECIMEN EQUIPPED FOR TESTING

to overcome static friction between the lead and the concrete surfaces, and, since friction depends upon the pressure between the surfaces, the test was repeated for increasing axial loads.

The hinge specimen was next mounted in the rotation machine described in Section 6 and shown in Fig. 4, and the eccentric adjusted to produce an angular movement of the hinge in both directions from its normal position of 0.004 radian. The speed of the machine was regulated so as to produce about fifteen reversals of rotation per minute. During this test the hinge was carefully observed to detect any possible structural damage or decrease in resistance to rotation.

After the specimen had been subjected to 10 000 cycles it was removed from the rotation machine, placed in the 3 000 000-lb.

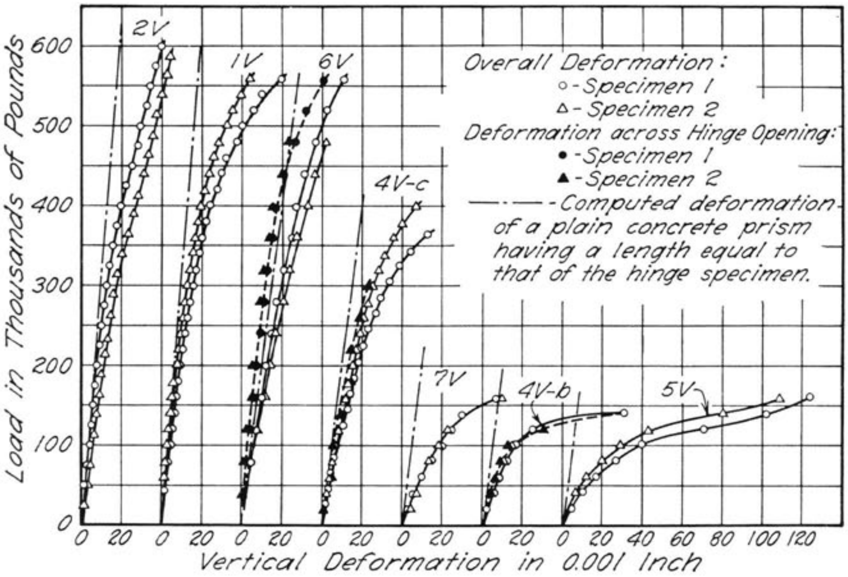

FIG. 8. LOAD–DEFORMATION CURVES FOR HINGES TESTED UNDER VERTICAL AXIAL LOADS

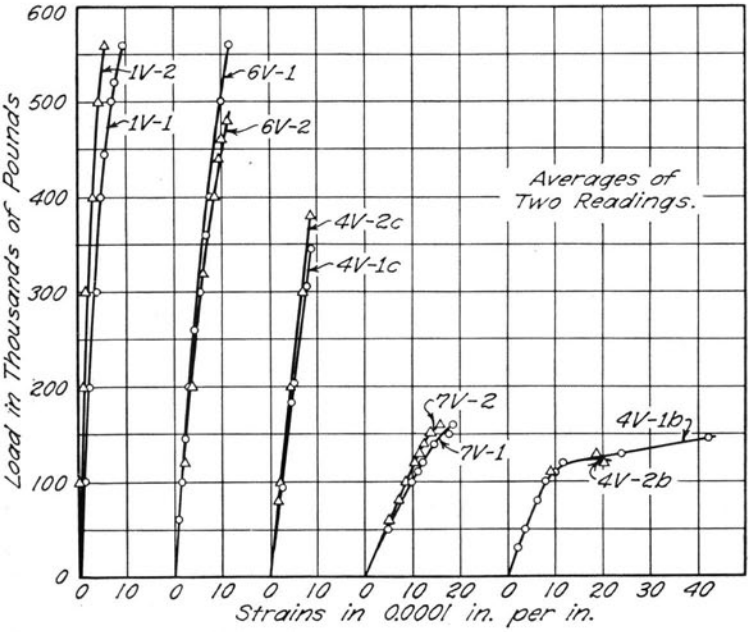

FIG. 9. LOAD–STRAIN DIAGRAMS FOR STEEL IN VERTICAL LOAD SPECIMENS

testing machine, and tested to failure under a static load. An initial rotation of 0.004 radian was induced at the beginning of this test by applying the load through tapered plates, one above and the other below the specimen. Enough load was applied to cause a rotation of 0.004 radian, the spherical blocks were then wedged in position to prevent further rotation, and the load increased until failure occurred.

10. *Time Yield Tests.*—Tests to determine the reduction in resisting moment of the hinge due to plastic yielding of the concrete for an angular rotation of 0.004 radian were performed on hinge types 4-c and 6. These, except for type 1, were the only hinges in which concrete directly participated in the action of the hinge. Type 1 was not tested because of its extreme rigidity, and because of the resulting damage to the specimen in rotating it. The testing apparatus and the method of rotating the hinge was the same as for the tests to determine the resistance of the hinge to angular rotation described in the preceding section. Each hinge was subjected to a sustained axial load corresponding to one-third of its estimated ultimate strength. The general testing procedure after the initial rotation of the hinge was to maintain the rotation constant by releasing the spring compression at the ends of the levers at frequent intervals during the test, and to measure the spring deformation immediately after each adjustment. The force exerted by the spring was determined from its calibration, and the resisting moment of the hinge was thus calculated.

IV. Results of Tests

11. *Strength of Hinges Subjected to Vertical Loads.*—Load-deformation curves for the vertical-load tests are shown in Fig. 8. The values plotted represent the average deformation as measured at the four corners of the specimen over its entire length, and in several instances the average deformation measured directly across the hinge opening. The curves are compared with the computed total deformation, shown by dot and dash lines, of a block of concrete with the same dimensions as those for the hinge specimens, and having an assumed modulus of elasticity of 3 500 000-lb. per sq. in. This comparison illustrates the relative stiffness of the various types of hinges when subjected to direct thrust. It is to be expected that a large percentage of the total deformation will occur across the hinge opening in the more flexible types of hinges. The data indicate that

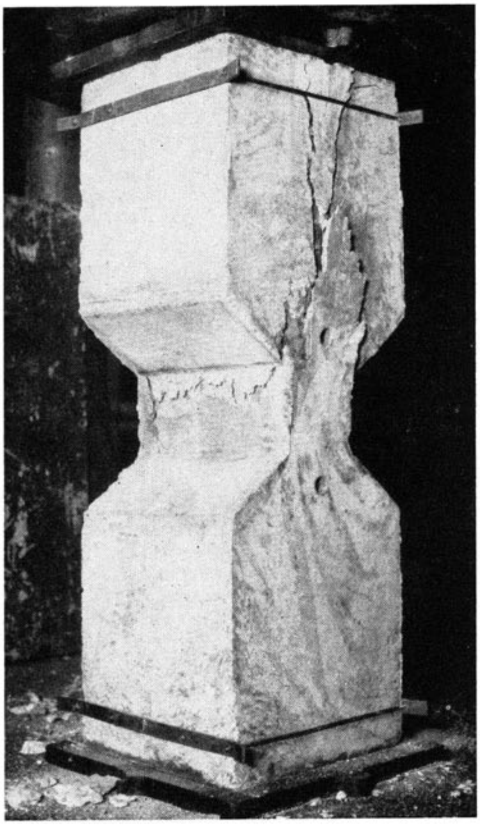

FIG. 10 (a) HINGE SPECIMEN AFTER TEST TO FAILURE

TABLE 3
COMPARISON OF COMPUTED MAXIMUM LOADS WITH TEST VALUES
Vertical Load Specimens

Hinge Type	Computed Maximum Load lb.	Test Value Maximum Load lb.	Ratio $\frac{\text{Test value}}{\text{Computed value}}$
1	515 700	625 500	1.21
2	912 000	864 000	0.95
4-c	390 700	394 500	1.01
4-b	135 700	164 200	1.21
5	541 000	275 500	0.51
6	492 000	542 500	1.10
7	135 480	230 750	1.70

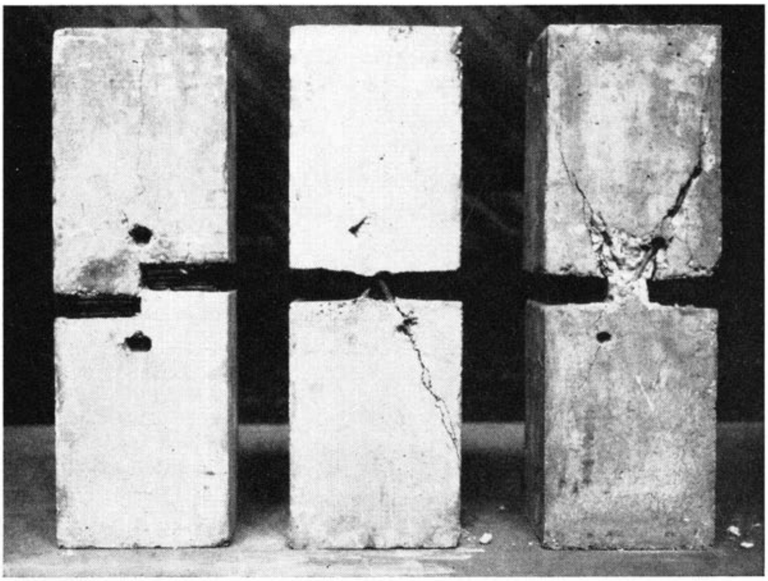

FIG. 10 (b) HINGE SPECIMENS AFTER TESTS TO FAILURE

practically all the deformation occurs across the hinge in types 4V-c within working loads, and in types 4V-b up to failure of the specimens. The results of specimen 3V are not included because it failed to sustain any appreciable load until practically all the filler underneath and along the sides was forced out. Further tests of this type of hinge were therefore discontinued. Load-strain curves for the steel bars crossing the hinge in types 1, 4, 6, and 7 are shown in Fig. 9, and the ultimate loads as well as the average strength of the control cylinders for each specimen are listed in Table 2.

The maximum vertical load that each hinge should support was computed on the basis of the concrete strength indicated by the control cylinders, and the yield strength of the reinforcement as given in Table 1. Since the length of bare bars in types 4-b and 7 was quite short, it was assumed in the computations that the full yield point of the steel might be developed. This made it unnecessary to apply the rather complex equations that have been developed for Mesnager hinges.* The values thus computed are compared with the average test values for each type of hinge in Table 3. It is inter-

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*See Parsons, D. E. and Stang, A. H. "Tests of Mesnager Hinges," Proc. A.C.I. Vol. 31, pp. 304-330, 1935.

esting to note the high strength developed by several of the hinges as compared with the computed values. Type 7, for example, resisted a load 70 per cent greater than the computed value. The actual strength of type 5 was considerably less than the computed value because the distribution of stress in the concrete adjacent to the angles was not according to the manner assumed. Furthermore, it is possible that transverse reinforcing just above the upper angle and just below the lower angle would have strengthened the hinge materially.

Views of several of the specimens after failure are shown in Fig. 10. The manner of failure of each type is briefly described in the following paragraphs. In each instance the companion test exhibited a similar type of failure.

Hinge IV. Failure of type IV specimens was due to splitting of the concrete along the diagonal steel bars. Splitting was first in evidence at a load of about 450 000 lb. when fine cracks were observed along the plane of the steel. The ultimate loads were 598 000 lb. and 653 000 lb. for IV-1 and IV-2, respectively.

Hinge 2V. Type 2V specimens failed by crushing of the concrete in the upper half of the hinge, developing approximately the same strength as the control cylinders. Diagonal cracks in the lower half radiating out from the cylindrical surface appeared just before failure. There was no apparent damage to the lead plate. The ultimate loads were 778 000 lb. and 950 000 lb. for 2V-1 and 2V-2, respectively.

Hinge 3V. Type 3V specimens failed to withstand loads greater than 10 000 lb. without causing serious extrusion of the filler underneath and along the sides of the joint. For this reason tests of this type of hinge were discontinued.

Hinge 4V-b. Primary failure of type 4V-b specimens was due to yielding of the steel as indicated by scaling of the exposed bars at a load of 100 000 lb. Final failure was caused by splitting of the concrete along the diagonal bars. There was no evidence of buckling of the exposed bars even at the capacity load. The ultimate loads were 155 400 lb. and 173 000 lb. for specimens 4V-b1 and 4V-b2, respectively, and a view of failure is shown in Fig. 10(b).

Hinge 4V-c. Initial failure of the type 4V-c specimens was due to cracking along the diagonal steel. Crushing of the concrete covering and buckling of the steel within the covering, as shown in Fig. 10(b), occurred at the ultimate loads of 366 000 lb. and 423 000 lb. for specimens 4V-c1 and 4V-c2, respectively.

Hinge 5V. Failure of the type 5V specimens was due to the crushing of the concrete below the fillet of the lower pivot angle, followed by diagonal splitting of the lower half of the specimen. In the companion test a crack appeared in the upper half of the specimen, starting at the corner of the upper angle and extending about 12 inches. This occurred at about 0.8 of the maximum load, but did not contribute to the final failure. Examination of the structural angles after failure revealed a slight flattening of the edge of the pivot angle and only slight indentation in the fillet of the upper bearing angle. The ultimate loads were 260 000 lb. and 291 000 lb. for specimens 5V-1 and 5V-2, respectively.

Hinge 6V. The type 6V specimens exhibited a rather peculiar type of failure in which the outstanding portion of the specimen above the reduced section literally sheared off, as shown in Fig. 10. Cracks originated at the reentrant angle at the end of the reduced section, extended vertically several inches, and, as the load was increased, veered off toward the plane of the vertical steel bars. The ultimate loads were 585 000 lb. and 500 000 lb. for specimens 6V-1 and 6V-2, respectively.

Hinge 7V. Failure of the type 7V specimens was caused by the vertical bars yielding, followed closely by splitting of the concrete along the steel, as shown in Fig. 10(b). The ultimate loads were 224 000 lb. and 237 000 lb. for specimens 7V-1 and 7V-2, respectively.

12. *Strength of Hinges Subjected to Oblique Loads.*—The results of the oblique-load tests are reported in Table 2 and are shown in Figs. 11 and 12. The curves in Fig. 11(a) show the relative lateral movement of the upper and lower halves of the specimen due to the shearing component of the applied load. They are plotted in terms of oblique load and lateral deformation. Hinges 1D and 2D showed relatively little lateral movement of the upper half of the hinge relative to the lower half as compared with the more flexible types, and are therefore not included. The deformation in the longitudinal direction of the specimen is shown in the curves of Fig. 11(b). Load-strain diagrams for the steel bars in types 1, 4, 6 and 7 are given in Fig. 12. The curves labeled "North" refer to the diagonal bars which were almost parallel to the direction of the applied load, due to the inclination of the hinge in the testing machine. Consequently they received practically the full effect of the load as an axial force, whereas the curves labeled "South" refer to the diagonal bars which resisted the shearing component of the applied load. The break in the curves for specimens 4D-1b and 4D-2b (south) clearly indicate

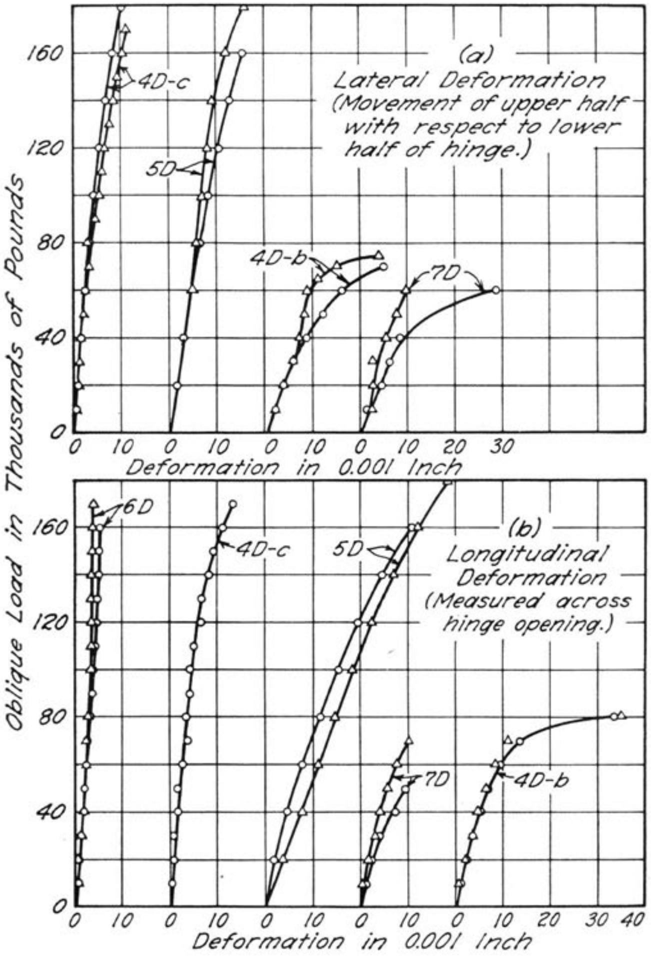

FIG. 11. LATERAL AND LONGITUDINAL DEFORMATIONS OF HINGES SUBJECTED TO OBLIQUE LOAD

bending of those bars at a load of 60 000 lb. These load-strain diagrams, together with those for specimens 4D-1c and 4D-2c, show very definitely the assistance of the concrete covering over the bars of type 4 in resisting an oblique thrust on the hinge.

The failure of the hinges subjected to an oblique load is due normally to a combination of a shearing thrust and a direct thrust, the individual effects of which are not readily separated. Failure in most of the hinges tested, however, was not so much influenced by shearing stresses as by other secondary effects, such as splitting

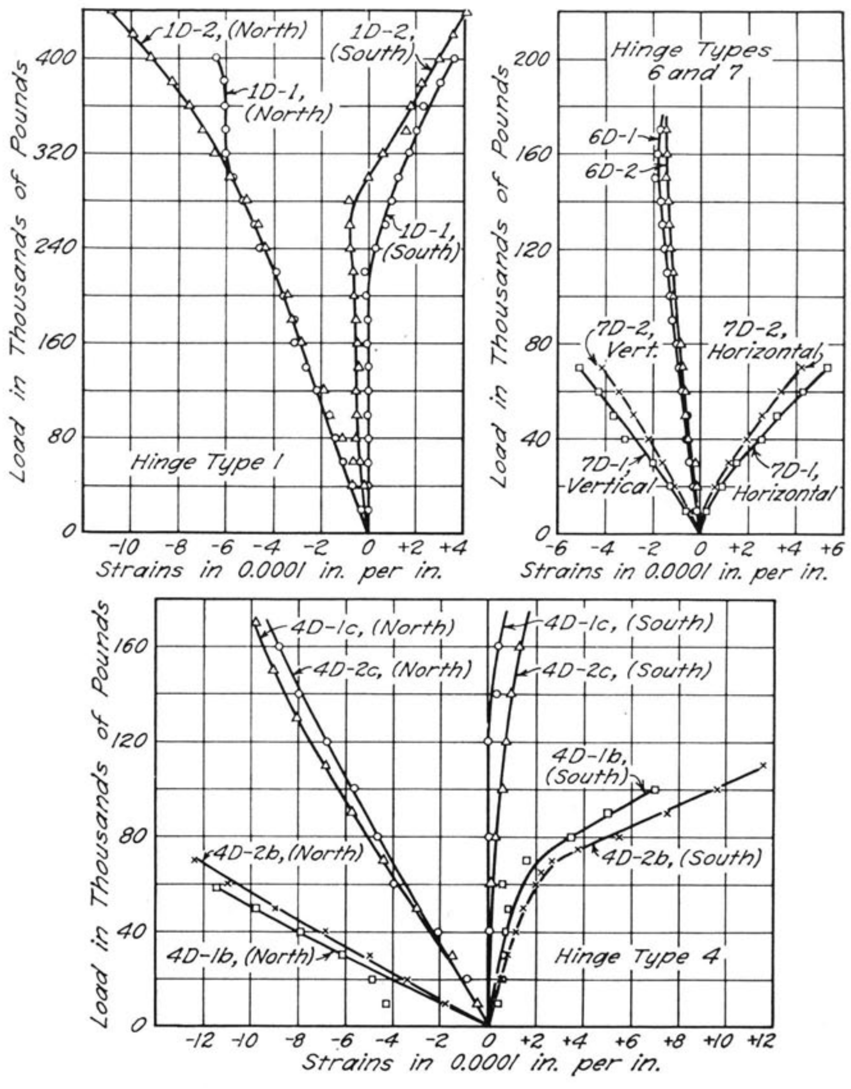

FIG. 12. LOAD–STRAIN DIAGRAMS FOR STEEL IN OBLIQUE LOAD SPECIMENS

of the concrete, or buckling and bending of the steel bars; nevertheless it is of interest to resolve the maximum oblique load into its components and to observe the effect of a shearing force on the hinge by comparing the component parallel to the longitudinal axis of the specimen with the maximum strength of the hinge when tested under a vertical load. This has been done in Table 4.

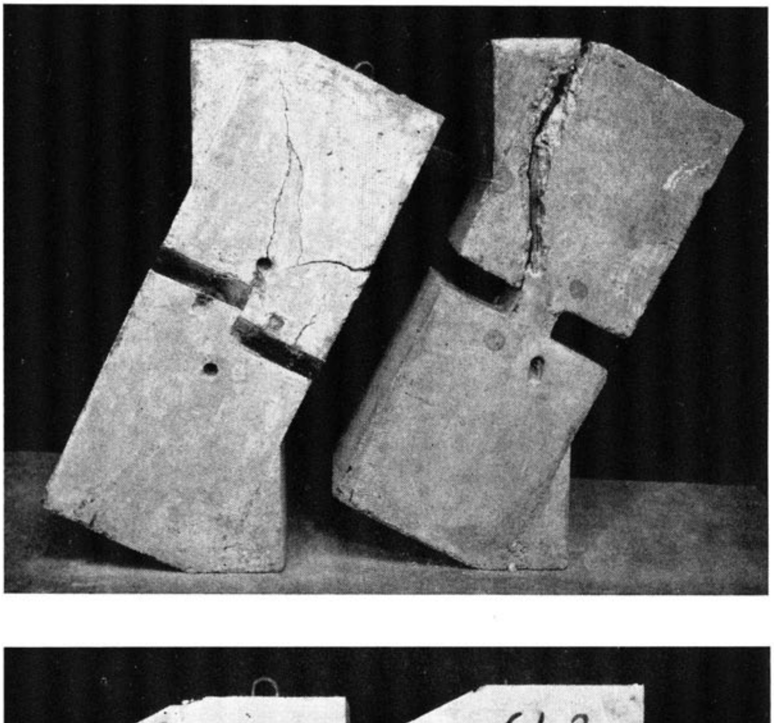

FIG. 13. HINGE SPECIMENS 7D, 4D-c, 4D-b AND 6D AFTER TESTS TO FAILURE

TABLE 4

LONGITUDINAL AND LATERAL COMPONENTS OF MAXIMUM OBLIQUE LOADS COMPARED WITH MAXIMUM VERTICAL LOADS

Maximum vertical loads in italics

Hinge Type	Maximum Oblique Loads lb.	Longitudinal Component lb.	Lateral Component lb.
1	479 000	428 000 *625 500*	214 000
2	403 100	360 000 *864 000*	180 000
4-c	210 000	188 000 *394 000*	94 000
4-b	117 000	104 800 *164 200*	52 400
5	187 500	168 000 *275 500*	84 000
6	213 500	191 000 *542 500*	95 500
7	90 750	81 200 *230 750*	40 600

Another comparison of the relative strengths of the hinges under oblique and vertical axial loads is shown as a ratio in Table 2.

It is interesting to note the relatively high value of the ratio exhibited by type 4-b as compared with type 4-c, which is a similar hinge except for the concrete covering over the bars at the hinge opening. The results might have been altered considerably had specimens of type 4-c been reinforced to prevent splitting of the concrete along the bars. The low value of the ratio shown by type 2 was due primarily to a premature failure of the base of each specimen, apparently because of its shape.

The manner of failure of several of the hinges is shown in Fig. 13, and a brief description of the failure of each specimen tested under an oblique load is given in the following paragraphs.

Hinge 1D. The specimens of type 1D failed by splitting of the concrete along the diagonal bars that were nearly parallel to the axis of the load in both the upper and lower portions of the hinge. Cracks first appeared at about ⅔ of the maximum load at the keyed joint. The ultimate loads were 443 000 lb. and 515 000 lb. for specimens 1D-1 and 1D-2, respectively.

Hinge 2D. The specimens of type 2D exhibited a general compression failure in the lower half of the specimen. There was no

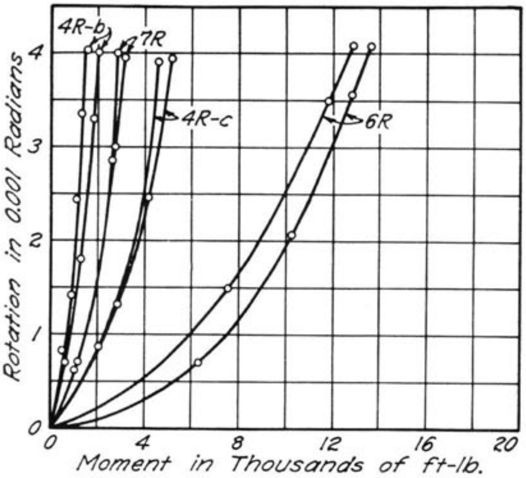

FIG. 14. RESISTANCE OF HINGES TO ANGULAR ROTATION

apparent damage to the lead joint. The ultimate loads were 416 000 and 390 000 lb. for specimens 2D-1 and 2D-2, respectively.

Hinge 4D-b. Buckling and bending of the exposed bars, accompanied by splitting of the concrete along the diagonal bars, occurred in type 4D-b at ultimate loads of 119 000 lb. and 115 000 lb. for specimens 4D-b1 and 4D-b2, respectively.

Hinge 4D-c. Specimens of type 4D-c failed by splitting of the concrete along the diagonal bars that were in the direction of the load, as shown in Fig. 13. The concrete covering the bars at the hinge, however, was intact. The ultimate loads were 220 000 lb. and 200 000 lb. for specimens 4D-c1 and 4D-c2, respectively.

Hinge 5D. The upper half of the first specimen of type 5D split diagonally above the corner of the upper bearing angle, the angle apparently acting as a wedge to cause the separation. The lower half of the hinge was intact. The companion specimen failed by a combination of crushing and splitting below the pivot angle in the lower half of the specimen, the upper half being intact. The ultimate loads were 180 000 lb. and 190 000 lb. for specimens 5D-1 and 5D-2, respectively.

Hinge 6D. The specimens of type 6D exhibited a typical diagonal tension failure at the reduced section of the hinge, as shown in Fig. 13, at ultimate loads of 220 000 lb. and 207 000 lb. for specimens 6D-1 and 6D-2, respectively.

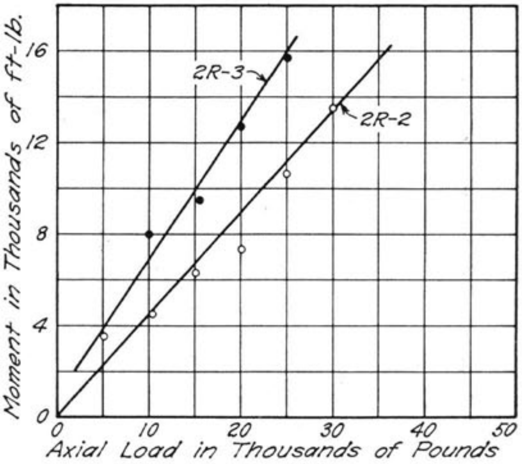

FIG. 15. RELATION BETWEEN AXIAL LOAD AND RESISTANCE TO INITIAL ROTATION OF HINGE TYPE 2

Hinge 7D. The failure of specimens of type 7D was caused by buckling of the vertical bars toward their unsupported side, that is, toward the side containing the felt filler, at the relatively low ultimate loads of 91 500 lb. and 90 000 lb. for specimens 7D-1 and 7D-2, respectively.

13. *Resistance of Hinges to Rotation.*—Moment–rotation curves plotted from data obtained from the tests described in Section 9 are given in Fig. 14 for types 4-b, 4-c, 6 and 7, and the relation between various axial loads and the moment required to overcome static friction in hinges of type 2 is shown in Fig. 15. In each case the data from tests of two specimens are plotted. Hinges of type 5 are not included, since they offer no resistance to rotation, type 3 was not tested, and type 1 was so rigid that the lever arms failed before any rotation was observed. In later tests of this hinge, in which rotation was forced by applying the load through tapered plates, it was necessary to exert a moment of approximately 25 000 ft. lb. in order to produce an angular movement of 0.004 radian. However, not until the base of the specimen was cracked and showed considerable evidence of splitting was there any appreciable rotation produced.

The friction characteristics of the two hinges of type 2 differ considerably, as might be expected, since it is difficult to reproduce the same surface conditions from one specimen to the next. A vertical axial load of 20 000 lb. over a length of 16 in. is probably a normal working load for this type of hinge, and for such a load the hinge can be expected to develop a resisting moment of from 10 000 to 12 000 ft. lb. before the static friction between the cylindrical surfaces is overcome to permit any rotation. Resistance to rotation of the other types of hinges, excluding types 1 and 5, range from about 1800 ft. lb. for type 4-b, to about 12 500 ft. lb. for type 6 for an angular movement of 0.004 radian. Expressed in other words, hinges of type 6 offer about seven times more resistance to an angular rotation of 0.004 radian than the more flexible hinges of type 4-b. However, the degree of flexibility loses its importance when one considers that the moment of 12 500 ft. lb. developed by the stiffest of these hinges is small compared to the moment required to maintain fixity at the bases of a rigid frame bridge.

All of the hinges tested for repeated rotation, namely types 4-b, 4-c, 6 and 7, withstood 10 000 repetitions of a cycle in which the hinge was rotated from +0.004 radian to −0.004 radian under one-third of its static load capacity without evidence of progressive failure, and the moment required to produce this rotation was not excessive, neither did it change materially.

14. *Strength of Hinges Subjected to Combined Load and Rotation.*—The ultimate strength of hinges subjected to a combination of vertical load and rotation, in the manner described in Section 9, is given in Table 2, and views of the specimens after failure are shown in Fig. 16. From a comparison of these values with those listed under vertical-load tests, it would appear that an angular rotation of 0.004 radian does not greatly affect the ultimate strength of such hinges when subjected to vertical loads. Except for hinges of type 2, the decrease in strength that can be attributed to the effect of rotation amounts to but 15 per cent at the most; and in several instances there appears to be no decrease. Although specimens of type 1 were somewhat damaged structurally due to rotation, they nevertheless developed about 90 per cent of the strength of similar specimens tested under vertical load without rotation. Failure occurred in the base of the specimen, as shown in Fig. 16(b). The hinges of type 2 showed a marked reduction in ultimate strength after they were rotated. The concrete failed in compression with no apparent damage to the lead plate. The hinges of type 4-c showed a reduction in strength of about 10 per cent, if a correction is made for variation in the strength of the concrete as given by control cylinders. Failure of these

rotated specimens was very similar to the failure of those subjected to the vertical-load tests, namely, by crushing of the concrete covering and buckling of the steel within the covering. The same type of hinge, except with the bars exposed, showed a decrease in ultimate strength of 15 per cent due to the rotation. Failure was due to yielding of the hinge bars accompanied by splitting of the concrete along their embedded length, as shown in Fig. 16(a). Specimens of type 6R developed approximately the same ultimate strength as specimens of type 6V although failure was due to flexure as well as direct load, the specimen failing in compression at the reentrant angle adjacent to the reduced section of the hinge. The manner of failure is shown in Fig. 16(a). The hinges of type 7 also showed approximately the same ultimate strength for both vertical-load and load–rotation tests, and both showed similar types of failure, namely, by yielding of the vertical bars.

15. *Effect of Plastic Yielding on Resistance of Hinge to Rotation.*—The effect of plastic yielding of the concrete in hinges of types 4-c and 6 on their moment resistance for a rotation of 0.004 radian is shown in Fig. 17. The moment decreased rapidly during the first 24 to 48 hours, then decreased less rapidly and finally became practically constant after 30 days. The total reduction in moment amounted to about 85 per cent for type 4-c and about 63 per cent for type 6. The residual moment of type 4-c after a 30-day period of plastic yielding was about one-third of the normal resisting moment developed by the same type of hinge except with exposed bars at the hinge opening. The reduction in moment of type 6 made its resistance to a sustained rotation of 0.004 radian after a period of 30 days about the same as that of type 4-c for an initial rotation of the same magnitude.

16. *Discussion of Results.*—Tests were made on a number of types of hinges to determine their relative merits, with the result that some proved to be of good design whereas others were deficient in some respects. Moreover, the manner of failure of some hinges indicated how the design could be changed so as to increase the quality of the hinge without adding greatly to its cost. The addition of ties around the diagonal bars of hinge types 1, 4-b and 4-c, between the bend and the hinge opening, as pointed out by other investigators, would be desirable. The placing of shear steel in the form of spirals is also recommended for hinges of type 6. Hinges of type 5 are simple to construct and permit of free rotation. The manner of failure of these

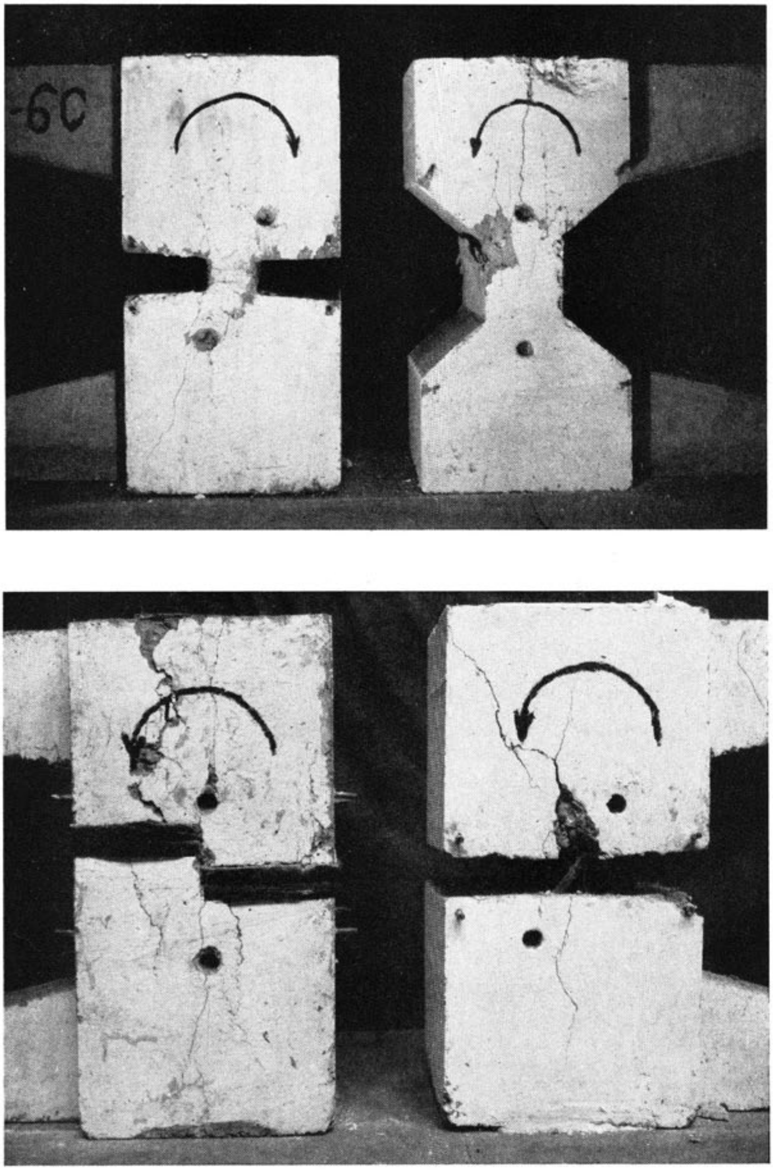

FIG. 16 (a) VIEWS OF HINGES AFTER LOAD–ROTATION TESTS TO FAILURE

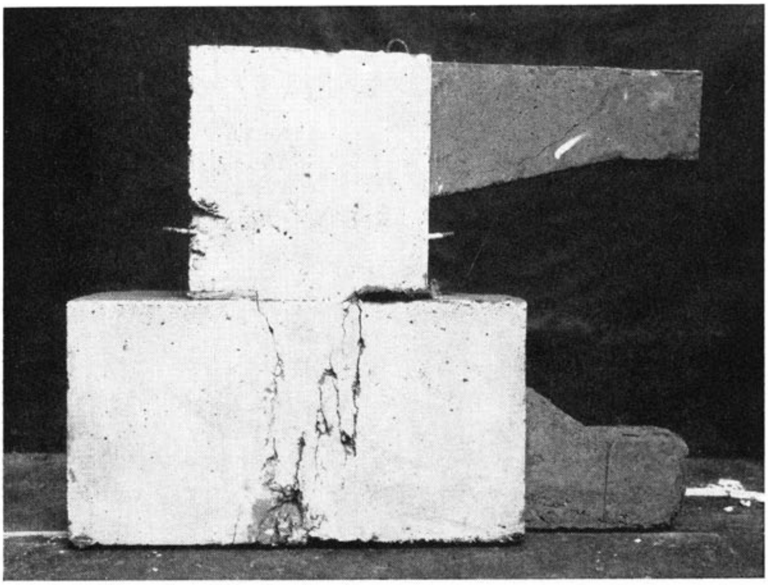

FIG. 16 (b) VIEW OF HINGE AFTER LOAD–ROTATION TEST TO FAILURE

hinges indicates that their strength would be increased by the use of transverse bars in back of the angles, or by other means of preventing the angle from splitting the concrete.

The hinges as designed developed strengths when tested under oblique loads that compare favorably with the strength required for the ordinary highway rigid frame bridge of medium spans. A study of rigid frame bridges designed for H-20 highway loading indicated probable maximum oblique thrusts at the hinged bases of these structures of 20 000 lb. to 60 000 lb. per foot of width for spans varying from 50 ft. to 100 ft. If a factor of safety of 3 is considered sufficient, all of the types tested, with the exception of 4-b and 7, would provide sufficient reserve strength under oblique loads to be considered adequate for spans up to possibly 70 ft., and with the suggested improvement in design they would be satisfactory for much greater spans. It should be noted that, except for hinges of type 4-b, the primary cause of failure of the hinge specimens tested under oblique loads was not over-stress in the steel bars, that is, yielding, so that a factor of safety is properly based on the ultimate strength.

The tests showed that the hinges had a greater resistance to vertical than to oblique loads. The thrust on the hinge of rigid

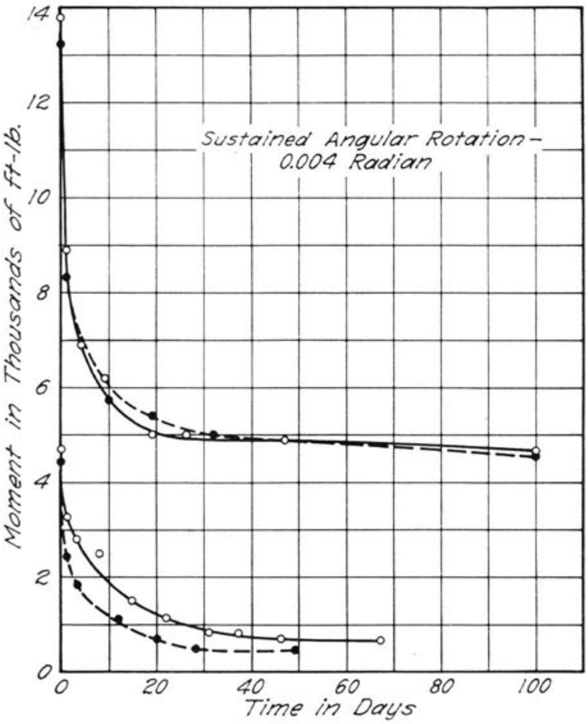

FIG. 17. REDUCTION OF RESISTING MOMENT DUE TO PLASTIC YIELDING—HINGE TYPES 4-C AND 6

frame bridges is oblique, but the angle between the two thrust lines, one for dead-load alone and the other for dead-load plus live-load, is not large. It would seem desirable, therefore, to decrease the angle between the thrust line and the axis of the greatest strength of the hinge by inclining the axis of the hinge in the actual structure. If this procedure were followed all of the hinges tested would have ample strength for the ordinary highway rigid frame bridge.

All of the hinges except type 1 were amply flexible to permit an angular rotation of as much as 0.004 radian. It is to be noted that the degree of flexibility of a hinge is not of so much importance as its ability to permit a given rotation without being structurally damaged. The flexural resistance of a hinge capable of a given angular rotation is in any case a small fraction of the flexural restraint necessary to prevent rotation at the bases of a rigid frame.

Probably about one-third of the total rotation at the hinges is due to changes in the length of the deck caused by shrinkage, the effects of which occur over a relatively long period of time. For those hinges in which concrete participates in the action of the hinge, plastic flow provides a large measure of relief from this rotation as well as that due to dead load, so that generally these hinges need only provide for a momentary rotation of about one-half to two-thirds of the maximum anticipated rotation. For a highway bridge of 50-foot span this amounts to about 0.0015 radian.*

V. Summary and Conclusions

17. *Conclusions.*—Definite conclusions cannot readily be drawn from tests of a limited scope such as reported in this bulletin. The principal value of these studies is in providing a basis for further detailed experimental studies of the various types of hinges tested. The results of the tests do, however, point out the most desirable types of hinges for a particular rigid frame bridge, and they suggest certain improvements in design.

The following statements briefly summarize the important results of these tests.

(1) The measured strength of hinges tested under a vertical axial load was as great as and in some cases materially greater than the computed maximum strengths.

(2) Of the hinges tested those of types 1, 2, 4-c, 5 and 6 developed ultimate strengths when tested under an oblique load that compare favorably, on the basis of a safety factor of 3 or more, with the load requirements of the ordinary rigid frame highway bridge of medium single spans. With certain improvements in the hinge details, including larger bar sizes, increased strengths can be expected.

(3) All of the hinges, with the exception of type 1, were sufficiently flexible to permit an angular rotation as large as 0.004 radian without causing structural damage to the hinge.

(4) There was no evidence of deterioration of the hinges tested under repeated rotation after 10 000 reversals of 0.004 radian angular movement.

(5) The ultimate strength of the hinges was not materially affected by combining a forced rotation of 0.004 radian with a vertical load.

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*See Bulletin No. 308, Part II, University of Illinois Engineering Experiment Station, Section 9, p. 37.

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