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16. ABSTRACT
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The most efficient method of anchor bolt installation tested utilized a metal canister filled with mortar and reinforced with hairpin tiebacks. A bolt deflection of 0.05 inches (1.27 mm) measured near the concrete surface was used as the governing criterion for establishing yield load levels. Design curves based on this criterion are presented for various parametric combinations.

From the tests performed it was determined that approximately 8 inches (203.2 mm) of edge distance is required to develop the ultimate shear strength of a 1-inch (25.4 mm) diameter A307 anchor bolt cast-in-place in nominally reinforced concrete; approximately 24 inches (609.6 mm) of edge distance would be required for a 2-inch (50.8-mm) diameter A307 bolt.

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Anchorages, anchor bolts, reinforced concrete, shear tests

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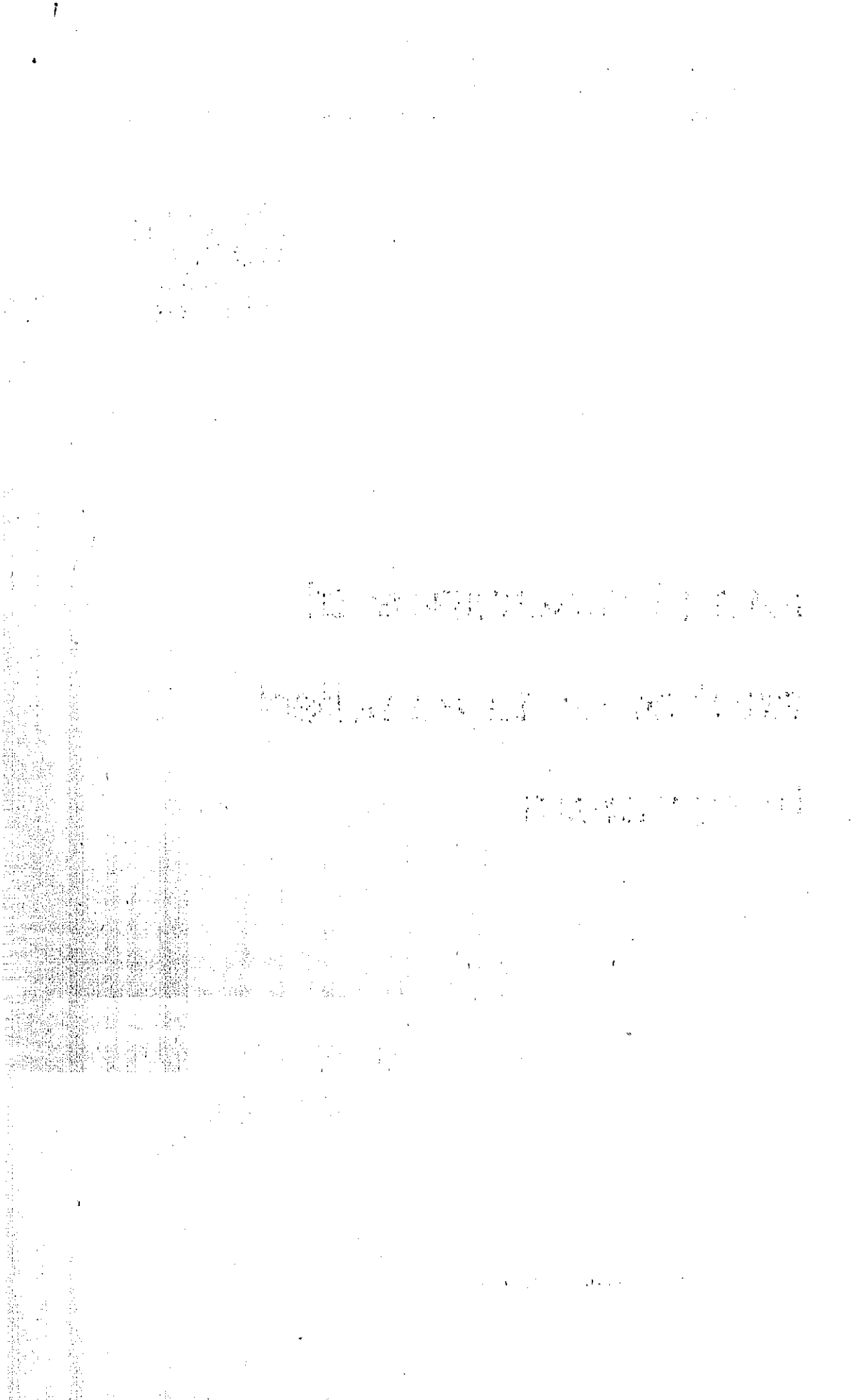

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8. p. 89, Appendix D-6: Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, and 40 to 20, 40, 60, and 80, respectively.

9. p. 90, Appendix D-7: Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, 40, and 50 to 20, 40, 60, 80, and 100 respectively.

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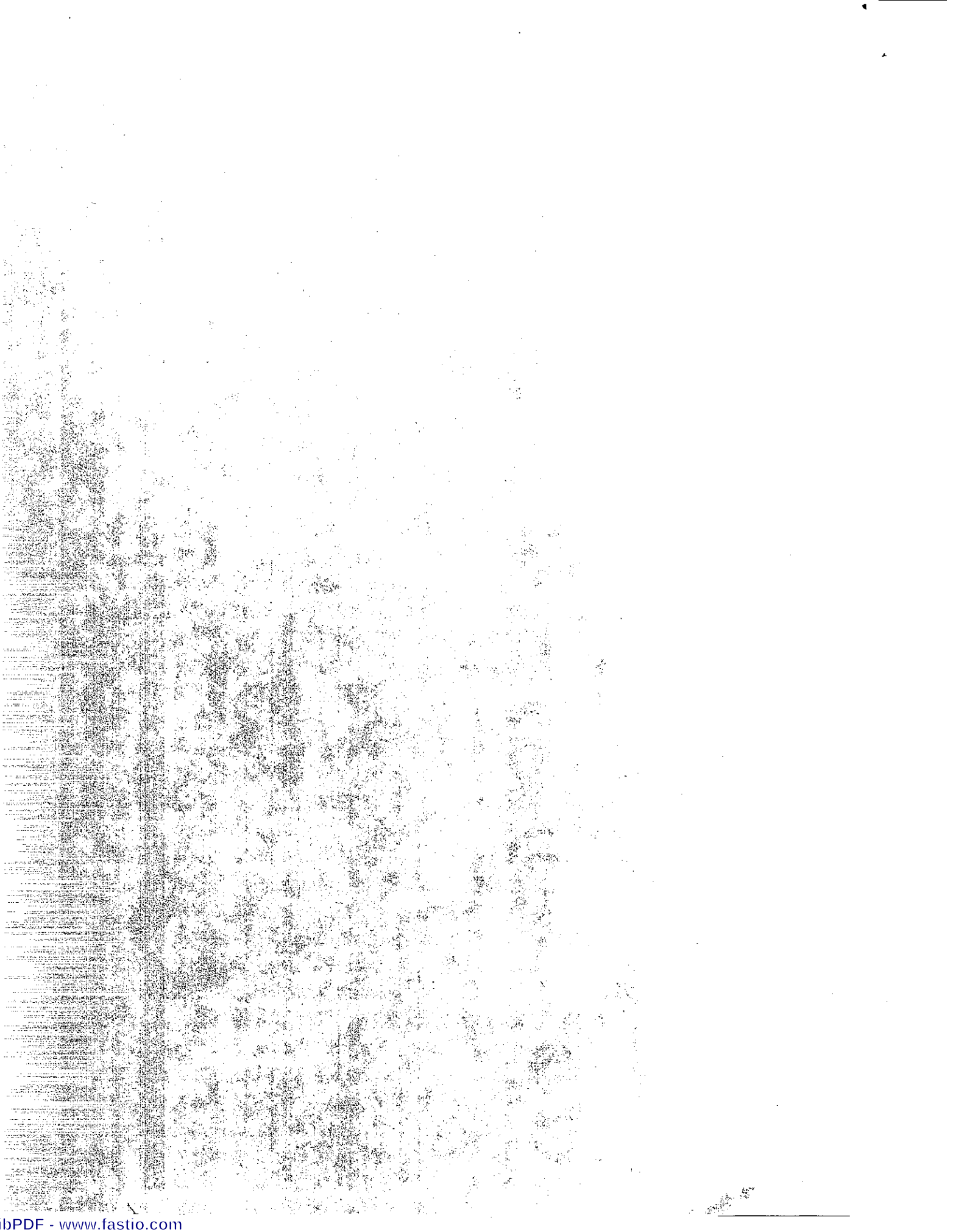

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5. p. 53, Figure 28:

a. Replace chart on graph with the following:

COMPARISON OF ULTIMATE LOADS, KIPS*			% INCREASE IN ULTIMATE LOAD CAPACITY	
Type of Bolt Installation				
Cast-in-Place	Cannister and Mortar			
without hairpins	without hairpins	with hairpins	② to ③	① to ③
25.8 ①	34.6 ②	86.2 ③	149	234
*Note: All concrete specimens contained nominal reinforcing steel.				

b. Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, 40, and 50 to 20, 40, 60, 80, and 100, respectively.

6. p. 54, Figure 29:

a. Replace chart at top of graph with the following:

COMPARISON OF ULTIMATE LOADS, KIPS*			% INCREASE IN ULTIMATE LOAD CAPACITY	
Type of Bolt Installation				
Cast-in-Place	Cannister and Mortar			
without hairpins	without hairpins	with hairpins	② to ③	① to ③
57.6 ①	62.4 ②	91.5 ③	47	59
*Note: All concrete specimens contained nominal reinforcing steel.				

b. Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, 40 and 50 to 20, 40, 60, 80, and 100, respectively.

7. p. 57, Figure 31: Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, and 40 to 20, 40, 60, and 80, respectively.

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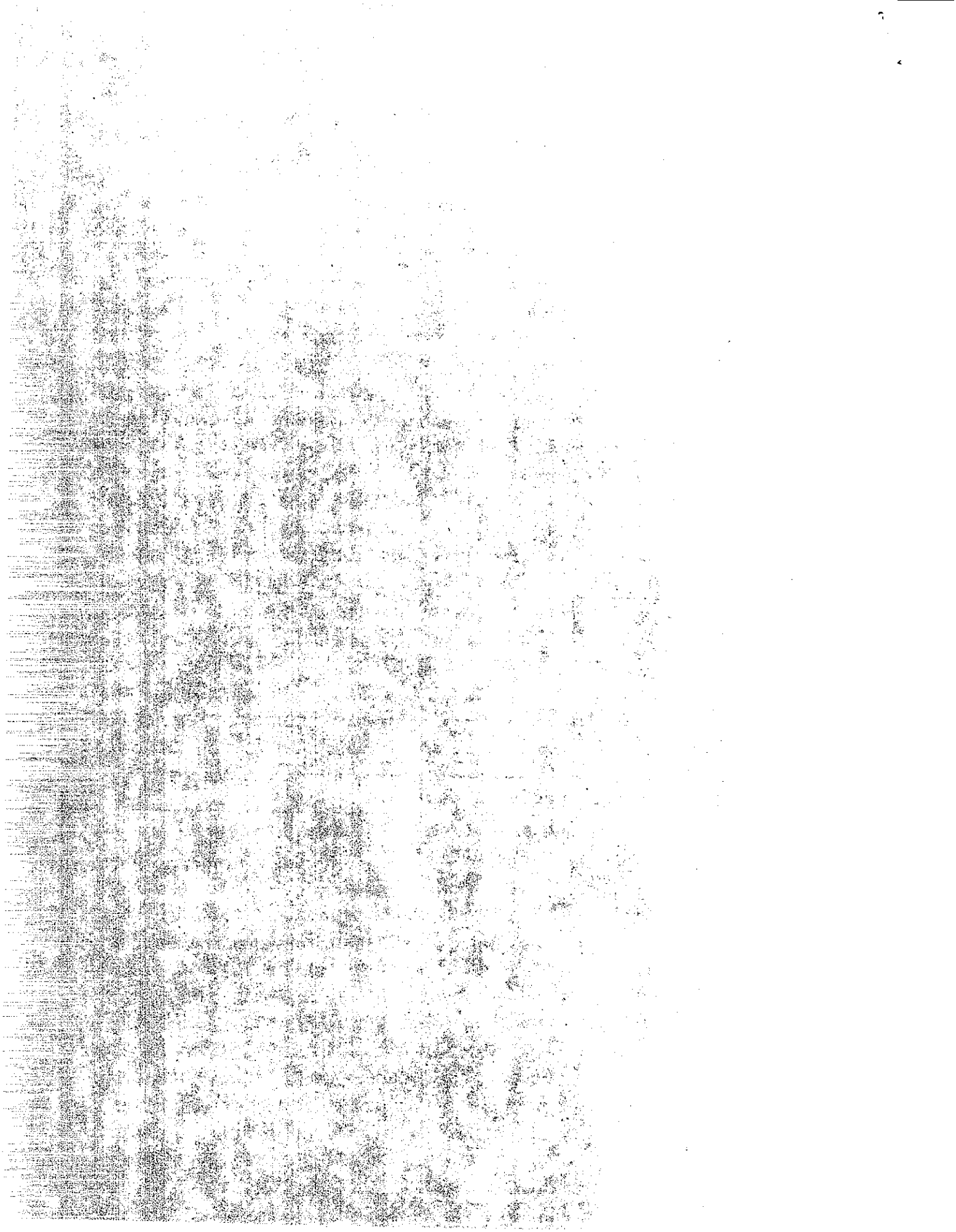

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1. p. 42, Figure 21:

   a. Change values shown on the ordinate scale, "Approved Load, Kips", from 10 and 20 to 20 and 40 respectively.

   b. Interchange entire description of curve on graph marked "Cast-in-Place" (dashed lines) with that labeled "5" Ø Cannister & Mortar".

2. p. 43, Figure 22: Change values shown on the ordinate scale, "Applied Load, Kips", from 10, 20, 30, and 40 to 20, 40, 60, and 80 respectively.

3. p. 45, Figure 23: Change ultimate load average of Cannister and Mortar installation with nominal reinforcing (without hairpins) from 18.6^{k} to 18.1^{k}.

4. p. 52, Figure 27: Replace chart on graph with the following:

COMPARISON OF ULTIMATE LOADS, KIPS*			% INCREASE IN ULTIMATE LOAD CAPACITY	
Type of Bolt Installation				
Cast-in-Place	Cannister and Mortar			
without hairpins	without hairpins	with hairpins	② to ③	① to ③
13.6 ①	18.1 ②	38.4 ③	112	182
*Note: All concrete specimens contained nominal reinforcing steel.				

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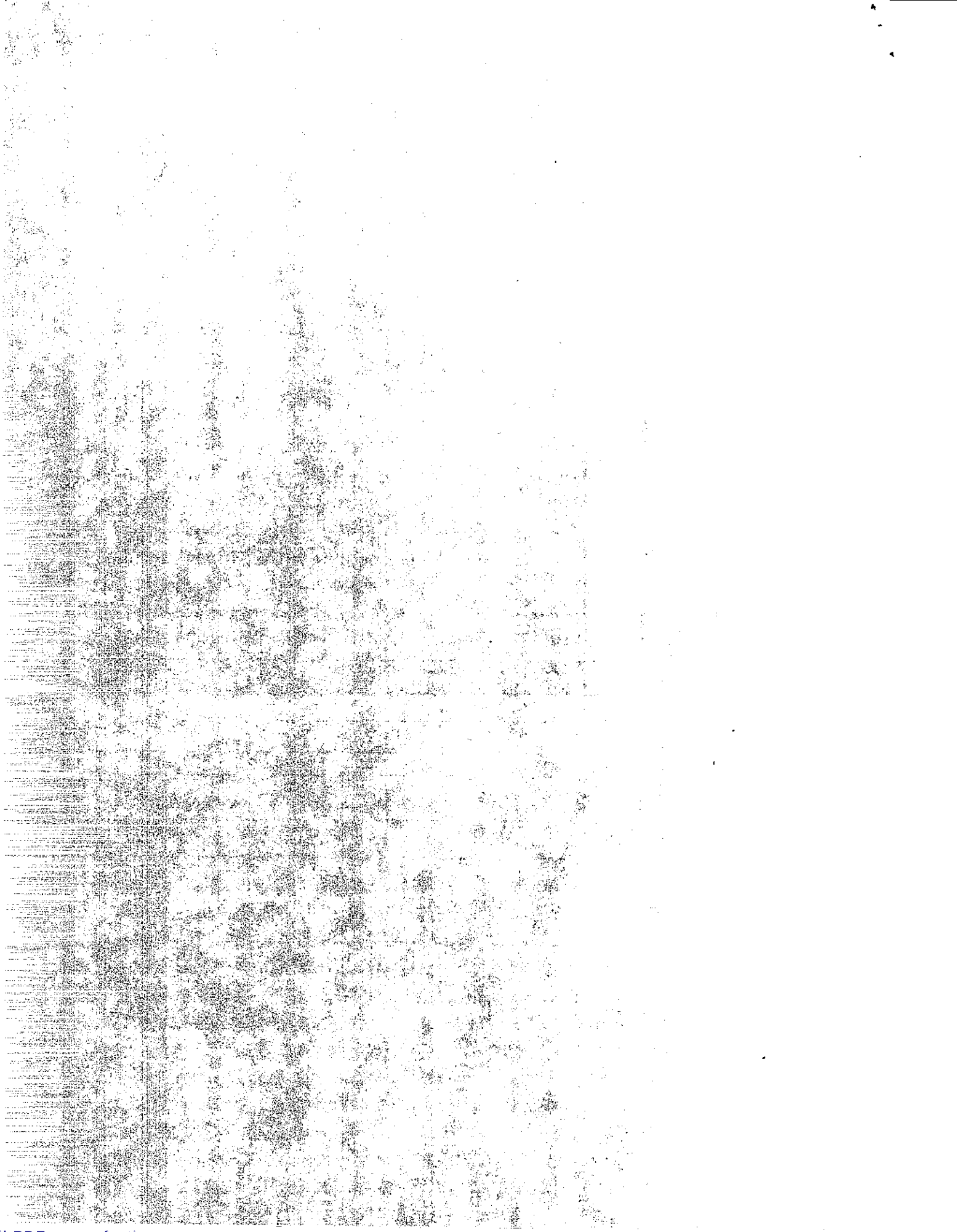

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From the tests performed it was determined that approximately 8 inches (203.2 mm) of edge distance is required to develop the ultimate shear strength of a 1-inch (25.4 mm) diameter A307 anchor bolt cast-in-place in nominally reinforced concrete; approximately 24 inches (609.6 mm) of edge distance would be required for a 2-inch (50.8-mm) diameter A307 bolt.

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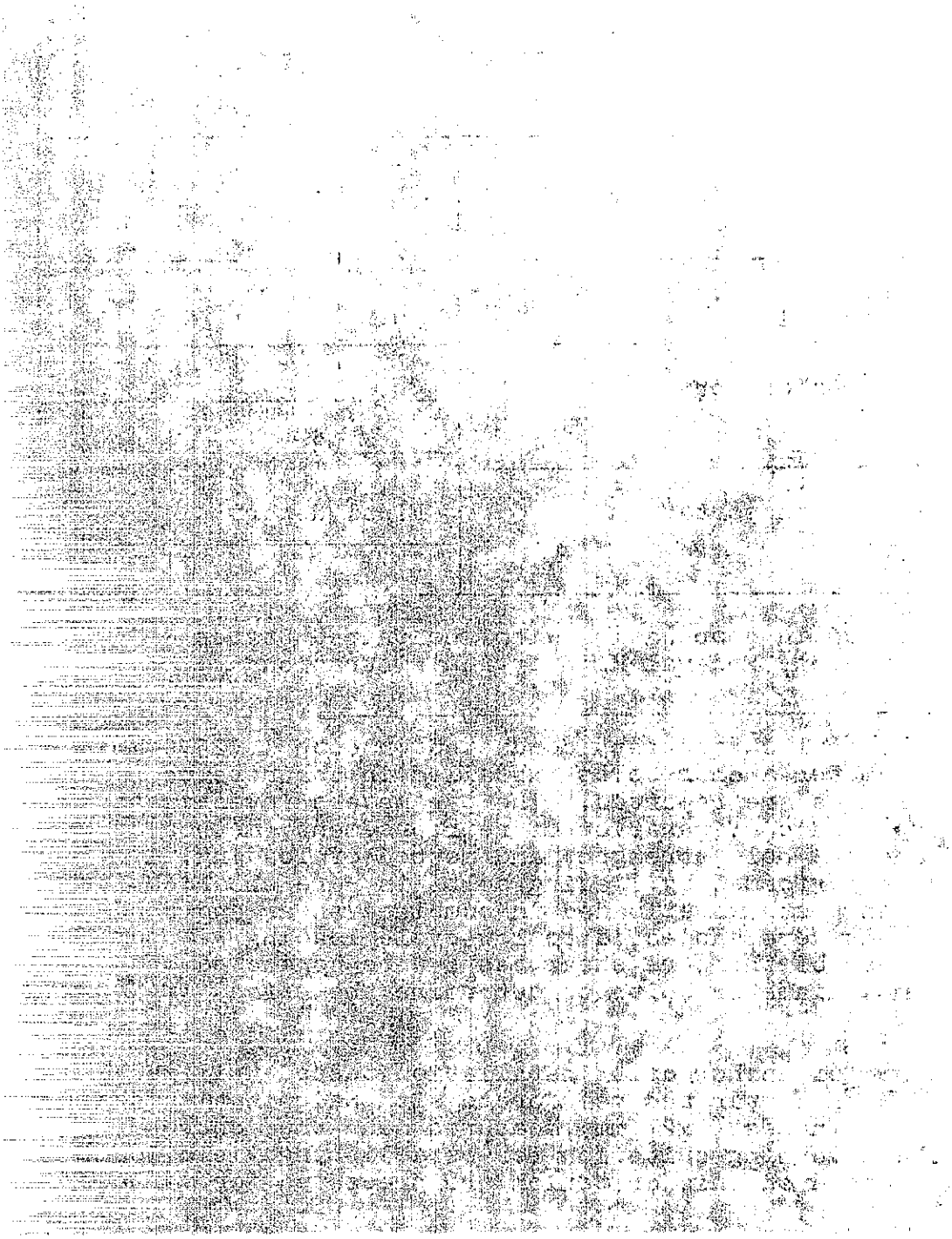

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IMPLEMENTATION STATEMENT

The results of the anchor bolt research have been implemented during the research as tests were completed and recommendations were made. Designers are now using increased edge distances and specifying hook bars anchored back into the concrete. Standard anchor bolt details for steel bearings and railings have been revised and are shown in Volume IV, Bridge Planning and Design Manual.

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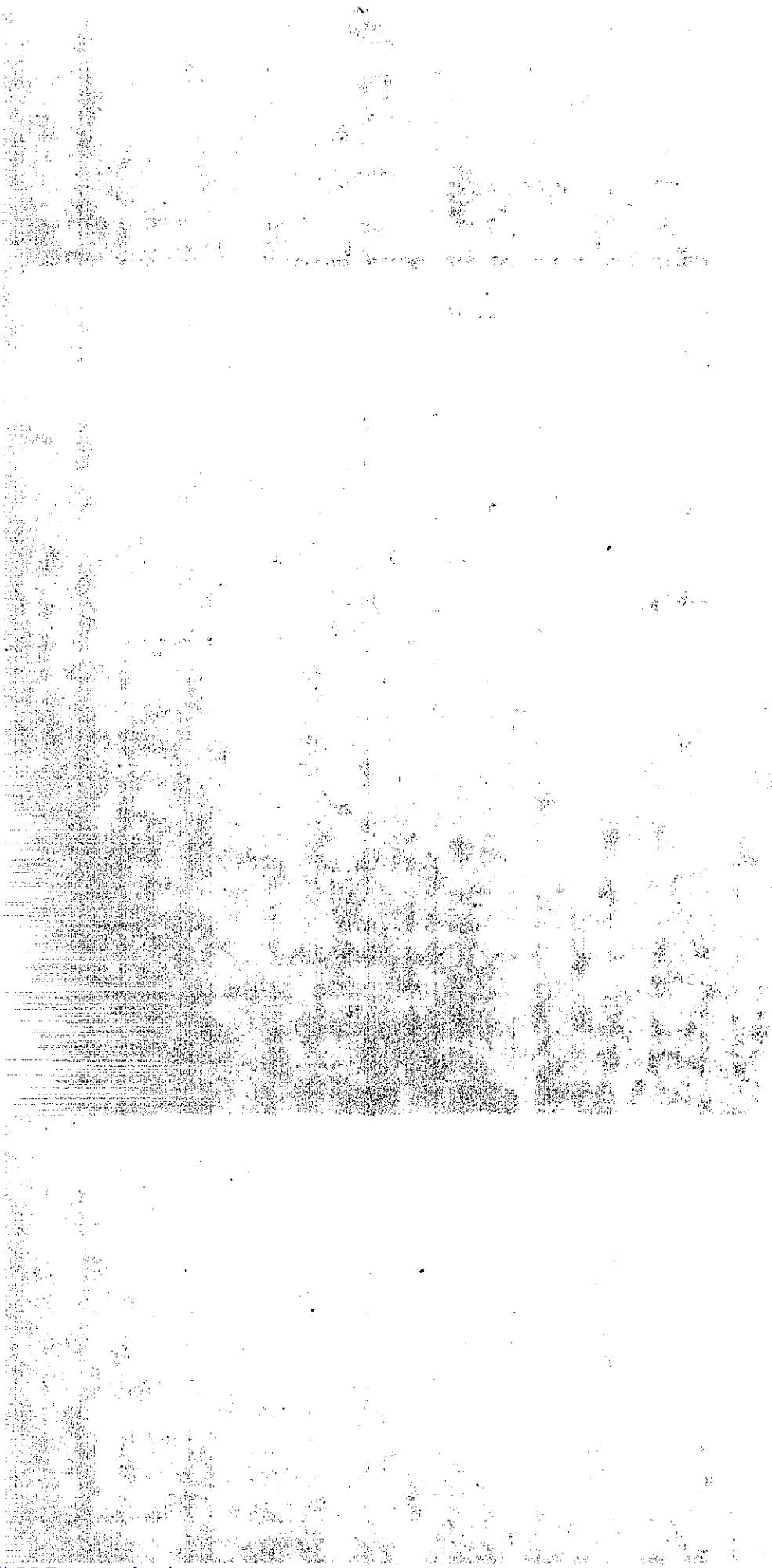

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The investigators wish to express their appreciation for the able assistance provided by the following staff members of the Transportation Laboratory in conducting this test program:

Floyd Martin.....Fabrication of Test Fixtures and Preparation of Specimens

Richard Johnson.....Instrumentation and Data Acquisition
Stanley Law

Dave Wong.....Concrete Strength Data

Richard Blunden.....Specimen Construction and Testing
Vince Martin

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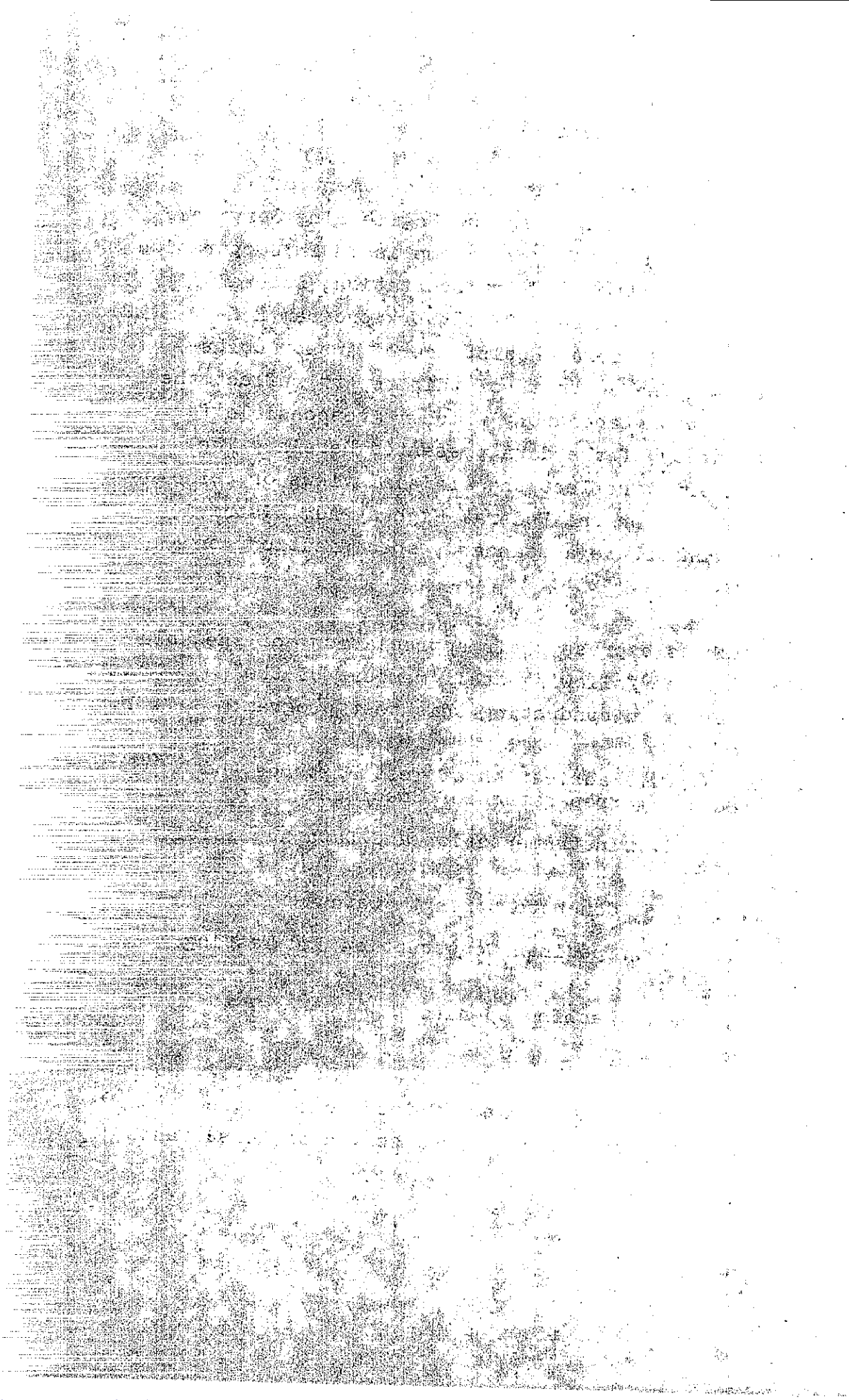

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I. INTRODUCTION

The increased lateral design forces which have been used in California bridge design since the 1971 San Fernando earthquake have intensified interest in developing realistic values for the lateral resistance of anchor bolts cast in concrete at superstructure to substructure connections as shown in Figure 1. It has been general practice to assume that the lateral resistance provided by these bolts was governed by the allowable shear stress for the type of bolt being used. Another assumption has been that all the bolts at a given bearing assembly participated equally in resisting applied loads. Actually, one or more bolts may be loaded to near failure before the remaining bolts come into bearing in the over-sized bolt holes normally found in the masonry plate of the bearing assembly as shown in Figure 2.

The Division of Structures and Engineering Services, Office of Project Development of the California Department of Transportation initiated this research project in order to determine the actual load carrying capabilities of bearing assembly connections on existing structures and to develop more efficient designs for inclusion in new bridges.

Both 1 (25.4-mm) and 2-inch (50.8-mm) diameter bolts were selected for testing as they are representative of the sizes normally called for in bearing assembly applications. All bolts were embedded a distance of ten bolt diameters into normally reinforced concrete blocks.

Four loading conditions were used: static shear loads, cyclic shear loads, static combined shear and bending moment loads, and cyclic combined shear and bending moment loads as shown in Figure 3. The bolt installations reflected various design parameters.

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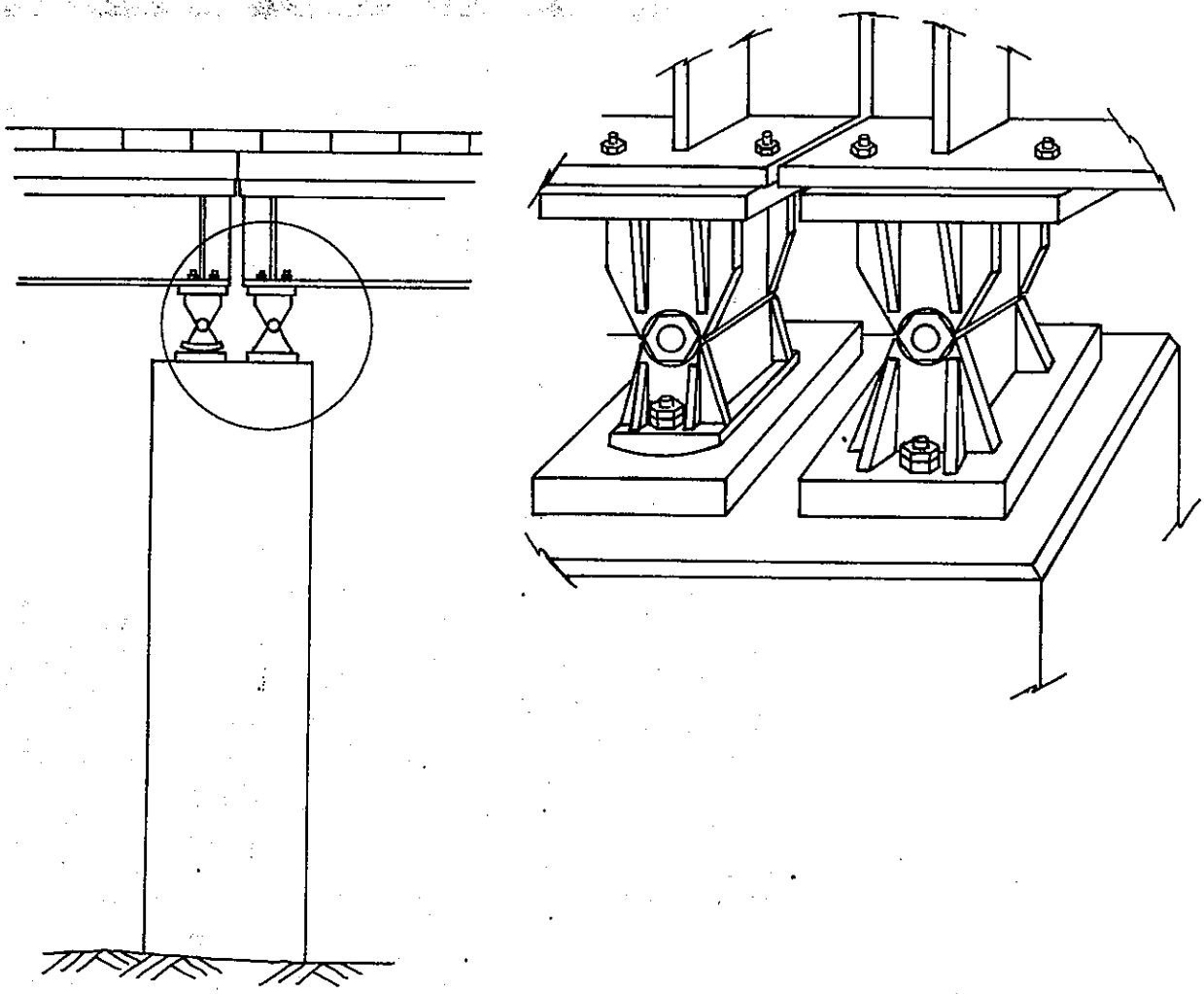

Figure 1. Typical bridge superstructure to substructure connection using anchor bolts.

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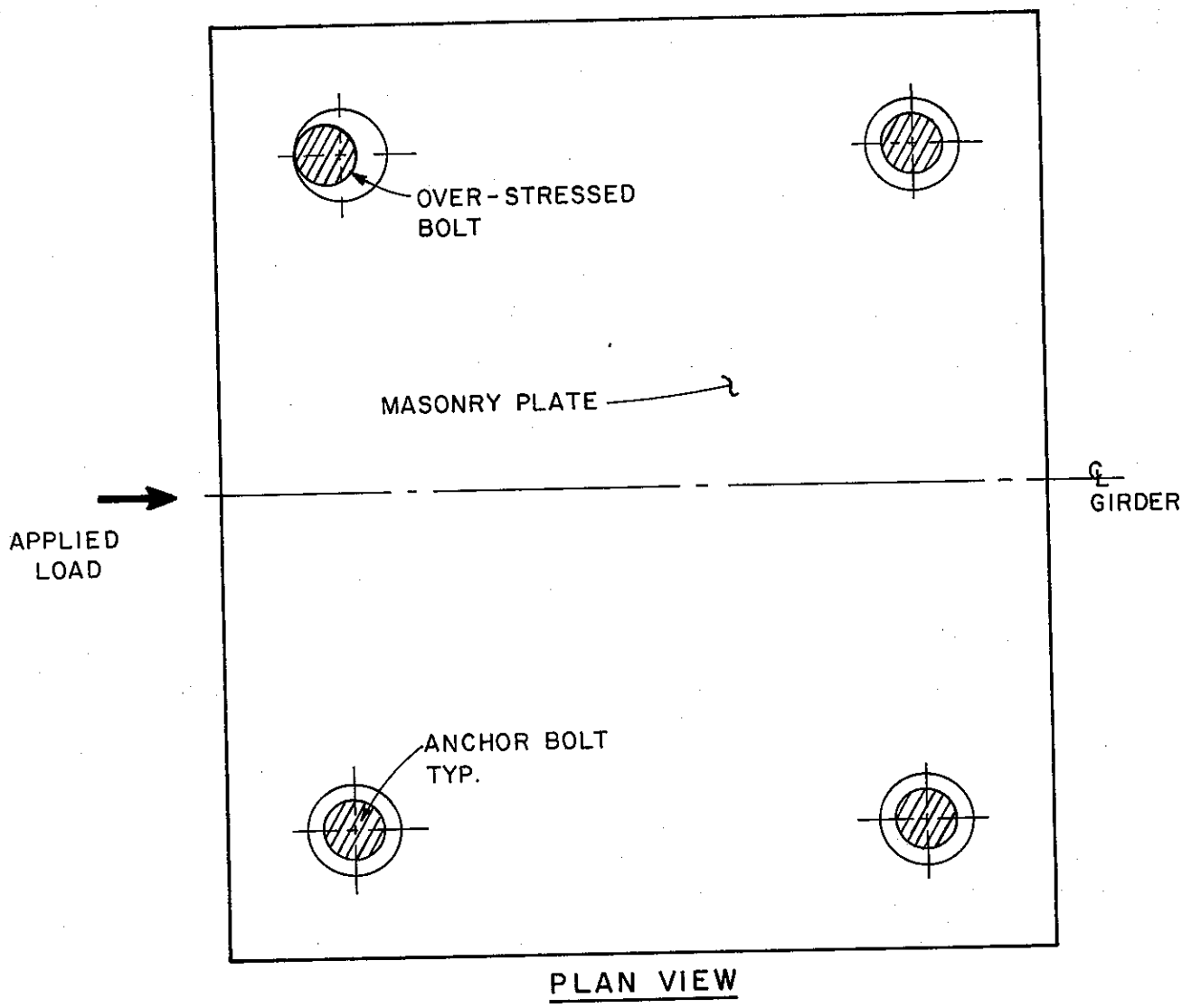

Figure 2. Relative masonry plate and anchor bolt positions which can lead to an overstressed anchor bolt.

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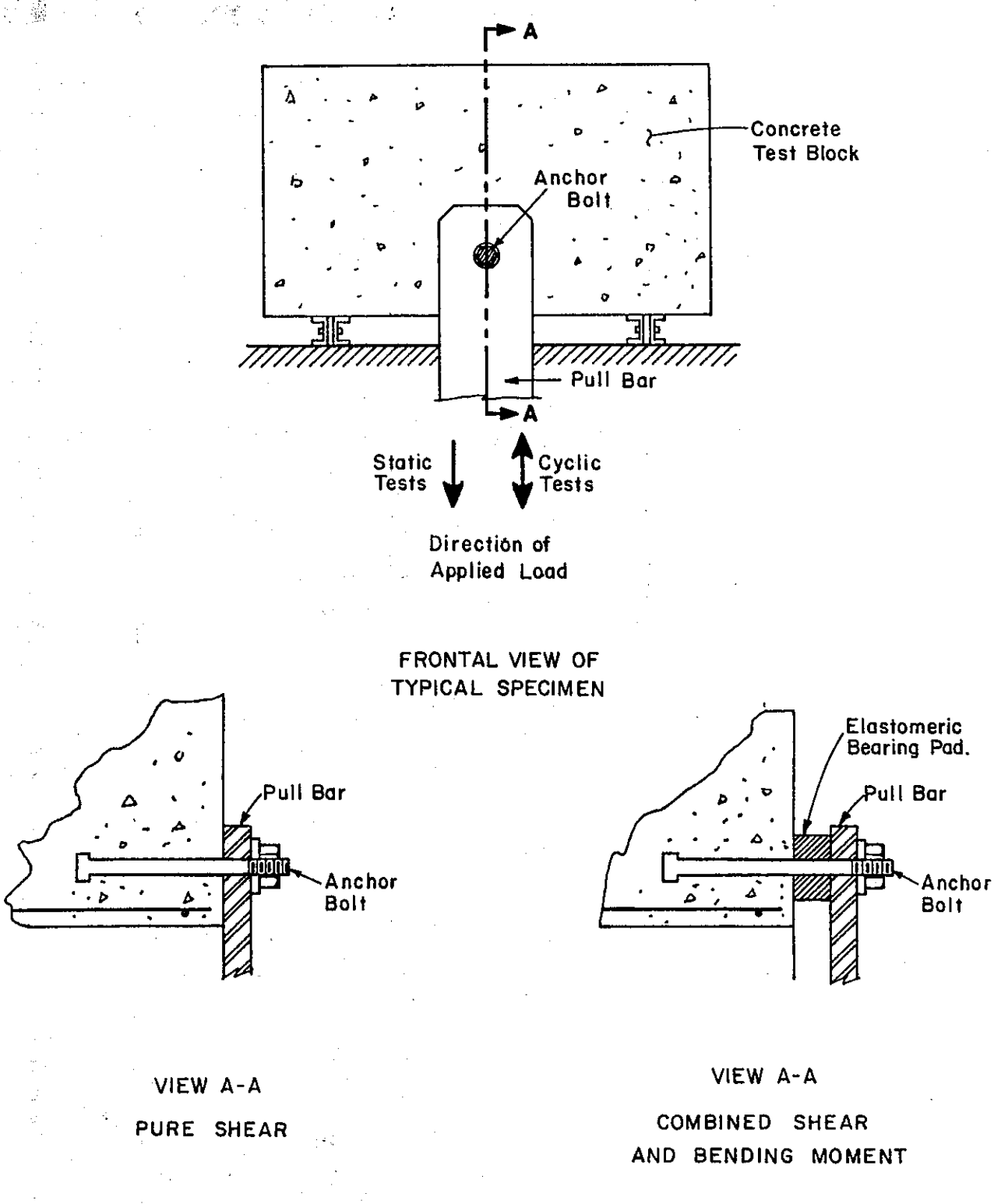

Figure 3. Types of loading used to determine lateral resistance.

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Significant parameters were:

1. Anchor bolt diameter: 1 (25.4 mm) and 2 inches (50.8 mm).

2. Type of steel in anchor bolt: mild (ASTM A307) and high-strength (ASTM A449).

3. Number of bolts: single and pair.

4. Method of bolt installation: Cast-in-place, cannister and mortar, and drilled hole and epoxy.

5. Edge distance of anchor bolts: 4 (101.6 mm) 6, (152.4 mm) 8 (203.2 mm) and 12 inches (304.8 mm) - distance from bolt center to nearest concrete face.

6. Reinforcement: nominal with and without hairpin tie-back.

To determine the effects of these variables, specimens were instrumented to measure applied load and bolt deflection. The ultimate load achieved for a given set of parameters, together with the corresponding load-deflection curve, formed the basis for evaluation.

Specimen fabrication and testing were performed by personnel at the Transportation Laboratory of the California Department of Transportation (Caltrans) in Sacramento. Design engineers from the Office of Project Development of Caltrans served as consultants.

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II. CONCLUSIONS

The lateral resistance characteristics of the various anchor bolt systems tested in shear are summarized quantitatively in Figures 4, 5, and 6. In Figure 4, lateral loads at which an anchor bolt deflection of 0.05 inches (1.27 mm) occurs have been plotted for the bolt edge distances considered; this deflection criterion was chosen in an attempt to select one best single deflection value at which yielding of the bolt/concrete system takes place. By using this 0.05-inch (1.27-mm) deflection value, a "yield" point or upper elastic limit was established up to which a linear elastic behavior could be anticipated. By studying load/deflection curves of a specific system under consideration within this report, a designer may find slightly higher or lower "yield" loads to be appropriate and may want to change allowable loads accordingly. The ultimate loads obtained from these tests have similarly been compared in Figure 5. Figure 6 compares the ultimate load capacity of a group of bolts as compared to a single bolt, dependent upon the spacing between bolts and the edge distance.

The following conclusions, both quantitative and qualitative, are intended to point out trends in the data which would be of particular interest to designers. These conclusions are drawn from average test results obtained from duplicate specimens. Where large discrepancies in test results occurred for specimen pairs, a third test was conducted.

1. For cast-in-place (CIP) installations with nominal reinforcement, where the edge distance is equal to or less than that required to develop ultimate bolt shear strength, both the load that produces 0.05 inches (1.27 mm) of deflection (hence forth called 0.05-inch (1.27-mm) load) and the ultimate load attained are proportional to edge distance. For 1-inch (25.4-mm) and 2-inch (50.8-mm)

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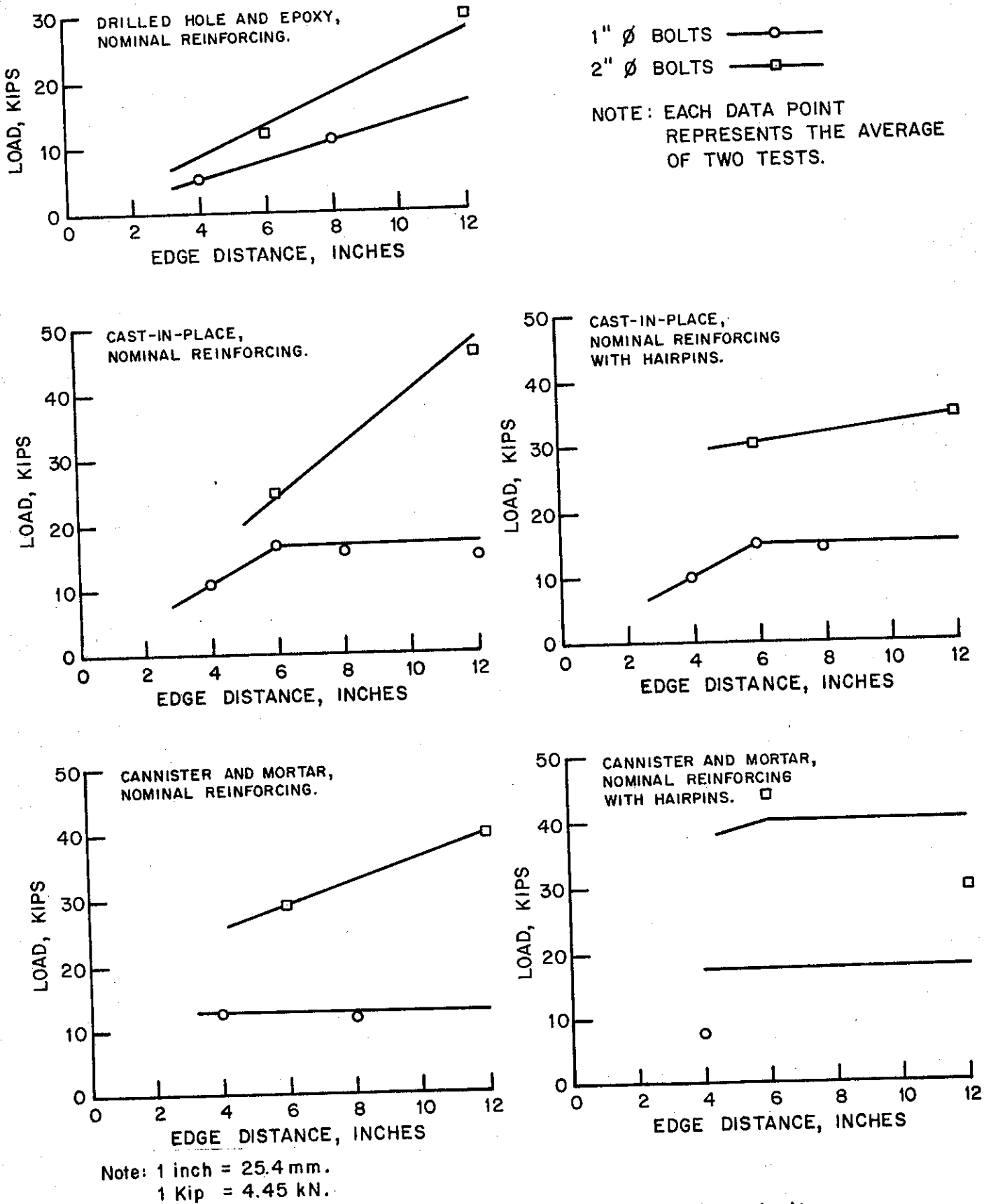

Figure 4. Lateral load resistance of anchor bolts at bolt deflections of 0.05 inches.

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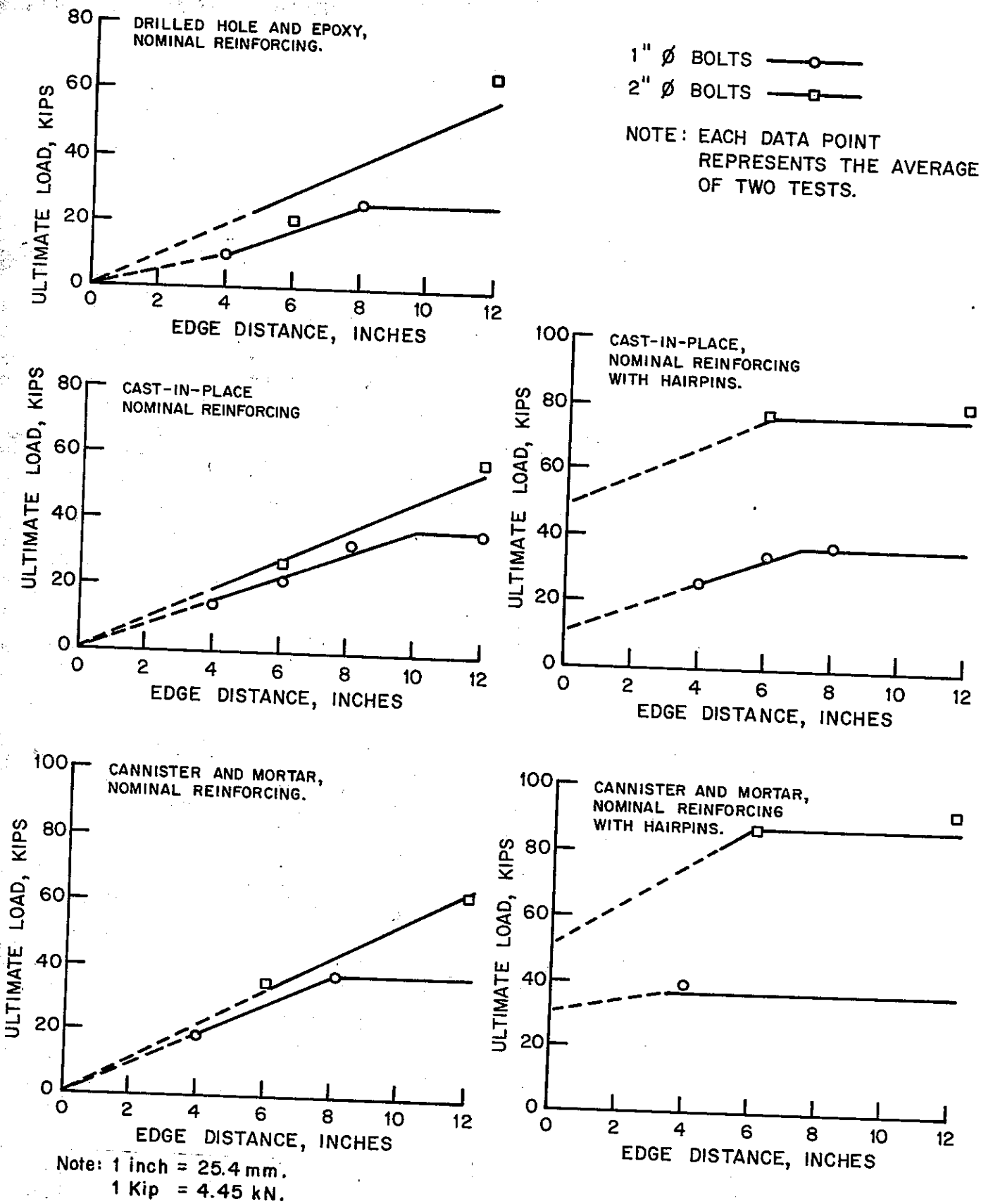

Figure 5. Ultimate lateral load resistance of various anchor bolt schemes tested in shear.

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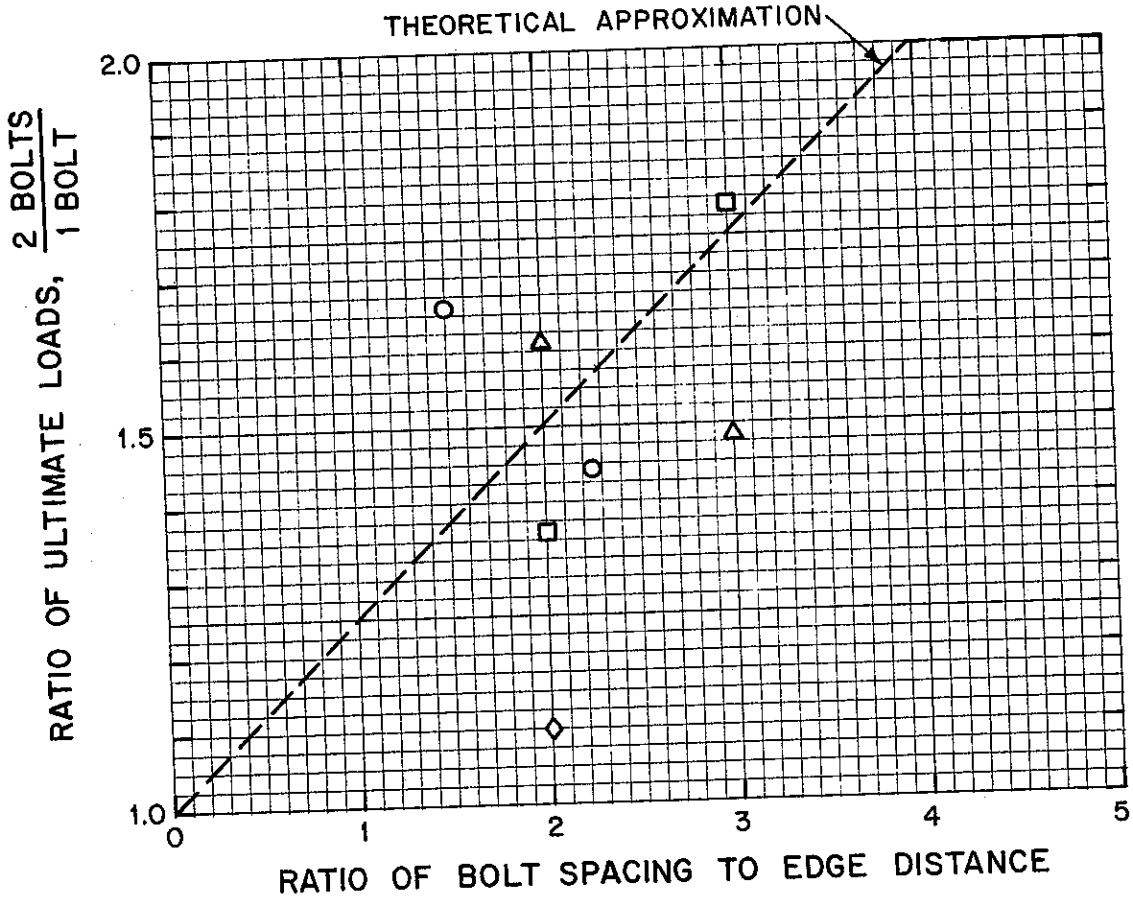

SYMBOL	SPACING	EDGE DISTANCE	TYPE OF REINFORCEMENT
□	12", 18"	6"	NOMINAL
◇	16"	8"	NOMINAL
△	12", 18"	6"	NOMINAL WITH HAIRPINS
○	12", 18"	8"	NOMINAL WITH HAIRPINS

NOTE: EACH DATA POINT REPRESENTS AN AVERAGE OF TWO TESTS.

1 inch = 25.4 mm.

Figure 6. Relationship between ultimate load ratio of pairs of bolts to single bolts and spacing/edge distance ratio for one-inch diameter anchor bolts.

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diameter bolts conforming to ASTM Designation: A307 the theoretical edge distances required to develop the minimum ultimate shear strength of the bolts are 8 inches (203.2 mm) and 24 inches (609.6 mm) respectively.

2. Epoxied installations offer slightly less desirable lateral resistance characteristics than CIP installations. Because of the relative flexibility of the epoxy and the reduction in bending stiffness due to the threading of the bolts for their full length as used in this study, the anchor bolt apparently tends to concentrate more stress near the top surface of the concrete leading to concrete failure at lower applied loads.

3. In general at small deflections, bolt systems employing the cannister and mortar installation methods do not provide as much lateral load resistance as with cast-in-place installations. At deflections greater than 0.2 inches (5.1 mm), however, cannister and mortar installations offer slightly improved ultimate lateral resistance characteristics over CIP installations because the effective bearing area of the bolt is increased.

4. The use of hairpin reinforcement around a CIP bolt can change the 0.05-inch (1.27-mm) load significantly, depending upon bolt diameter and edge distance, but more importantly increases system ductility and ultimate load substantially regardless of bolt diameter or edge distance.

5. Of all the bolt systems tested, the cannister and mortar installations tied back by hairpin reinforcement offered the most desirable lateral resistance characteristics with regard to ultimate load and system ductility.

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6. The use of a high-strength bolt has little effect upon lateral resistance unless the bolt is supported such that the shear strength of a mild steel bolt would be exceeded.

7. Although group action test data is limited, Figure 6 provides an approximation of the combined effects of bolt spacing and edge distance on lateral resistance. As can be noted, the combined load resistance of an anchor bolt pair is less than the sum of the individual bolt capacities if the spacing perpendicular to the loading direction is less than approximately 4 times the minimum edge distance.

8. Combined loading (shear and bending), as was expected, produced substantially less lateral resistance at 0.05-inch (1.27-mm) loads and significantly greater deflections at a given shear stress level, particularly for the smaller diameter bolts.

9. Low cycle loadings with maximum loads less than 0.05-inch (1.27-mm) loads shown in Figure 4 have no significant effect upon the lateral resistance. At higher load levels, the cyclic loads tend to disintegrate the concrete and thus reduce the ultimate lateral load resistance and ductility of the system.

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III. RECOMMENDATIONS

Based on the scope and findings of this study, it is recommended that:

1. The curves presented in Figure 4 be used when selecting allowable lateral loads for anchor bolts. These curves are based on the lateral load which produces a bolt deflection at the surface of the concrete of 0.05 inches, (1.27 mm) as used herein to define the "yield" load. An appropriate factor of safety would be used with these "yield" loads for working stress level design.

2. The cannister and mortar method of anchor bolt installation with hairpin tie-back reinforcement be used whenever large lateral resistance is required. This method also provides for adjustment of the anchor bolts to fit the holes in the bearing plates.

3. Hairpin reinforcement be used whenever anchor bolt edge distances are minimal, or whenever the design loads require the use of 2-inch (50.8-mm) or larger anchor bolts. Based on the test results obtained during this study, the following design details for hairpins are suggested as minimums:

   a. Use #4 Grade 60 reinforcing steel for 1-inch (25.4-mm) A307 bolts either cast-in-place or installed with mortar in cannisters and for 1-inch (25.4-mm) A449 bolts cast-in-place.

   b. Use #5 Grade 60 reinforcing steel for 1-inch (25.4-mm) A449 bolts installed with mortar in cannisters and for 2-inch (50.8-mm) A307 bolts cast-in-place.

   c. Use #6 Grade 60 reinforcing steel for 2-inch (50.8-mm) A449 bolts cast-in-place and for 2-inch (50.8-mm) A307 bolts installed with mortar in cannisters.

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d. The hairpins should be bent to the minimum radius as specified for Grade 60 steel in the provisions of the Building Code Requirements for Reinforced Concrete of The American Concrete Institute for stirrups and ties, or to fit the diameter of the cannister where said radius would be larger. The included angle of the hairpins should be approximately 60°.

e. The distance from the end of the hairpin to the center-line of the bolt should be that required to develop the strength of the reinforcing steel in bond.

f. The bolt or the cannister should be in direct contact with the interior bend of the hairpin reinforcement.

g. A minimum of two hairpins should be placed around each anchor bolt with the upper and lower hairpins located 2 inches and 8 inches below the bearing surface of the concrete respectively.

h. Additional reinforcement located across the potential failure planes of the concrete may be considered where edge distances, bolt spacings, loads, etc. may dictate larger restraint than can be offered by hairpin reinforcement alone.

4. The following areas are recommended for any future research on the lateral resistance of anchor bolts:

a. Cyclic loading tests with complete stress reversal.

b. Impact loading tests.

c. Further experimentation with various reinforcement schemes.

d. Further group action tests.

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IV. DESCRIPTION OF EXPERIMENTAL PROGRAM

A. Testing Program

The most critical location for an anchor bolt is near the edge or corner of a column or abutment. The concrete in this area generally is laterally unrestrained except for nominal reinforcement, such as #4 reinforcing bar spaced at 18 inches (457.2 mm). To simulate lateral loading conditions on anchor bolts at this location in an actual structure, a testing program was conducted in which a total of 92 lateral shear tests was performed. In this testing program, individual 1-inch (25.4-mm) and 2-inch (50.8-mm) diameter bolts and pairs of 1-inch (25.4-mm) diameter bolts were installed in concrete blocks and loaded laterally with a pull bar in a 1 million-pound (4.45-MN) capacity testing machine, as shown in Figure 7.

The purpose of this program was to determine allowable design loads for anchor bolts from lateral loads recorded during shear tests, and the amount of ductility available in each system tested. The complete testing program summary is shown in Figures 8A and 8B. Important parameters considered in the testing program include:

- Bolt diameter: 1 (25.4 mm) and 2 inches (50.8 mm).
- Type of steel in anchor bolts: mild (ASTM A307) and high-strength (ASTM A449).
- Edge distance of anchor bolts: 4 (101.6 mm), 6 (152.4 mm), 8 (203.2 mm), and 12 inches (304.8 mm).
- Method of loading:

  1. static shear loading
  2. static combined shear and bending moment loading

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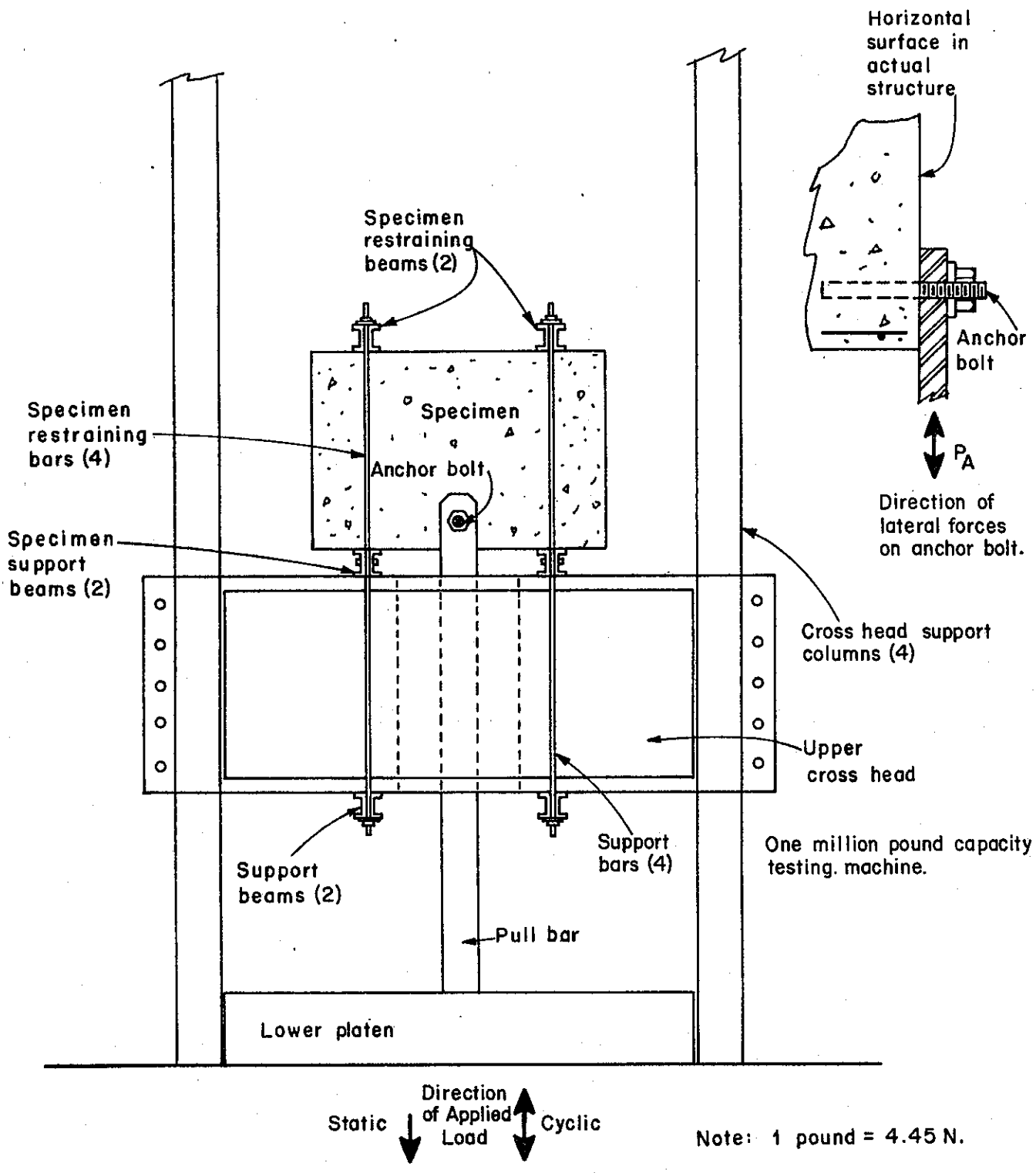

Figure 7. Test set-up.

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BOLT DIAMETER	EDGE DISTANCE	TYPE OF LOADING*				
INSTALLATION:		CAST - IN - PLACE		CANNISTER AND MORTAR		DRILLED HOLE AND EPOXY
REINFORCEMENT:		NOMINAL	NOMINAL WITH HAIRPIN	NOMINAL	NOMINAL WITH HAIRPIN	NOMINAL
1"	4"	↗ (3) ↗ (2) (W/STIRRUPS)	↗ (6)	↗ (2)	↗ (3)	↗ (2)
	6"	↗ (6) ↗ (2) ↗ (2)	↗ (2) ↗ (2) ↗ (4) ↗ (2)			
	8"	↗ (2)	↗ (2)	↗ (2)		↗ (2)
	12"	↗ (2)				
2"	6"	↗ (2)	↗ (4) ↗ (2) ↗ (4) ↗ (2)	↗ (2)	↗ (2)	↗ (2)
	12"	↗ (2)	↗ (2)	↗ (2)	↗ (2)	↗ (2)

* ↗ STATIC SHEAR LOAD (MILD STEEL BOLTS)

↗ CYCLIC SHEAR LOAD (MILD STEEL BOLTS)

↗ STATIC COMBINED SHEAR & MOMENT (MILD & HIGH-STRENGTH BOLTS)

↗ CYCLIC COMBINED SHEAR & MOMENT (HIGH-STRENGTH BOLTS ONLY)

(2) NUMBER OF SPECIMENS TESTED

NOTE: SEE APPENDIX A FOR COMPLETE SPECIMEN LISTING.
TOTAL NUMBER OF SINGLE ANCHOR BOLTS TESTED WAS 78.
1 inch = 25.4 mm.

Figure 8A. Summary of testing program for single anchor bolts.

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Edge Distance (inches)	Spacing (inches)	Type of Reinforcement	
		Nominal	Nominal with Hairpins
6	12	(2)	(2)
6	18	(2)	(2)
8	12		(2)
8	16	(2)	
8	18		(2)

NOTE: 1. Total number of tests on bolt pairs is 14.

2. All specimens loaded in pure shear.

3. (2) Number of specimens tested

4. 1 inch = 25.4 mm.

Figure 8B. Testing program summary for pairs of one-inch diameter, cast-in-place anchor bolts.

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3. cyclic shear loading
4. cyclic combined shear and bending moment loading (see Section IV.D.2 for complete explanation)

- Method of bolt installation:

1. cast-in-place
2. cannister and mortar
3. drilled hole and epoxy

- Method of concrete reinforcement

1. nominal
2. nominal with hairpins

As shown in Appendix C-1, the spacing of the support beams on which each concrete specimen was placed, was varied according to the anchor bolt diameter and the distance from the bolt center to the concrete face, so that 30° failure planes could result. This is further discussed in Section V.D of this report. Edge distance as used in this study is defined as the distance from the center of the bolt to the face of the concrete regardless of method of installation. The load on anchor bolts which were tested in static shear was applied at a rate of 4 kips (17.79 kN) per minute. Some of the specimens were subjected to cyclic loading at a low frequency in an effort to determine residual strength.

The objective of tests conducted on pairs of 1-inch (25.4-mm) diameter mild steel bolts was to determine the effect of bolt spacing at various edge distances upon the ultimate loads attainable, and to compare lateral resistance attained with that of single or isolated bolts.

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B. Test Specimens

1. Design

All anchor bolts tested were embedded in reinforced concrete blocks a distance of 10 bolt diameters using installation methods shown in Figure 9. Individual block dimensions and anchor bolt positions are shown in Appendix B for each test series 1 through 6. All concrete blocks were designed so that the width and breadth of each block would be adequate (1) to insure sufficient bearing area when positioned on "I" beams of the testing apparatus (see Appendix C-1), and (2) to prevent significant anchor bolt movement via beam action or bending of the concrete block while testing.

2. Materials

The concrete and steel reinforcement used in the fabrication of the test specimens were of the same type and quality normally used for bridge construction in California. A concrete mix containing six sacks (255.8 kg) of Type II modified portland cement and having a water-cement ratio of 0.50 and a maximum aggregate size of 1 inch (25.4 mm) was used. The aggregate was a typically rounded, river run material from the American River near Sacramento and would be considered of better than average quality. This mix produced an average compressive strength, on days when anchor bolt lateral load tests were conducted, of 4200 pounds per square inch (28.96 MPa) as determined from compressive strength tests of concrete cylinders made from the same batch of concrete mix as were each of the test blocks. The median specimen age was 15 days at the time of testing with an average age of 18 days. Average slump and unit weight were 3 inches (76.2 mm) and 151 pounds per cubic foot (2.42 Mg/m^3) respectively. Average air content was 1.3 percent.

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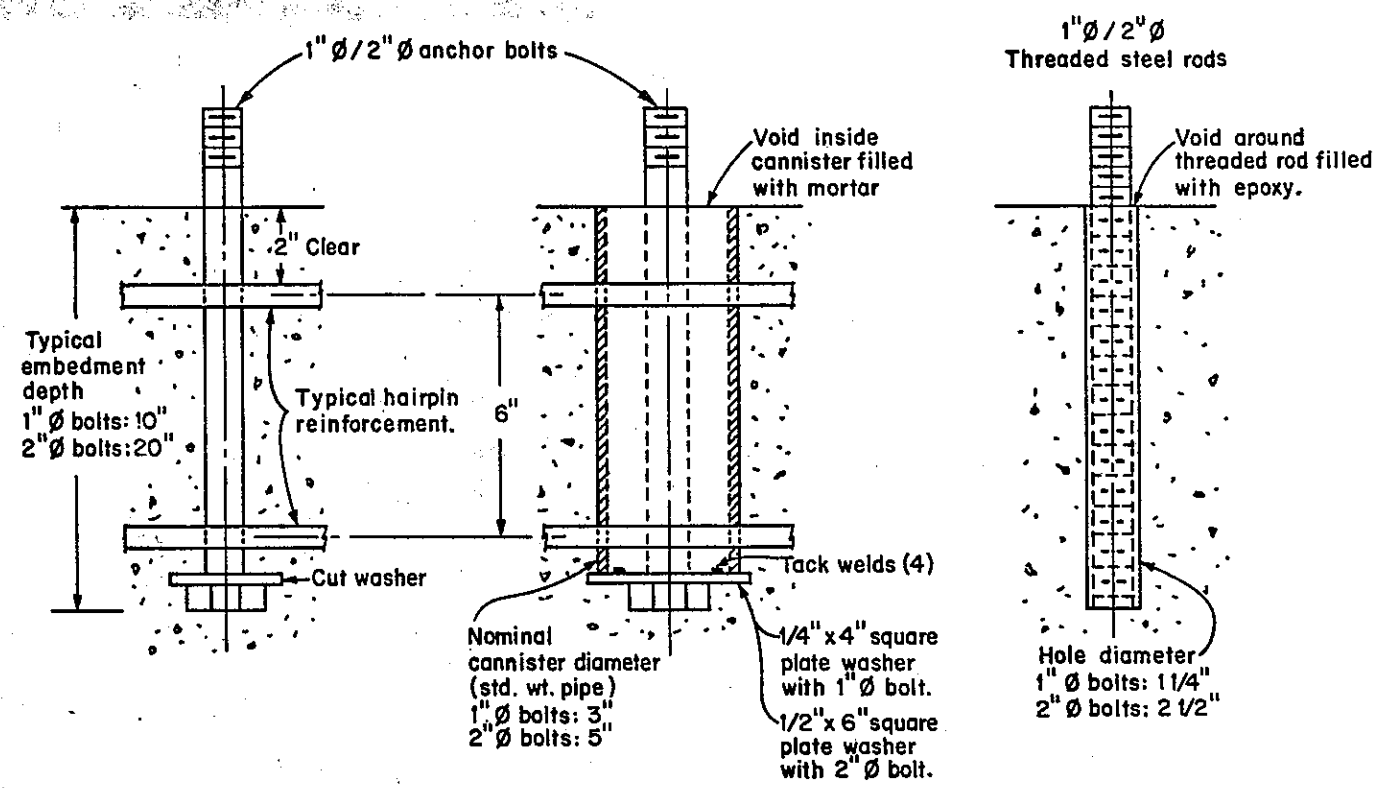
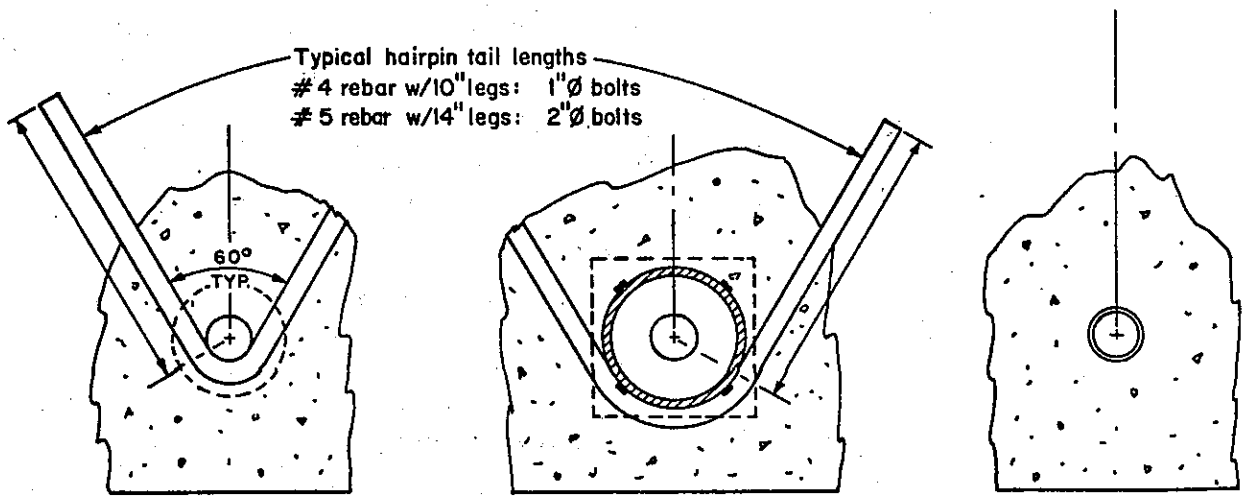


ELEVATION VIEWS



PLAN VIEWS

Note: 1 inch = 25.4 mm.

Figure 9. Anchor bolt installation methods.

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Concrete reinforcement consisted of Grade 60 deformed steel reinforcing bars conforming to ASTM Designation: A615. The test bolts conformed to ASTM Designations: A307 and A449 for mild steel and high-strength bolts respectively. Bolts for the drilled hole and epoxy specimens were A307 bolts threaded for their full length. All other bolts were threaded in a manner to exclude threads from within the body of the concrete and from the region of shearing stresses.

Standard weight pipe was used for the cannister and mortar installations; 3-inch diameter pipe (88.9-mm O.D. and 5.49-mm wall thickness) was used for 1-inch (25.4-mm) bolts and 5-inch diameter (141.3-mm O.D. and 6.55-mm wall thickness) pipe for the 2-inch (50.8-mm) bolts. Square plate washers were tack welded to the bottom of the pipe cannisters; 4-inch x 1/4-inch (101.6-mm x 6.35-mm) washers were used on the 3-inch (88.9-mm O.D.) pipe, and 6-inch x 1/2-inch (152.4-mm x 12.7-mm) washers for the 5-inch (141.3-mm O.D.) pipe. One part of Type II portland cement to 3 parts of sand was used for the mortar.

The epoxy used for the drilled hole and epoxy specimens conformed to California State Specification 721-80-28, a low viscosity liquid polysulfide extended epoxy. Drilled holes, 1 1/4 inches (31.75 mm) in diameter, were used for the 1-inch (25.4-mm) bolts, and 2 1/2-inch (63.5-mm) diameter drilled holes for the 2-inch (50.8-mm) bolts.

3. Fabrication and Curing

Since it was desired to simulate actual construction conditions, the specimens were cast with the test bolts in a vertical position. Field construction techniques and methods were closely followed in the fabrication of the test specimens. The exposed surface (top) of the concrete blocks containing the anchor bolts was

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cured with a chlorinated rubber curing compound applied shortly after placing the concrete. After a minimum curing period of 5 days the plywood side forms were stripped.

C. Test Apparatus

1. Equipment and Fixtures

The specimens were loaded to failure on a 1 million-pound (4.45-MN) capacity, electro-hydraulic, universal testing machine with cyclic loading capabilities. The remote console of the testing machine could be programmed for various loading schedules. A custom loading frame was required to support the test specimen on the upper cross-head of the test machine and to resist overturning moments as shown in Figure 7. An adjustable pull bar was designed and built for the tests performed on pairs of 1-inch (25.4-mm) diameter bolts and is shown in Figure 10.

2. Instrumentation

Instrumentation consisted of a single displacement potentiometer mounted on the concrete block to measure lateral bolt deflection up to 1 1/2 inches (38.1 mm) and the load cell in the test machine to measure the applied load. A typical potentiometer set-up is shown in Figure 11 along with probe locations for the various tests. An "X-Y" plotter provided in-progress visual monitoring of the behavior of a given bolt under load as well as a permanent record of the actual load and deflection.

D. Test Procedure

The earliest date that a specimen could be tested was determined from the results of concrete compressive strength tests performed on concrete cylinders molded on the day of specimen fabrication.

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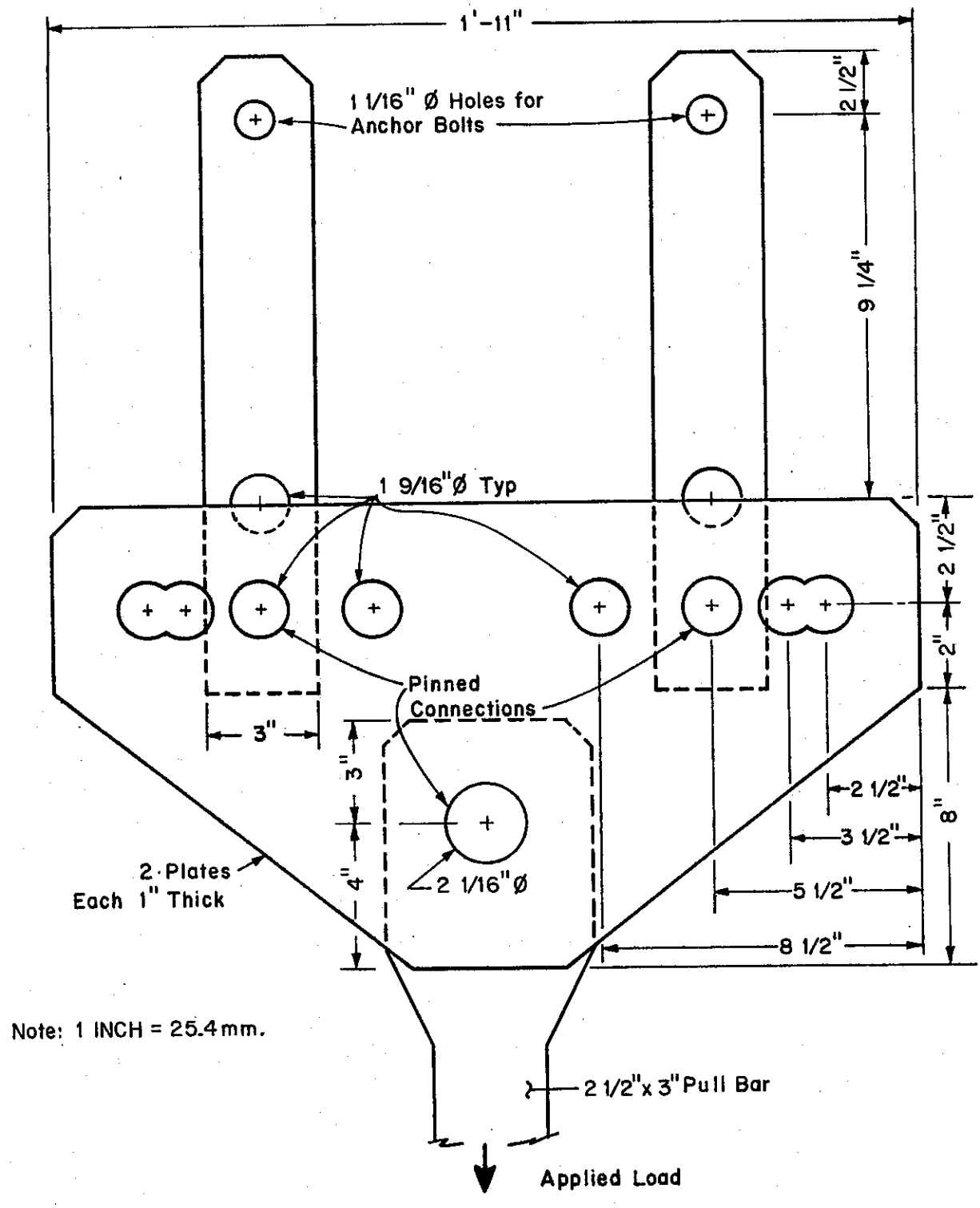

Figure 10. Pull bar assembly for tests on one-inch diameter bolt pairs.

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The required minimum strength was established as 4000 pounds per square inch (27.58 MPa). At the beginning of a test series a minimum of three cylinders were tested to verify that the required strength had been attained.

1. Test Installation Procedures

The specimen support beams as shown in Figure 7 were positioned and secured to the upper crosshead of the test machine to provide the required clear span distance as shown in Appendix C-1. The concrete block containing the anchor bolt to be tested was then centered and lowered onto the support beams. The pull bar, loosely attached to the anchor bolt at this stage, passed through the well in the upper crosshead into the grip-jaws of the loading platen below. After the pull bar was gripped and a nominal 250-pound (1.11-kN) preload was applied, the bar was secured with a nut on the anchor bolt. The specimen restraining beams were then connected to the support beams. The displacement potentiometer was next installed and aligned. With the 250-pound (1.11-kN) preload applied, the potentiometer was set at zero.

2. Loading Procedures

a. General - The four methods of load application used for the shear tests on individual bolts were static shear, cyclic shear, combined shear and bending moment, and cyclic combined shear and bending moment. All tests on pairs of bolts were statically run. Loading was continued until the anchor bolt(s) had sheared or the concrete had cracked severely, regardless of method of load application.

b. Procedure for Static Tests - A ramp function was used for the static tests. The load was applied at a constant

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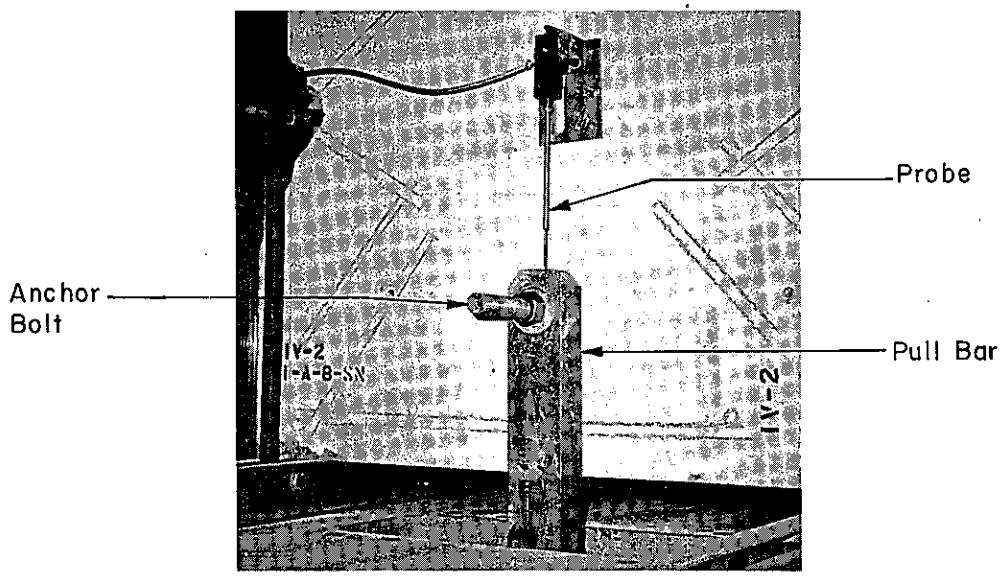
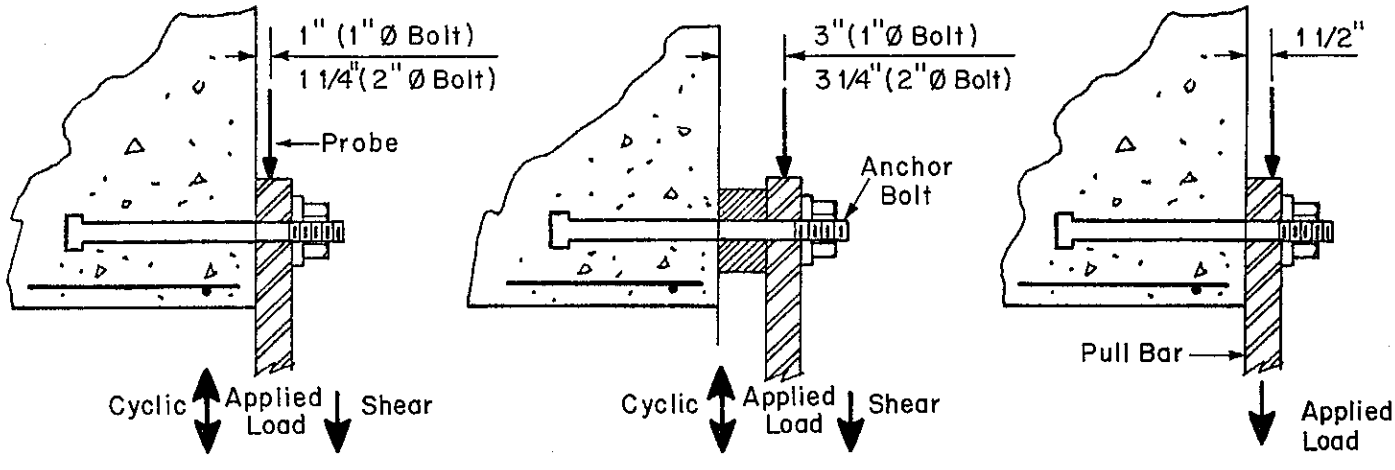


FRONTAL VIEW



SINGLE BOLT SHEAR LOADING

SINGLE BOLT COMBINED SHEAR AND BENDING MOMENT LOADING

BOLT PAIR STATIC SHEAR LOADING

SIDE VIEWS

Note: 1 inch = 25.4 mm.

Figure 11. Locations of displacement potentiometer probes.

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rate of 4 kips (17.79 kN) per minute to failure. The X-Y plotter provided a continuous record of load and deflection up to 1 1/2 (38.1 mm) inches of deflection.

c. Procedure for Cyclic Tests - Ten specimens (both 1 (25.4-mm) and 2-inch (50.8-mm) diameter bolts), representing 5 combinations of the various parameters were subjected to cyclic loading. The loading schedule for these specimens is tabulated in Figures 12 and 13. The cyclic load was applied sinusoidally between nominally 0 kips and predetermined maximums for nine of the specimens. The remaining specimen was cycled sinusoidally between two pre-selected positive loads.

The loading procedure used was as follows: A predetermined load was applied statically with the X-Y plotter in operation. Upon the attainment of this load, the plotter was placed on stand-by. The specimen was then cycled. At the completion of cycling the load was maintained at the predetermined maximum static load. Load and deflection were recorded at this point. Next, the applied load was diminished to nominal zero. The X-Y plotter was then reactivated for subsequent static loading up to the next higher load. A similar procedure was followed for each subsequent load range shown in Figures 12 and 13. When it became obvious that the bolt-concrete system was yielding, the above procedure was terminated and load was increased statically until specimen failure.

E. Data Reduction Procedures

The raw data consisted of load-deflection curves (up to 1 1/2 inches (38.1 mm) of bolt deflection) from a recording X-Y plotter, and a manually recorded maximum load read-out from the test machine console. The applied external load at the time of initial

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Anchor Identification No.	Load Ranges (Kips)	No. of Cycles	Frequency (Hertz)
1A6CH-Cyclic	0 - 8.7	50	1.5
	0 - 13.6	50	1.5
	0 - 17.3	50	1.5
	0 - 40.1	Static	4 k/minute
1B6CH-Cyclic	0 - 8.8	50	1.5
	0 - 16.2	50	1.5
	0 - 36.0	Static	4 k/minute
1A6CN-Cyclic	0 - 10.1	50	1.5
	0 - 14.6	50	1.5
	0 - 24.0	Static	4 k/minute
1B6CN-Cyclic	0 - 7.7	50	1.5
	0 - 12.5	50	1.5
	0 - 16.2	50	1.5
	0 - 21.0	Static	4 k/minute
1A6CH-H.S.-Comb Cyclic	0 - 9.8	50	1.5
	0 - 14.8	50	1.5
	0 - 31.0	Static	4 k/minute
1B6CH-H.S.-Comb Cyclic	0 - 9.7	50	1.5
	0 - 14.6	50	1.5
	0 - 19.6	50	1.5
	0 - 29.7	Static	4 k/minute

Notes: 1 See Appendix A for explanation of specimen identification.

2 1 kip = 4.45 kN.
1 inch = 25.4 mm.

Figure 12. Summary of cyclic loading program - one-inch diameter bolts.

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Anchor Identification No.	Load Ranges (Kips)	No. of Cycles	Frequency (Hertz)
2A6CH-Cyclic	0 - 14.5	50	1.5
	0 - 19.4	50	1.5
	0 - 24.1	50	1.5
	0 - 29.0	50	1.5
	0 - 33.8	50	1.5
	0 - 38.7	50	1.5
	0 - 48.1	50	1.5
	0 - 72.8	Static	4 k/minute
2B6CH-Cyclic	0 - 19.7	50	2.0
	0 - 39.6	50	2.0
	40.1 - 59.5	50	1.5
	30 - 50.0	111	1.5
	32 - 48.0	220	2.0
	31 - 49.0	675	1.5
	0 - 55.5	Static	4 k/minute
2A6CH-H.S.-Comb Cyclic	0 - 14.5	50	2.0
	0 - 21.0	50	1.5
	0 - 28.0	50	1.5
	0 - 37.0	50	1.5
	0 - 68.4	Static	4 k/minute
2B6CH-H.S.-Comb Cyclic	0 - 16.6	50	1.5
	0 - 25.6	50	1.5
	0 - 29.8	60	1.5
	0 - 42.5	75	1.5
	0 - 67.0	Static	4 k/minute

Notes: 1. See Appendix A for explanation of specimen identification.

2. 1 kip = 4.45 kN.
1 inch = 25.4 mm.

Figure 13. Summary of cyclic loading program - two-inch diameter bolts.

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visible cracking of the concrete was also noted for most tests. The determination of this initial cracking was subjective in nature.

In order to automate the drawing of curve families used for comparative analyses, the co-ordinates of selected points on the original load deflection curves were manually transcribed and subsequently key-punched. A computer-controlled X-Y plotter was then used to reproduce the curves with adjustments made for take-up during the initial loading stage.

A computer program was written which averaged the load-deflection curves for replicate tests.

The averaging process causes minor discrepancies between maximum load values obtained from the average load-deflection curve and the average of maximum loads obtained from individual tests. The fact that maximum loads rarely occur at identical bolt deflections is the cause of the variation.

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V. TEST RESULTS AND ANALYSIS

A. General

Test results are presented in graphic and tabular form and represent the average of duplicate tests unless noted otherwise. A summary of test results and specific information for all specimens appears in Appendix A. The discussion to follow is based in large measure upon a qualitative comparison of the average of two load-deflection curves for each of the various parametric combinations. The magnitude of the initial slope and the general curve shape tell us much about the influence of a given variable upon the lateral resistance of an anchor bolt. No one particular curve shape emerged from the entire testing program.

B. Allowable Loads

As can be seen by a perusal of the many curves of load versus deflection and the tabular data presented herein, the lateral resistance of anchor bolts varies widely depending on the parameter of interest. The determination of a safe working allowable shear load that can be used by the designer will also vary depending on the parameters chosen. To aid the designer in assigning allowable shear loads to anchor bolts, Figure 4 referred to in the Conclusions was developed based on the various parameters examined within this study. The selection of a "yield" load as that load to produce a deflection of 0.05 inches (1.27 mm) was somewhat arbitrary and in general is considered to be conservative. A study of the curves of lateral load versus deflection indicates that the yield load is approximately equal to the 0.05-inch (1.27-mm) deflection or greater. For some of the parameters studied, yield occurs quite closely to a deflection of 0.05 inches (1.27 mm); for others the yield occurs at larger deflections. In any event visual cracking of the concrete in most cases occurred

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at a load producing a deflection in excess of 0.05 inches (1.27 mm). Thus the selection of a yield load at a 0.05-inch (1.27-mm) deflection, with an appropriate safety factor applied, is considered to be a safe and reasonable design criterion to be used in determining allowable shear loads for anchor bolts.

As the data obtained in this study was limited particularly with regards to some of the parameters investigated, the curves of proposed "yield" loads presented in Figure 4 were developed considering factors such as the yield strength of the hairpin reinforcement and the yield strength of the anchor bolts, both in shear and in bending. The "yield" loads presented were also determined considering only the size of hairpin reinforcement used in this study. The use of higher allowable loads may be reasonable if larger hairpin reinforcement were used, particularly for instances where 2-inch (50.8-mm) diameter bolts are installed using the cannister and mortar technique. In any event the use of #6 hairpin reinforcement would be recommended for use with 2-inch (50.8-mm) A449 bolts cast-in-place and for 2-inch (50.8-mm) A307 bolts installed with mortar in cannisters, although #5 hairpin reinforcement was used in this study. The shear and bending strength of these bolts is of a magnitude that #5 hairpin reinforcement cannot by itself develop the strength of these 2-inch (50.8-mm) bolts.

C. Specimen Behavior

Specimen failure consisted of the anchor bolt shearing and/or a tensile failure of the concrete. Extensive cracking of the concrete was observed in nearly all specimens. The concrete failure planes emanated from the mid-diameter of the anchor bolt, and terminated at the inside edges of the flanges of the supporting beams, thereby forming a 30° angle with the edge of the concrete block face.

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In test series 2, 6 of the 10 specimens (test numbers 21-26, Appendix A-3) were tested to determine the influence of the spacing of the specimen support beams on the ultimate lateral load and the concrete failure angle of the nominally reinforced concrete blocks. The load-deflection curves from these tests are shown in Figure 14. As can be seen, increased spacing of the supports results in decreased toughness (as defined by the area under the load/deflection curve) of the bolt-concrete system with little change in ultimate strength. It would appear that the difference between shapes of the load deflection curves is leveling off at an approximate failure plane angle of 14°. This reduction in toughness for nominally reinforced specimens must be kept in mind when evaluating the various conclusions reached in the report as actual loading conditions may more closely resemble the longer span used.

It would have been impractical to use anything less than a 30° angle for the assumed fracture plane as this would have required much larger specimens. Nonetheless, valid conclusions can be drawn from a comparison of the tests because the 30° failure plane assumption was constant throughout the test program.

D. Effect of Edge Distance

Figures 15 and 16 demonstrate the anticipated and pronounced effect of edge distance upon the lateral resistance of a given cast-in-place anchor bolt. The increased lateral resistance associated with increasing edge distance is, of course, due to the greater area of concrete in tension. For a given bolt diameter, the initial slope of the load-deflection curve appears to be independent of edge distance. This seems reasonable in light of the structural integrity of the concrete at these lower load levels. Figures 15 and 16 also indicate much of this integrity is lost before a bolt displacement of one-tenth of an inch (2.54 mm) is reached. Visible cracking of the concrete

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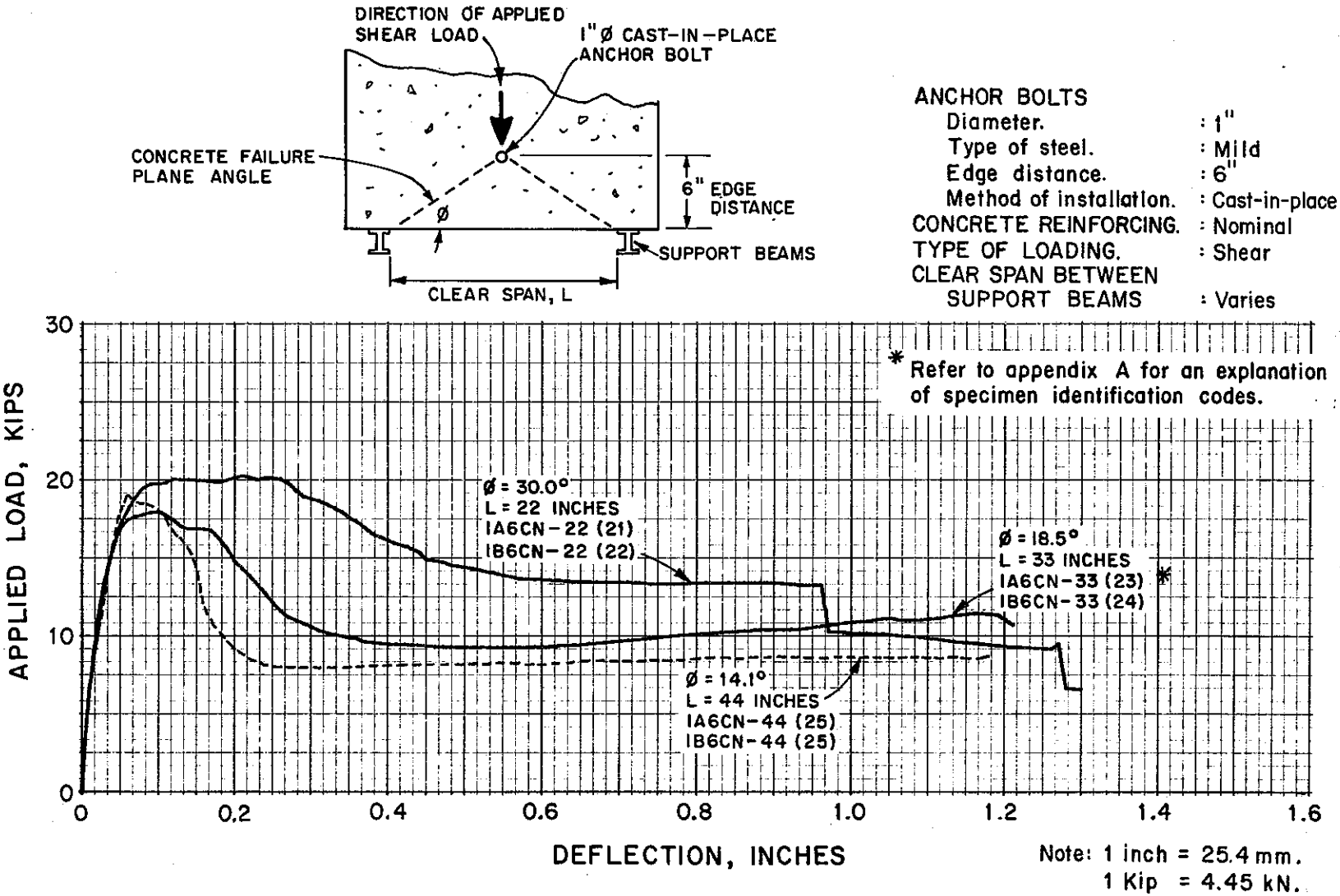

Figure 14. Influence of clear span distance, L, on lateral resistance of one-inch diameter anchor bolts.

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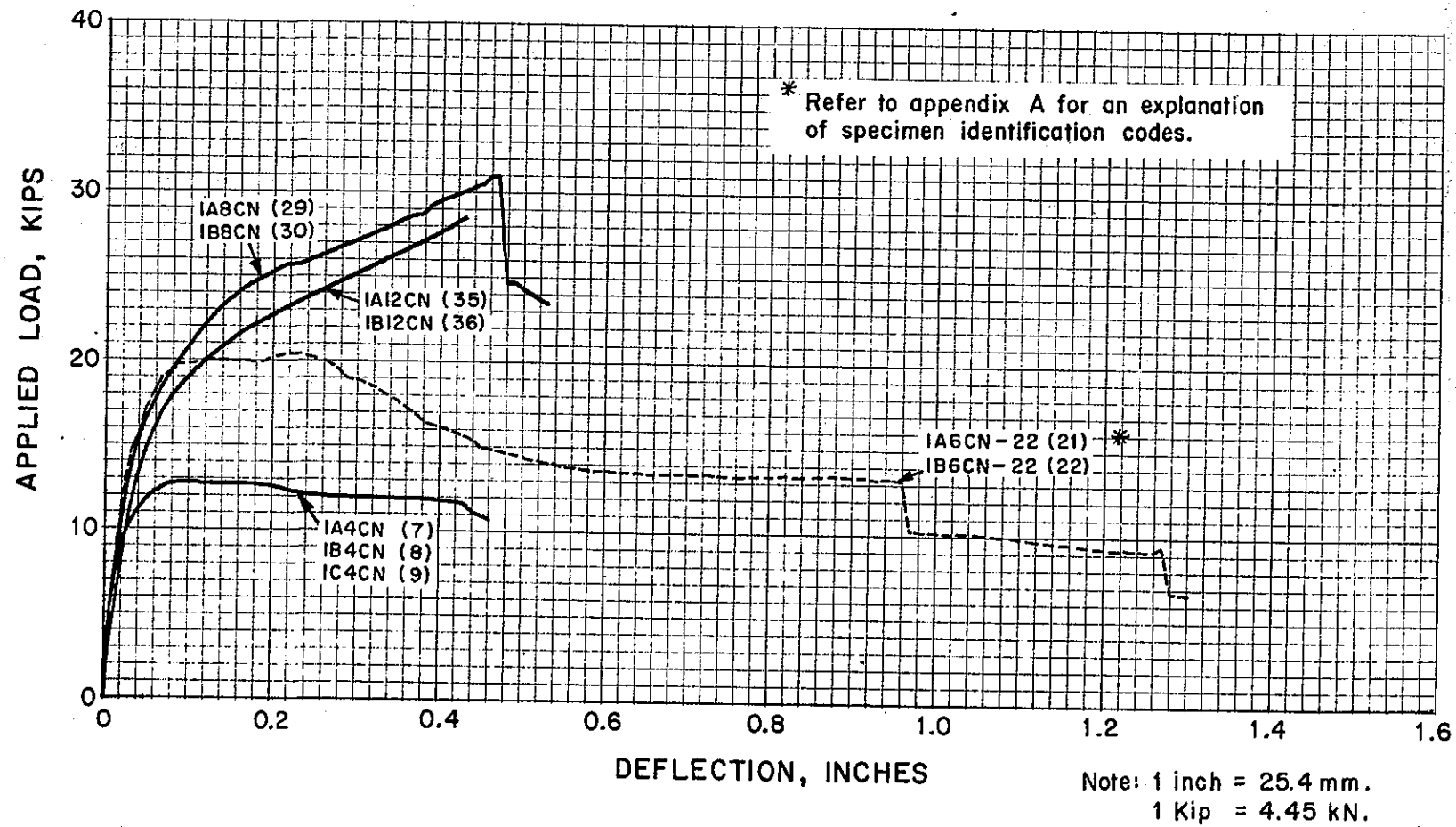
ANCHOR BOLTS
Diameter. : 1"
Type of steel. : Mild
Edge distance. : Varies
Method of installation. : Cast-in-place
CONCRETE REINFORCING. : Nominal
TYPE OF LOADING. : Shear



Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 15. The effect of varying edge distances on lateral resistance of one-inch diameter anchor bolts.

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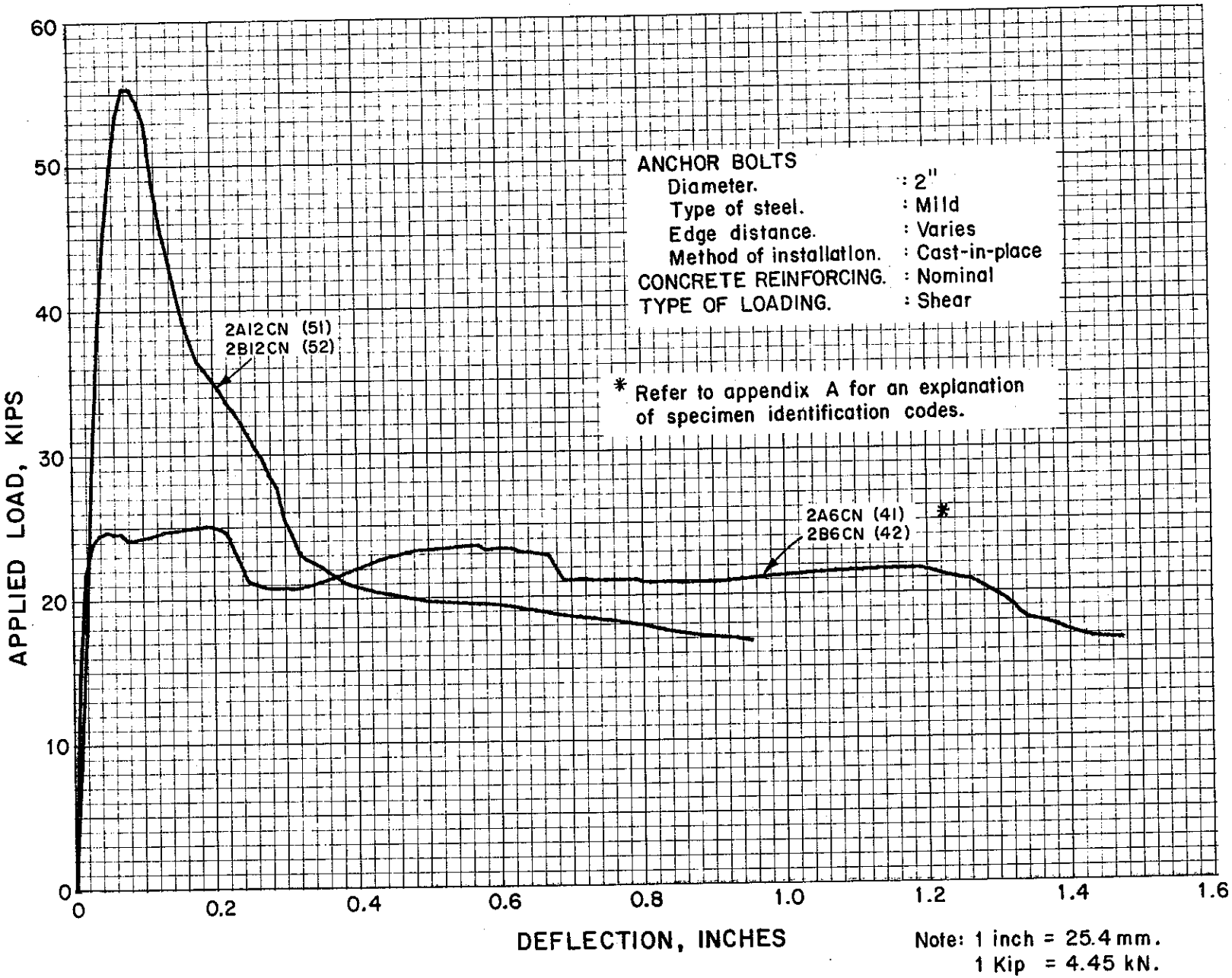

Figure 16. Effect of varying edge distance on lateral resistance of two-inch diameter anchor bolts.

between the bolt and each support had become obvious prior to this displacement. The relationship between ultimate load and edge distance can be seen graphically in Figure 17 for cast-in-place installations with nominal reinforcement. Approximately 4 kips (17.79 kN) of lateral resistance can be developed for each inch (25.4 mm) of edge distance regardless of bolt diameter for the bolt diameters tested. For the case of a bolt grouted inside a pipe sleeve with nominal reinforcement, 5 kips (22.24 kN) of resistance is developed per one inch (25.4 mm) of edge distance as shown in Figure 18. The increase of 1 kip per inch (175.13 N per mm) is probably due to the greater rigidity of the sleeve-bolt combination. This increased rigidity more evenly distributes the applied load along the length of the bolt thereby placing more concrete in tension.

E. Effect of Bolt Diameter

Figures 15 and 16 reveal the additonal stiffness attainable with 2-inch (50.8-mm) diameter bolts as compared with 1-inch (25.4-mm) diameter bolts for given edge distances. For a 6-inch (152.4-mm) edge distance, the 1-inch (25.4-mm) diameter anchor bolt-concrete system yields at 20 kips (88.96 kN) of applied load and 0.08 inches (2.03 mm) of deflection. At the same edge distance the 2-inch (50.8-mm) diameter anchor bolt-concrete system yields at 25 kips (111.2 kN) and 0.04 inches (1.02-mm) of deflection. A similar increase in stiffness of the 2-inch (50.8-mm) diameter anchor bolt-concrete system as well as a substantially higher yield load can be observed at a 12-inch (304.8-mm) edge distance.

Theoretically, a 2-inch (50.8-mm) diameter bolt is 16 times more rigid than a 1-inch (25.4-mm) diameter bolt based on their respective moments of inertia. This greater capacity is not fully realized because of the limited restraint provided by the concrete and nominal reinforcing steel at the edge distances under consideration. The greater stiffness of the 2-inch (50.8-mm)

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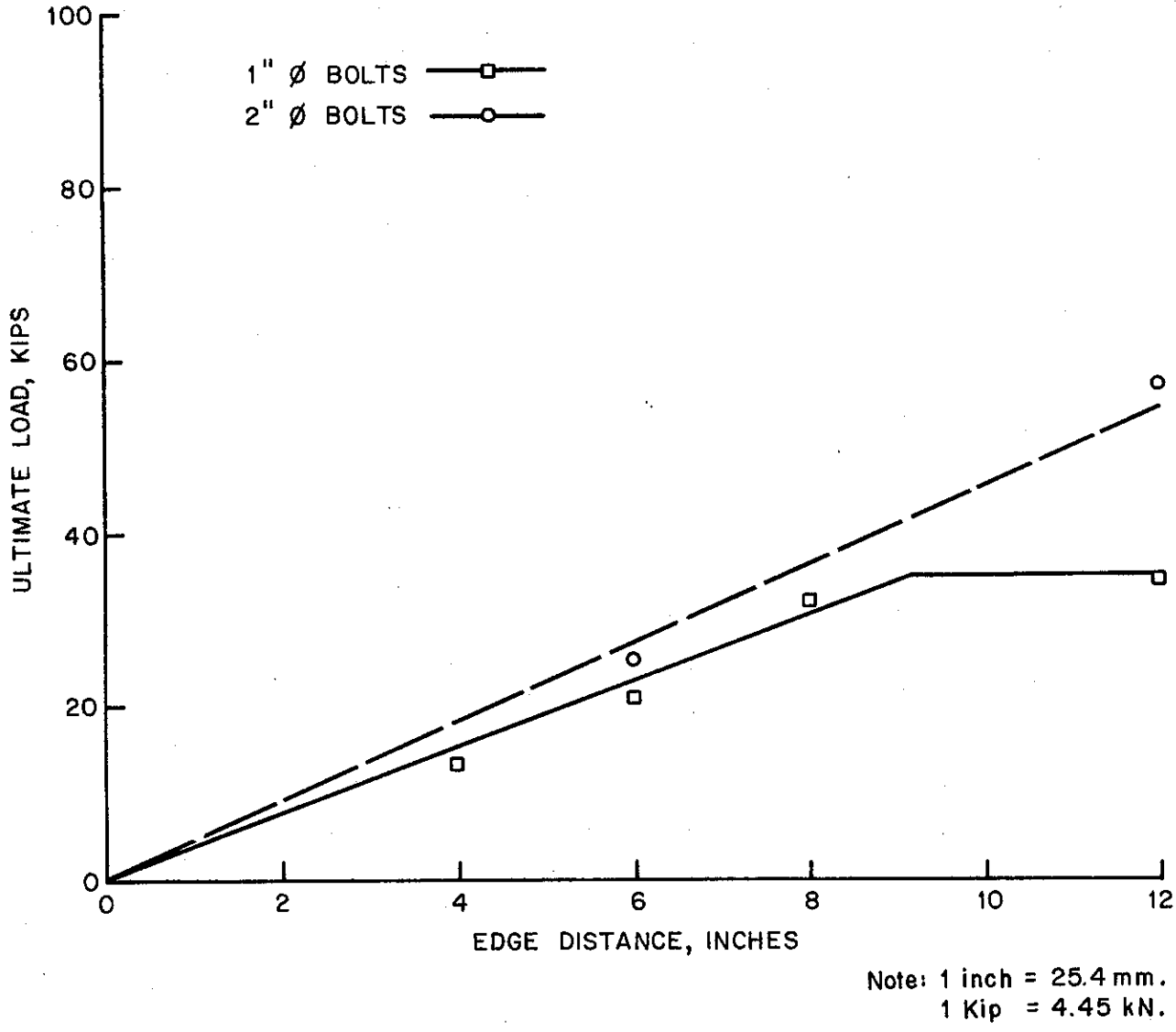

Figure 17. Comparison between average ultimate loads versus edge distances of cast-in-place one-inch and two-inch diameter anchor bolts in nominally reinforced concrete.

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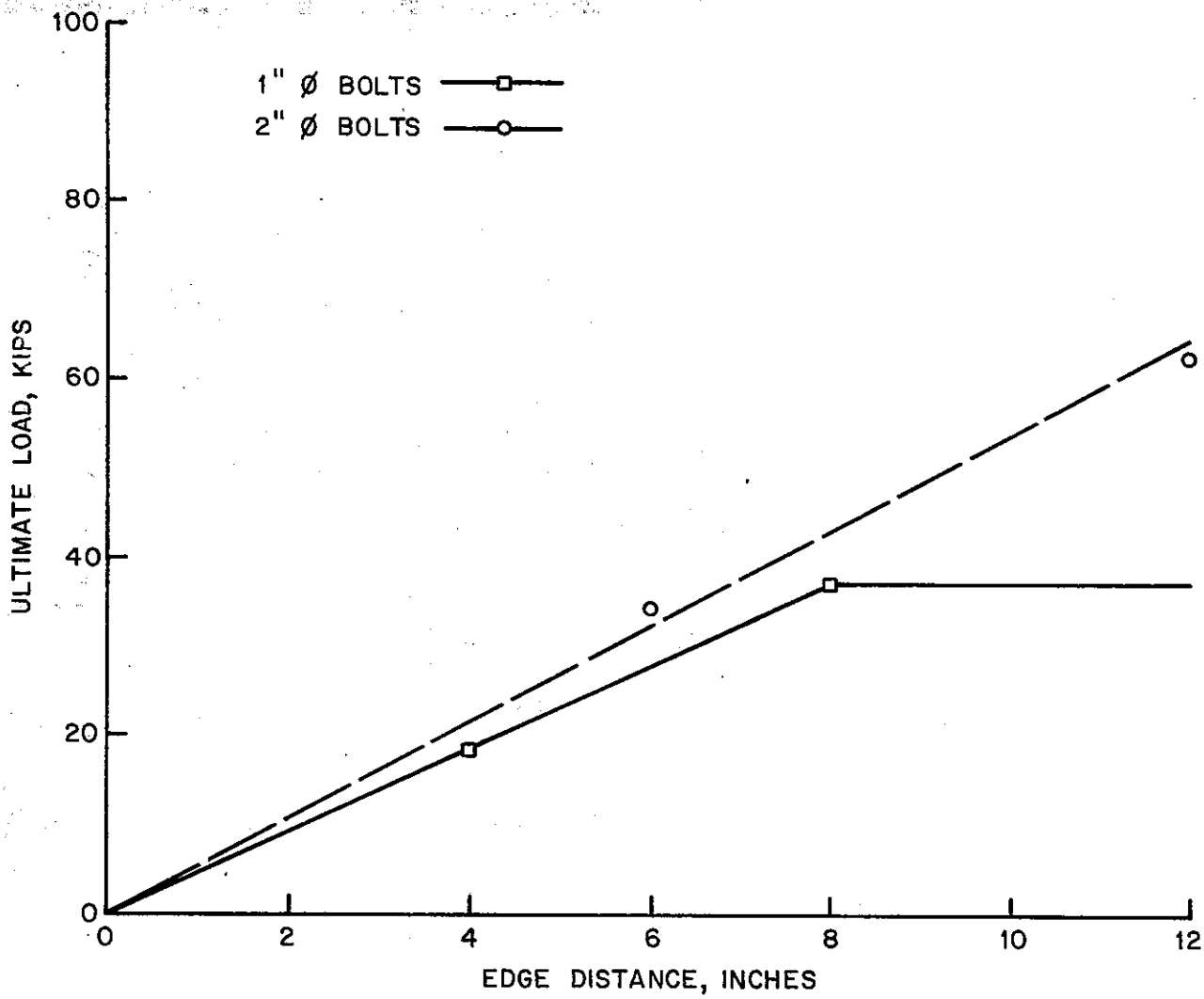

Figure 18. Comparison between average ultimate loads versus edge distances of one-inch and two-inch diameter anchor bolts installed in nominally reinforced concrete using the cannister and mortar method.

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diameter bolt causes the restraining concrete to crack to a greater depth than for a 1-inch (25.4-mm) bolt. The net result is a longer unsupported bolt length and a disproportionately low stiffness for the 2-inch (50.8-mm) diameter anchor bolt-concrete system.

Regardless of edge distance, the average initial slopes of the load-deflection curves for the 2-inch (50.8-mm) and 1-inch (25.4-mm) diameter bolts are 940 kips per inch (164.6 kN per mm) and 450 kips per inch (78.8 kN per mm) respectively indicating a relative stiffness of roughly 2:1.

A minimum of 8 inches (203.2 mm) of edge distance is required before a 2-inch (50.8-mm) diameter bolt cast-in-place in nominally reinforced concrete can be used efficiently as can be seen by comparing Figures 15, 16, and 17. Where space limitations are present however, the 2-inch (50.8-mm) bolt can be used to reduce deflections. It will sustain the same load as a 1-inch (25.4-mm) diameter bolt with less deflection, i.e., less cracking of the concrete.

F. Effect of Method of Installation

Figures 19 through 22 reveal the pronounced differences in load-deflection behavior for the three basic methods of installation with nominal reinforcement, namely cast-in-place, cannister and mortar, and drilled hole and epoxy.

Of the three types of installations tested, the cast-in-place installation provides the greatest initial rigidity and hence the highest lateral load resistance at small deflections. This is due to the lower compressive modulus of elasticity of the mortar used in the cannister installations as compared with that of concrete which surrounds the cast-in-place bolts, and the reduced cross section of the threaded bolts used in the epoxied installations

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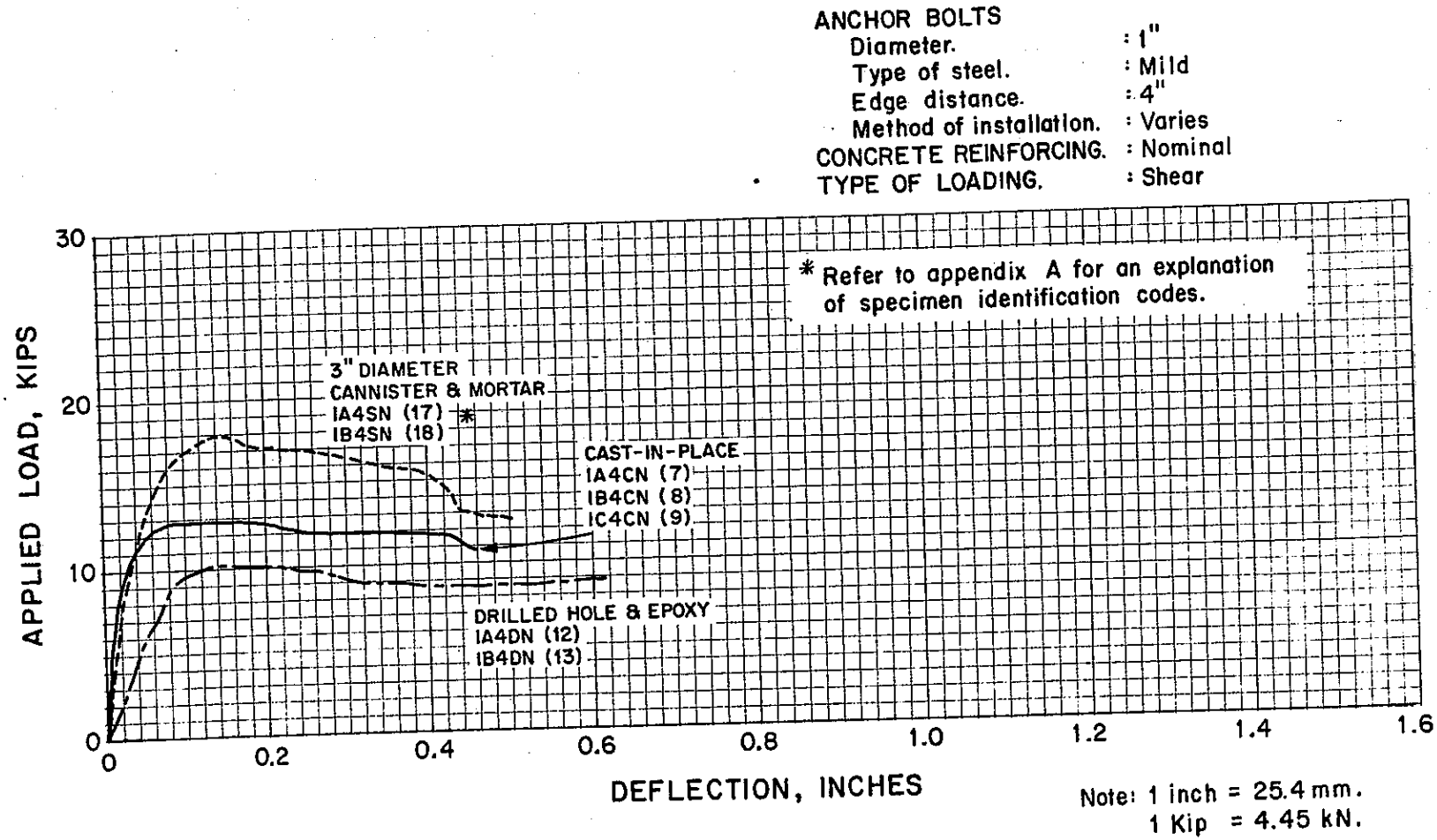

Figure 19. The effect of using different methods of installing individual one-inch diameter anchor bolts at a four-inch edge distance on lateral resistance.

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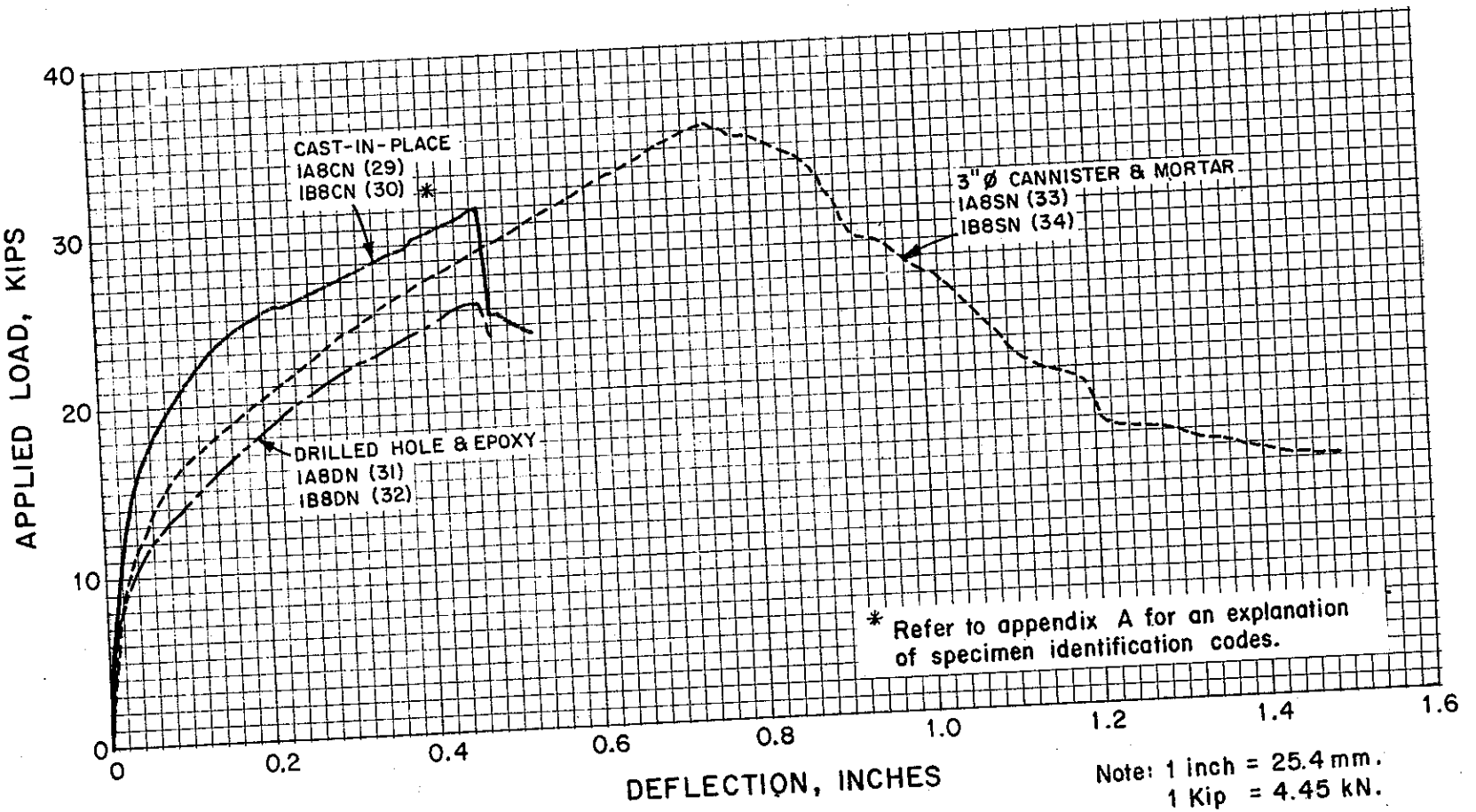

Figure 20. The effect of using different methods of installating individual one-inch diameter anchor bolts at an eight-inch edge distance on lateral resistance.

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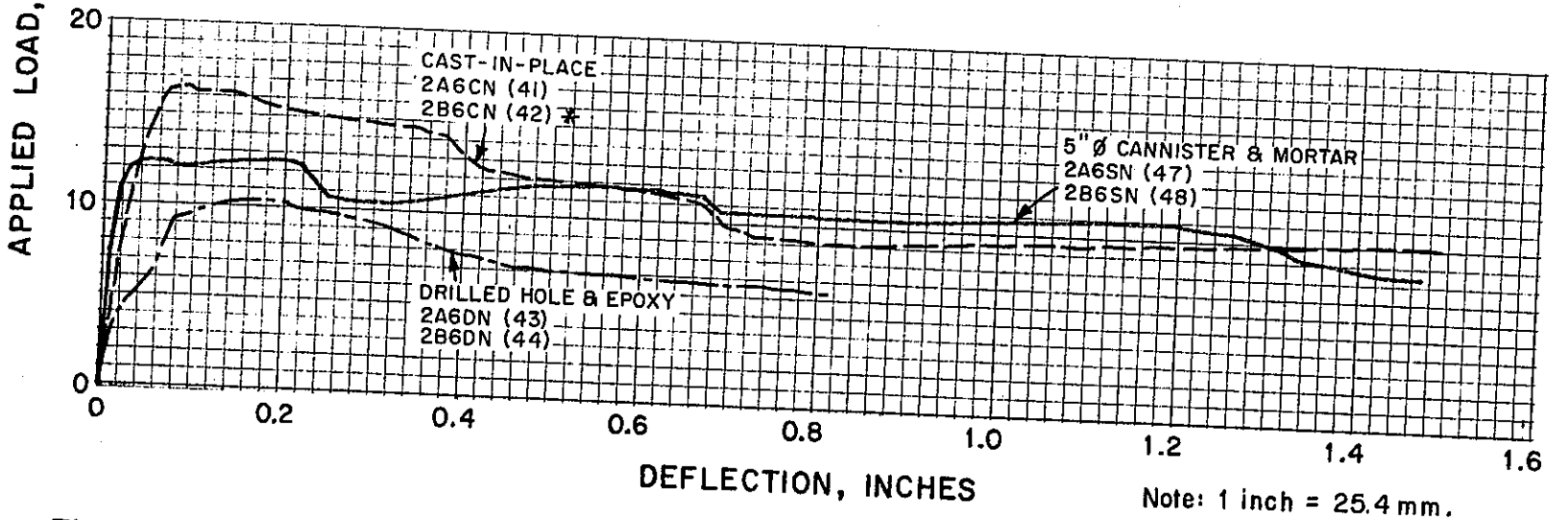
ANCHOR BOLTS
Diameter. : 2"
Type of steel. : Mild
Edge distance. : 6"
Method of installation. : Varies
CONCRETE REINFORCING. : Nominal
TYPE OF LOADING. : Shear

* Refer to appendix A for an explanation of specimen identification codes.



Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 21. The effect of using different methods of installing individual two-inch diameter anchor bolts at a six-inch edge distance on lateral resistance.

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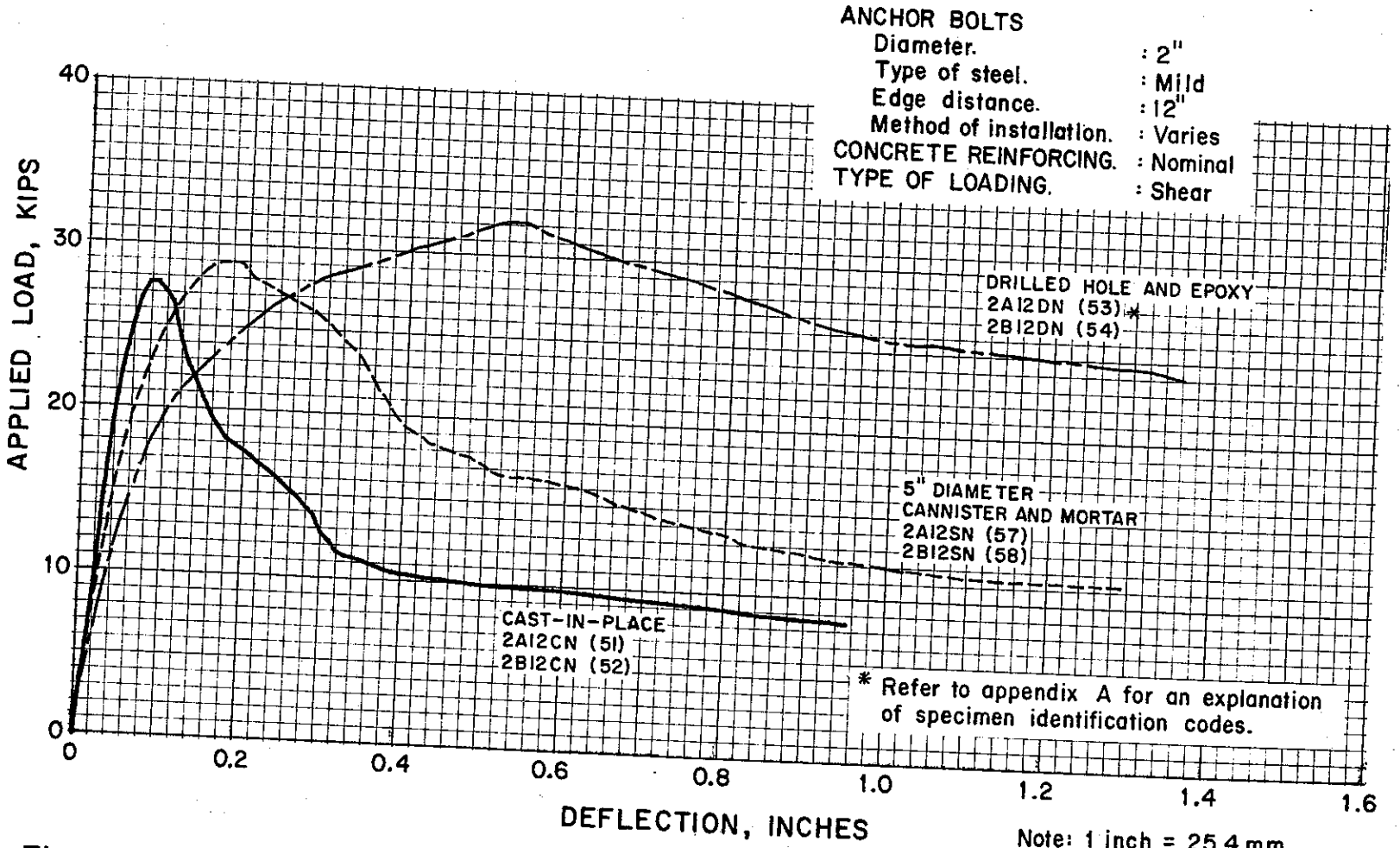

Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 22. The effect of using different methods of installing individual two-inch diameter anchor bolts at a twelve-inch edge distance on lateral resistance.

in conjunction with the much lower modulus of elasticity of the epoxy.

The cannister and mortar installation method, however, increases ultimate lateral load carrying capacity of the anchor bolts by approximately one-third for both the 1 (25.4-mm) and 2-inch (50.8-mm) diameter bolts at the smaller edge distances and by one-tenth at the larger edge distances. The effectiveness of the cannister to restrain the lateral movement of a bolt appears to be independent of bolt diameter and seems to have the greatest effect at small edge distances. Figure 23 summarizes these results.

These relationships demonstate the mechanics by which a cannister increases the resistance of the bolt-concrete system. Obviously, the cannister does not strengthen the bolt. Instead it serves to confine the mortar surrounding the bolt, and therefore the bolt itself, while distributing the bolt load over a larger volume of concrete. Distribution of load is critical at the smaller edge distances and this accounts for the greater effectiveness of using the cannister and mortar method of bolt installation in these instances.

An epoxied installation requires that the bolt be threaded full-length for adequate bonding. The resulting reduced cross-section and the low elastic modulus of the epoxy causes the relatively low stiffness for this method of installation. The load carrying capacity of the epoxied bolt-concrete system was generally twenty percent less than for the cast-in-place system. The 2-inch (50.8-mm) diameter epoxied bolts, however, with 12 inches (304.8 mm) of edge distance yielded 13 percent higher ultimate loads than the same cast-in-place installations.

To add to the perplexity of this last result is the ten percent lower strength of the concrete for this particular epoxied installation. The individually recorded maximum loads (presented in Appendix A) for the epoxied test pair varied by 12.3 percent

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Bolt Diameter (inches)	Edge Distance (inches)	ULTIMATE LOAD AVERAGES (kips)				
		Drilled Hole and Epoxy	Cast-in-place Nominal Reinforcing		Cannister and Mortar Nominal Reinforcing	
			without hairpins	with hairpins	without hairpins	with hairpins
1	4	10.4 (2)	13.6 (3)	25.4 (4)	18.6 (2)	38.4 (3)
1	6	—	21.0 (2)	33.6 (2)	—	—
1	8	26.5 (2)	32.4 (2)	37.2 (2)	37.2 (2)	
1	12	—	35.0 (2)	—	—	—
2	6	20.8 (2)	25.8 (2)	46.5 (2)	34.6 (2)	86.2 (2)
2	12	65.0 (2)	57.6 (2)	79.0 (2)	62.4 (2)	91.5 (2)

NOTES: 1. 1 inch = 25.4 mm.
1 kip = 4.45 kN.

2. (2) = Number of specimens averaged.

Figure 23. Comparison of ultimate load averages for various anchor bolt systems subjected to static shear.

resulting in a near overlap of data with the cast-in-place bolts. This variation in data seems to indicate that the difference in bolt rigidity for threaded and unthreaded 2-inch (50.8-mm) diameter bolts may not be significant at 12 inches (304.8 mm) of edge distance. This amount of restraining concrete, while it cannot develop the ultimate shear strength of these larger diameter bolts, may be sufficient to allow a redistribution of the more concentrated concrete tensile and shear stresses resulting from the differences in bending properties of the bolts in question.

G. Effect of Reinforcement

The two major types of reinforcement used to restrain the anchor bolts were nominal reinforcement with and without hairpin tie-back reinforcement. The nominal reinforcement consisted of #4 Grade 60 deformed steel bars spaced at 18-inch (457.2-mm) centers horizontally and vertically with 2 inches (50.8 mm) of concrete cover. The hairpin tie-backs were #4 bars for the 1-inch (25.4-mm) diameter bolts and #5 bars for the 2-inch (50.8-mm) diameter bolts. They were fabricated to provide approximately 20 bar diameters of bond length on each leg measured from centerline of anchor bolt with the exception of Test Nos. 3 and 4; the included angle of the bend was 60°. Two were positioned around each bolt, one each at 2 inches (50.8 mm) and 8 inches (203.2 mm) below the top surface of the concrete block.

A pair of tests, Nos. 10 and 11, was performed where vertical stirrups were used for additional reinforcement as shown in Figure 24. The stirrups were fabricated from #4 Grade 60 deformed steel bars and had 6-inch (152.4-mm) long legs. They were spaced on 4-inch (101.6-mm) centers.

1. Hairpin Tie-Back Reinforcement Around Cast-in-Place Bolts

Figure 25 reveals the added resistance provided by the use of hairpin reinforcement around 1-inch (25.4-mm) diameter bolts.

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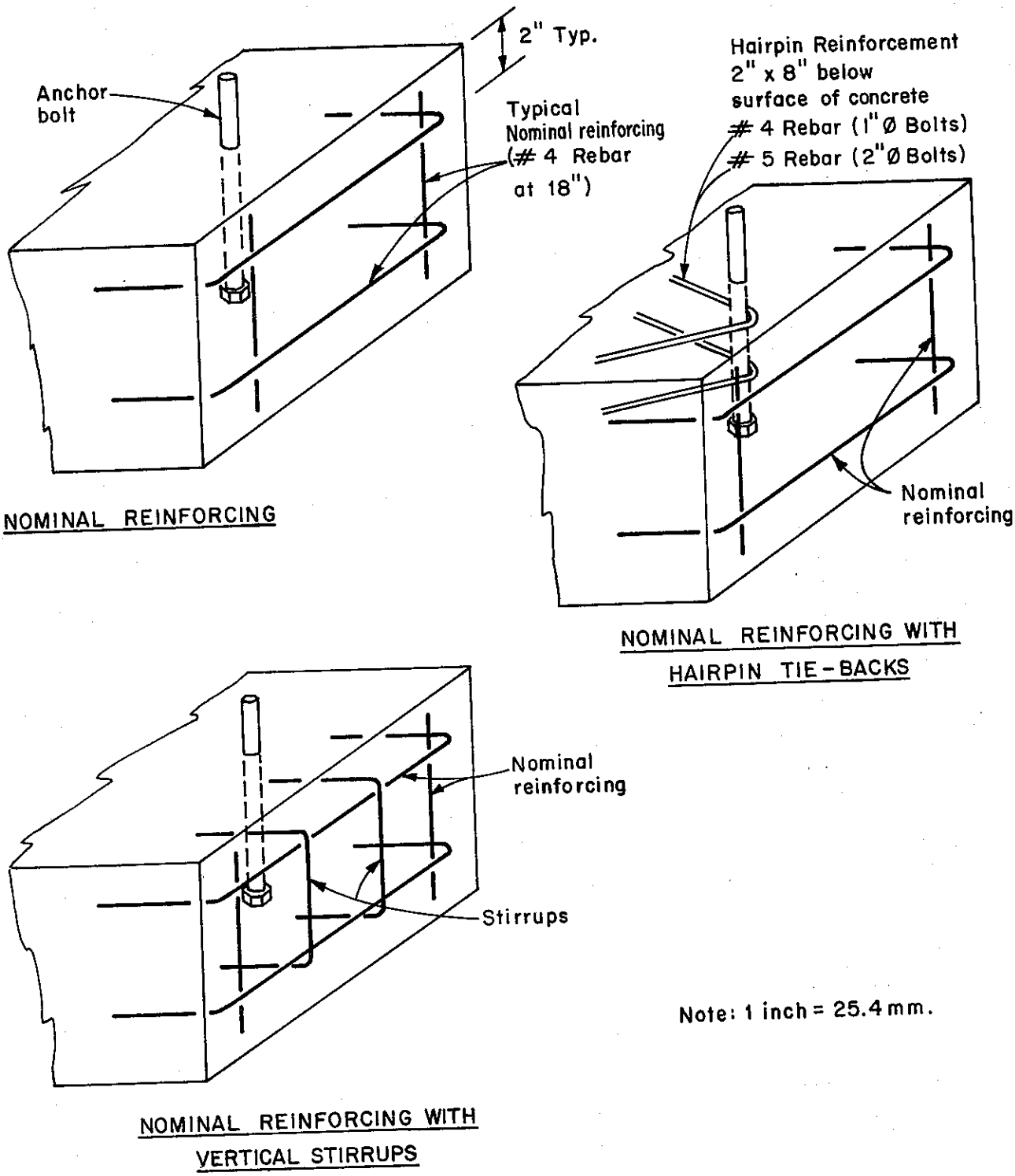

Figure 24. Reinforcement schemes

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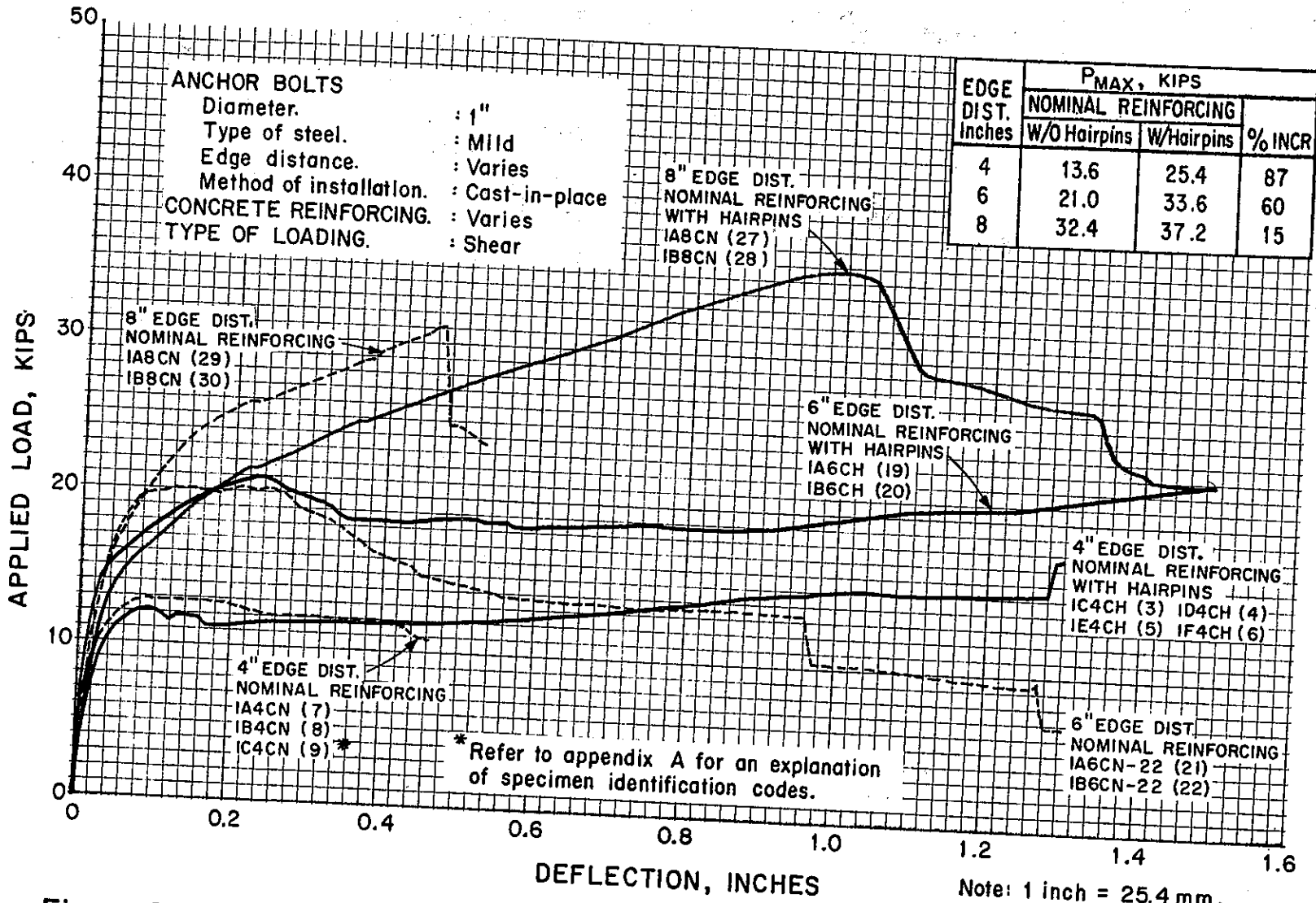

Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 25. Influence of hairpin reinforcement on one-inch diameter anchor bolts cast-in-place at various edge distances.

This is achieved however, only after large deflections have occurred. The three pairs of curves exhibited the pronounced bending effect of hairpins on the 1-inch (25.4-mm) diameter bolts (i.e., the hairpins tended to decrease the initial rigidity). This is apparently due to the discontinuity in the bolt support conditions created by the presence of the hairpins.

The effectiveness of the hairpin diminishes with increasing edge distance. At an edge distance of 4 inches (101.6 mm), the use of a hairpin increases the ultimate load carrying capacity by 87 percent. At an edge distance of 8 inches (203.2 mm) the increase is approximately 15 percent. Results from Test Nos. 1 and 2 (1A4CH and 1B4CH) are not included in Figure 25, as these tests were terminated prior to the attainment of ultimate shear loads; these test results are shown, however, in Appendix D-1.

Figure 26 also demonstrates increased ultimate load carrying capacity for hairpin reinforced 2-inch (50.8-mm) diameter bolts. The percentage increases are markedly greater however. The more rigid 2-inch (50.8-mm) diameter bolt and the larger cross-sectional area of the hairpins used for this bolt size are undoubtedly responsible. This is further evidenced by the substantial gains in load carrying capacity at lesser deflections than for 1-inch (25.4-mm) diameter bolts. Since the 2-inch (50.8-mm) diameter bolts did not fail, it is possible that hairpins of larger bar size would result in greater resistance. Too large a hairpin however might produce load-deflection curves similar to those for the 1-inch (25.4-mm) diameter bolts, i.e., excessive bending about the hairpin would occur thereby limiting its usefulness.

As previously mentioned, two tests were performed using stirrups in addition to nominal reinforcement to determine if additional lateral resistance could be gained by their use. Some improvement resulted, but the minor increase in lateral resistance was considered to be insignificant. Further testing of the stirrup method of

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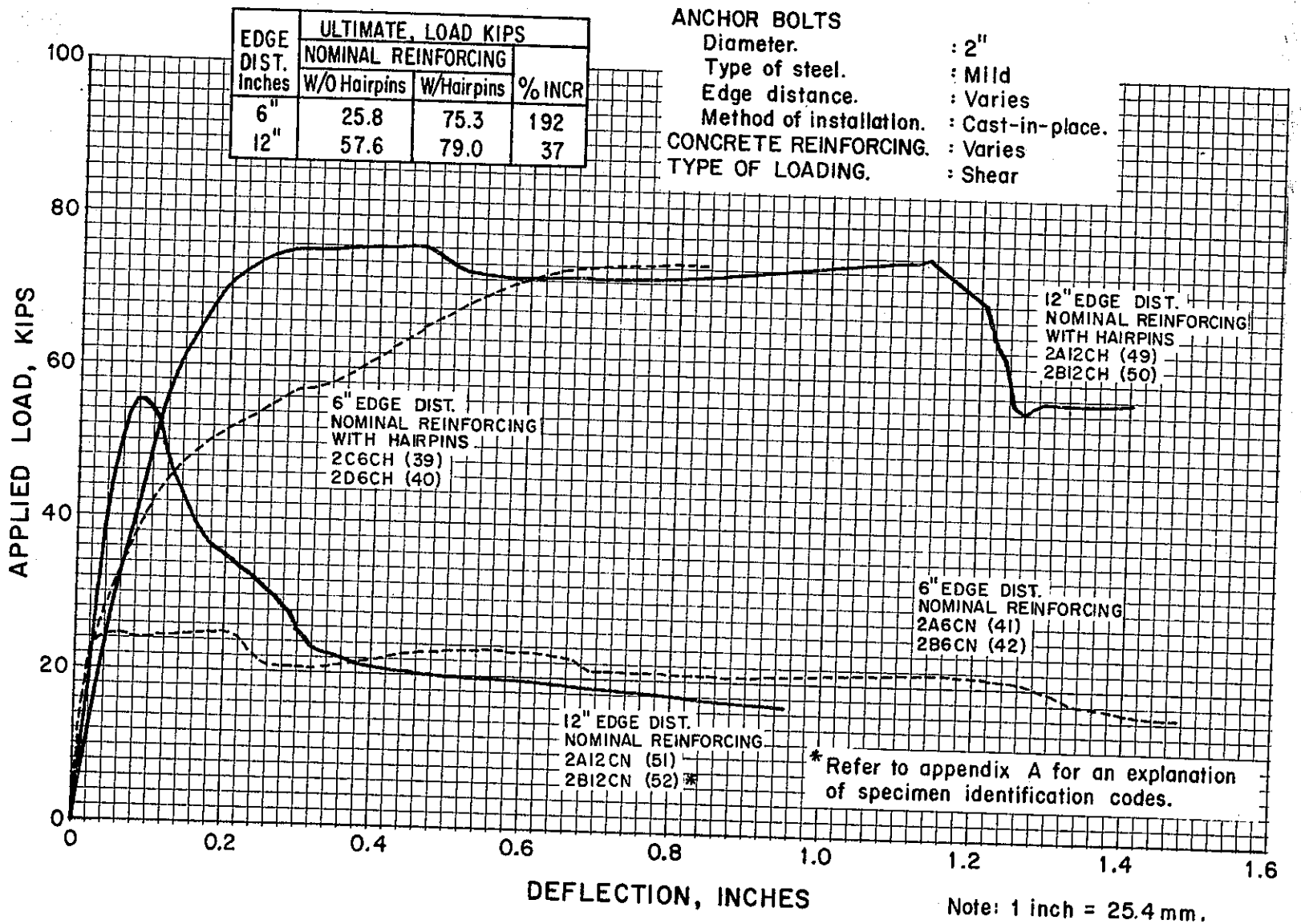

Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 26. Influence of hairpin reinforcement on lateral resistance of two-inch diameter anchor bolts cast-in-place at various edge distances.

reinforcement was discontinued in favor of hairpin reinforcement which provided more direct support of the anchor bolts and more efficient reinforcement of the concrete. A plot of the load-deflection relationship of this test pair is shown in Appendix D-2.

2. Hairpin Tieback Reinforcement Around Cannister and Mortar Installations

Increased resistance due to hairpin reinforcement is evident as shown by Figures 27 through 29 for the cannister and mortar installations of the 1 (25.4-mm) and 2-inch (50.8-mm) diameter bolts.

It can be noted from the curves that there exists a large difference in initial slopes of curves for the 1-inch (25.4-mm) bolts while this is not so for the 2-inch (50.8-mm) bolts. Bear in mind that the total deflection for a cannister and mortar installation is the sum of 3 components: compression of the mortar, actual bending of the bolt, and the displacement of the restraining concrete. It is conceivable that the lesser initial slope of the load-deflection curve for the hairpin reinforced cannister in Figure 27 is a result of large compressive strains within the mortar localized near the top of the mortar surface. At 4 inches (101.6 mm) of edge distance, a nominal reinforced cannister would probably fail the restraining concrete before crushing of the mortar proceeded to any great degree. This seems to be borne out by the nearly identical initial slopes of the load-deflection curves for nominally reinforced, cast-in-place, and cannister and mortar installations shown in Figure 19. Again, as was the case for cast-in-place installations, the hairpins are most effective for large diameter bolts at small edge distances.

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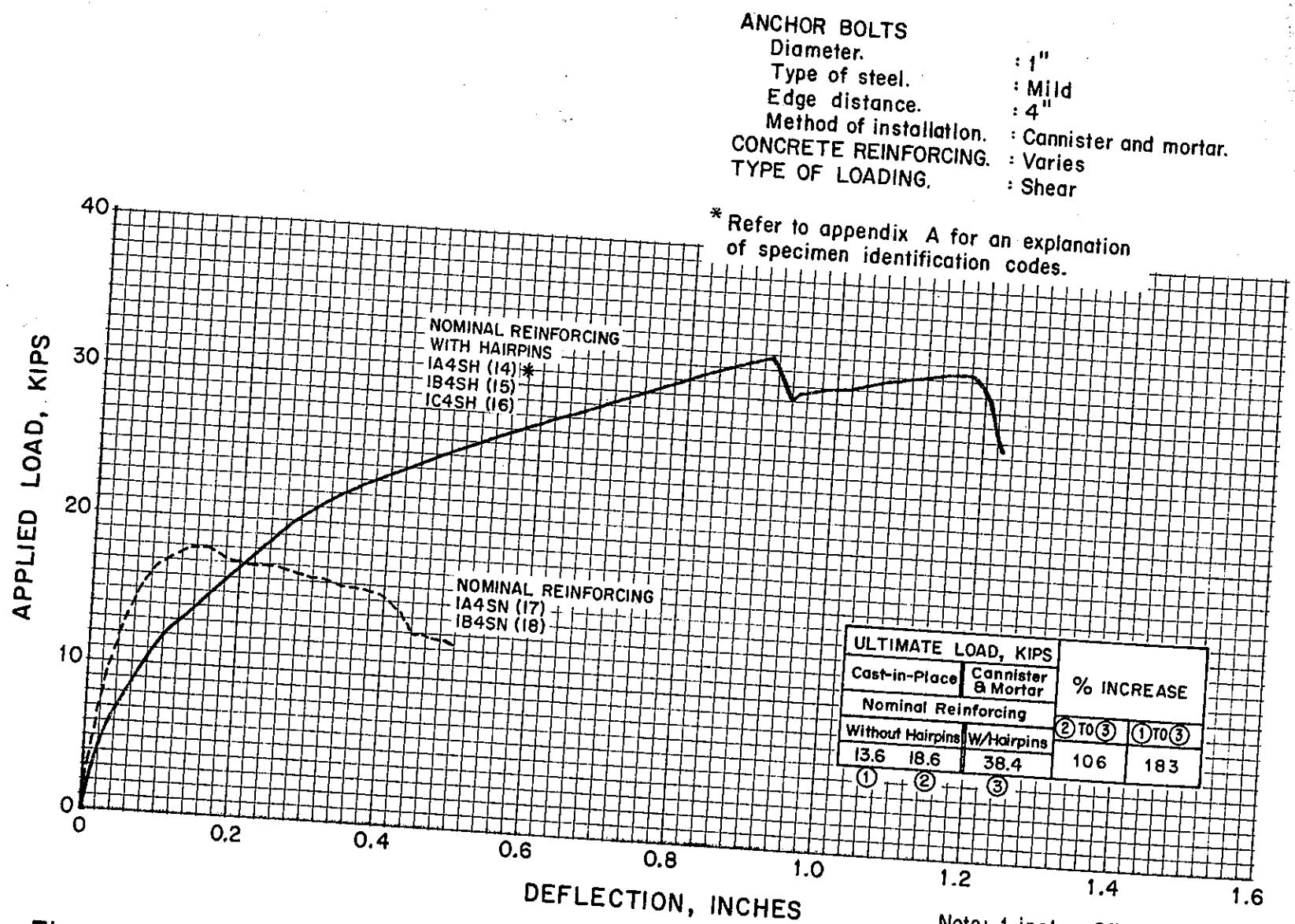

Figure 27. Influence of hairpin reinforcement on lateral resistance of one-inch diameter anchor bolts installed using the cannister and mortar method at at a four-inch edge distance.

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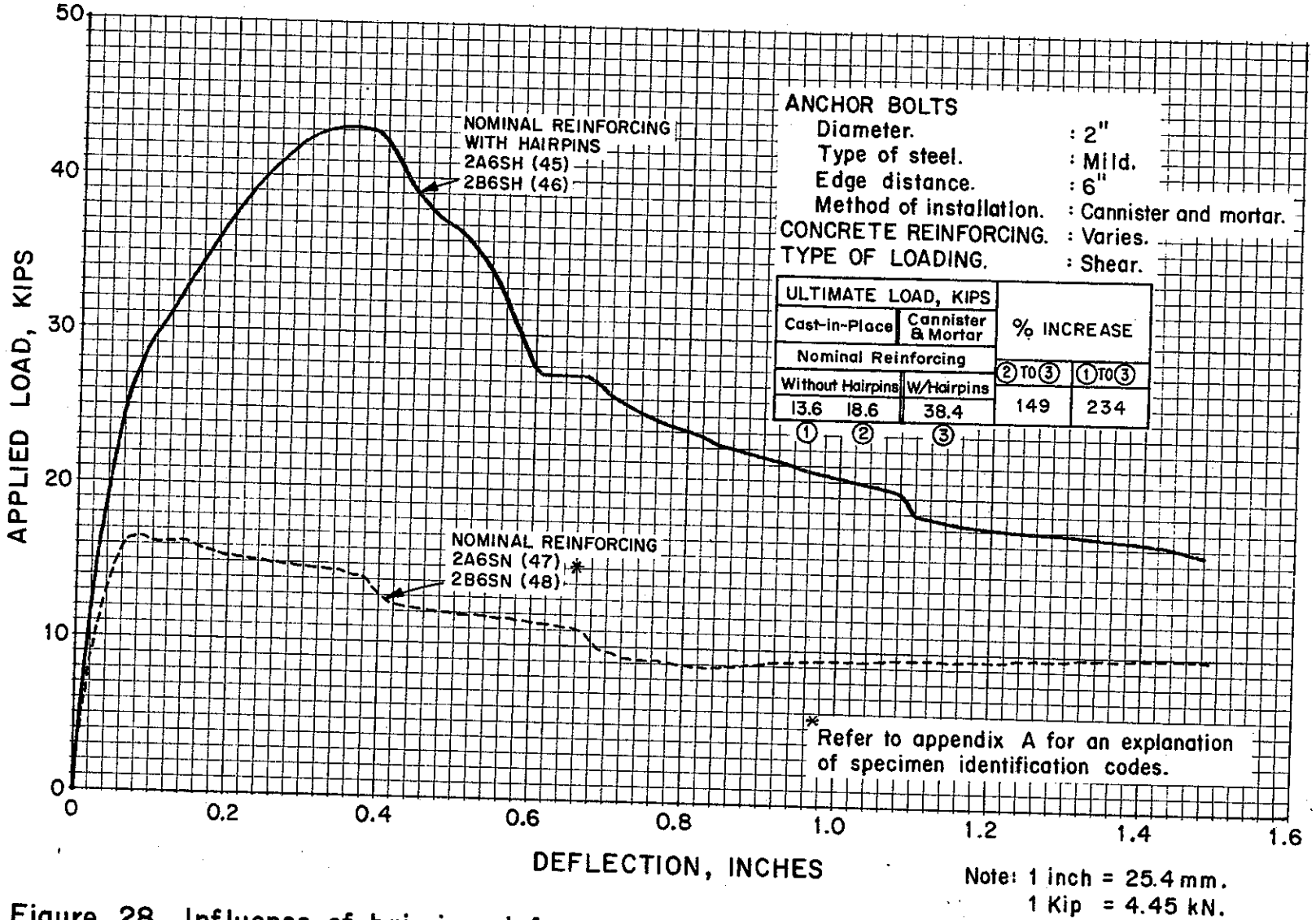

Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Figure 28. Influence of hairpin reinforcement on lateral resistance of two-inch diameter anchor bolts installed using the cannister and mortar method at a six-inch edge distance.

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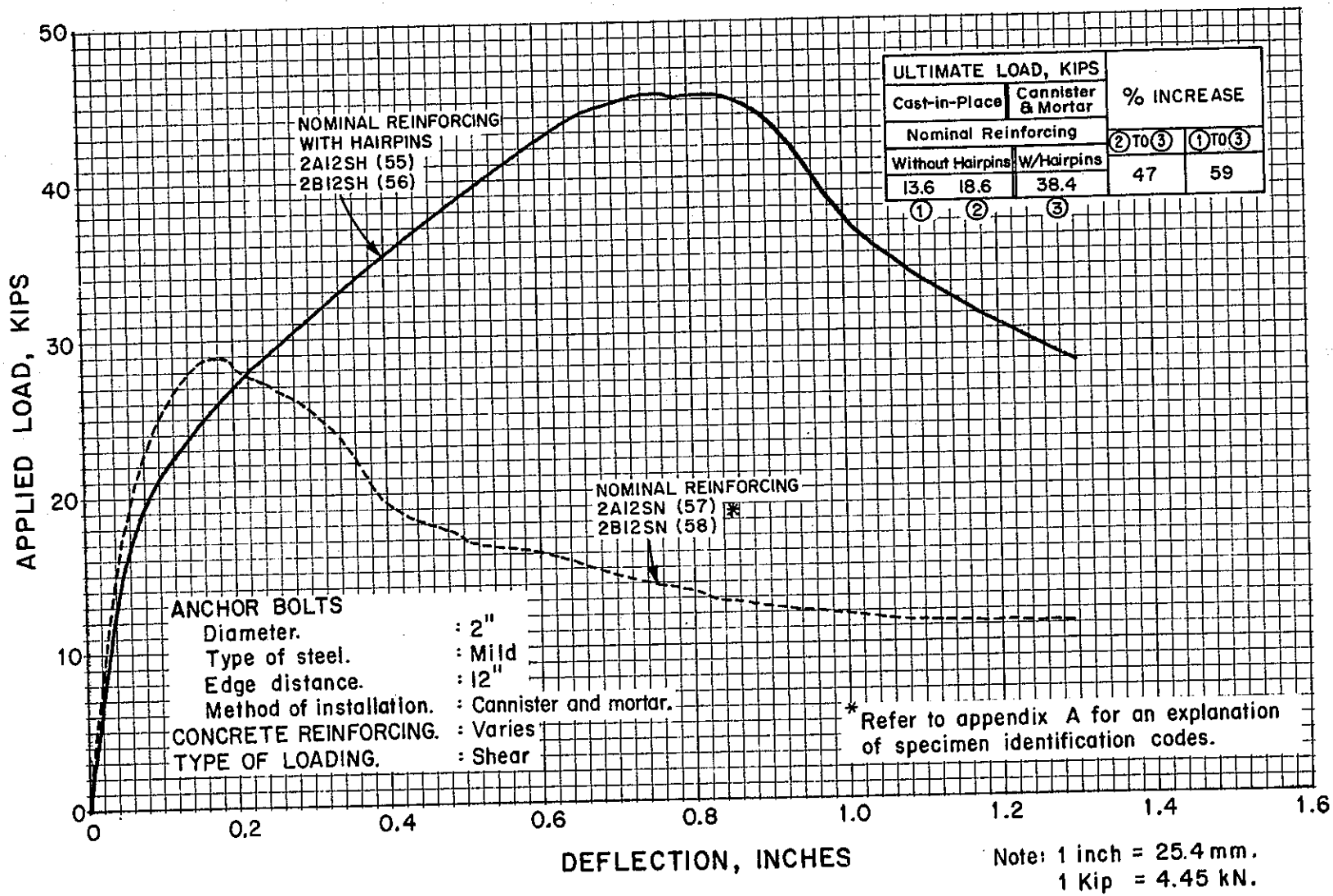

Figure 29. Influence of hairpin reinforcement on lateral resistance of two-inch diameter anchor bolts installed using the cannister and mortar method at a twelve-inch edge distance.

H. Effect of Combined Shear and Bending Moment Loading

Combined shear and bending moment loading as used in this report, refers to application of the lateral load a distance of 2 inches (50.8 mm) from the surface of the concrete. Elastomeric bearing pads were used as the spacer to duplicate field installations. In this way, an exterior bending moment was applied to the anchor bolt in addition to the shear load. Hairpin reinforcement and an edge distance of 6 inches (152.4 mm) were used for all tests in this series, except for two tests, Nos. 75 and 76 (1A8CN-COMB and 1B8CN-COMB), whose average plot is shown in Appendix D-4.

Figures 30 and 31 show the marked difference in bolt behavior produced by combined loading. The addition of a bending moment causes the restraining concrete to initially crack at lower loads: 14 kips (62.3 kN) versus 18 kips (80.1 kN) for the 1-inch (25.4-mm) diameter and 17 kips (75.6 kN) versus 25 kips (111.2 kN) for the 2-inch (50.8-mm) bolts.

The bending moment also produced greater final deflections than shear loadings only, 60% for the 1-inch (25.4-mm) diameter bolts and 90% for the 2-inch (50.8-mm) diameter bolts. Part of the 90% increase in deflection for the 2-inch (50.8-mm) bolts subjected to combined loading was undoubtedly due to the use of bolts having a 30% lower yield strength than the 2-inch (50.8-mm) bolts furnished for the direct shear tests.

The 1-inch (25.4-mm) diameter combined load-tests showed a 13% increase in load resistance over the 1-inch (25.4-mm) diameter shear load tests while the 2-inch (50.8-mm) diameter tests showed an 18% decrease. Again a portion of this decrease must be attributed to lower yield strength material.

The overall mode of failure however does not appear to be affected by the introduction of an initial bending moment. One bolt in each 1-inch (25.4-mm) diameter pair failed in shear with the

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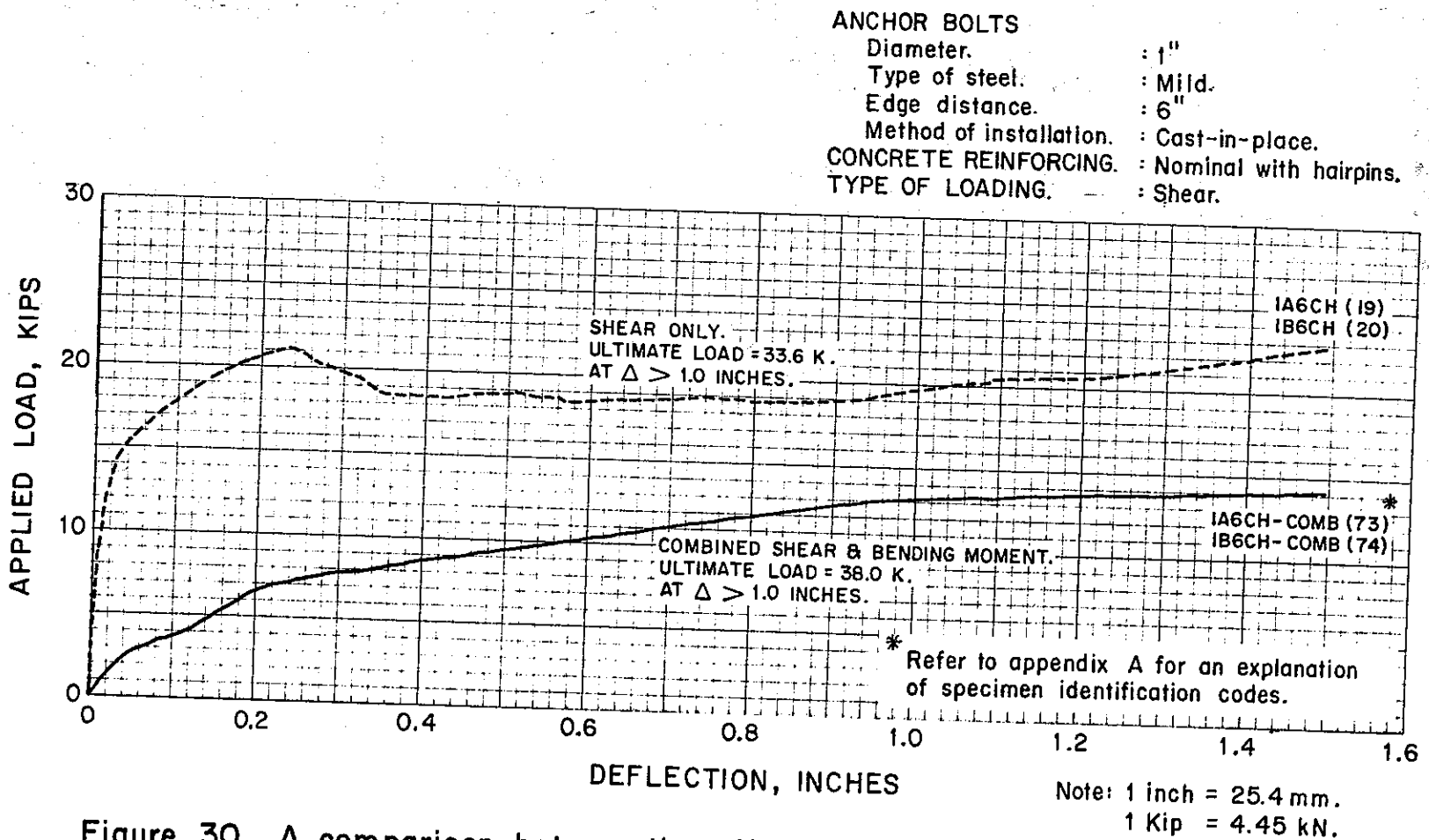

Figure 30. A comparison between the effects of pure shear and combined shear and bending moment loading on the lateral resistance of one-inch diameter anchor bolts.

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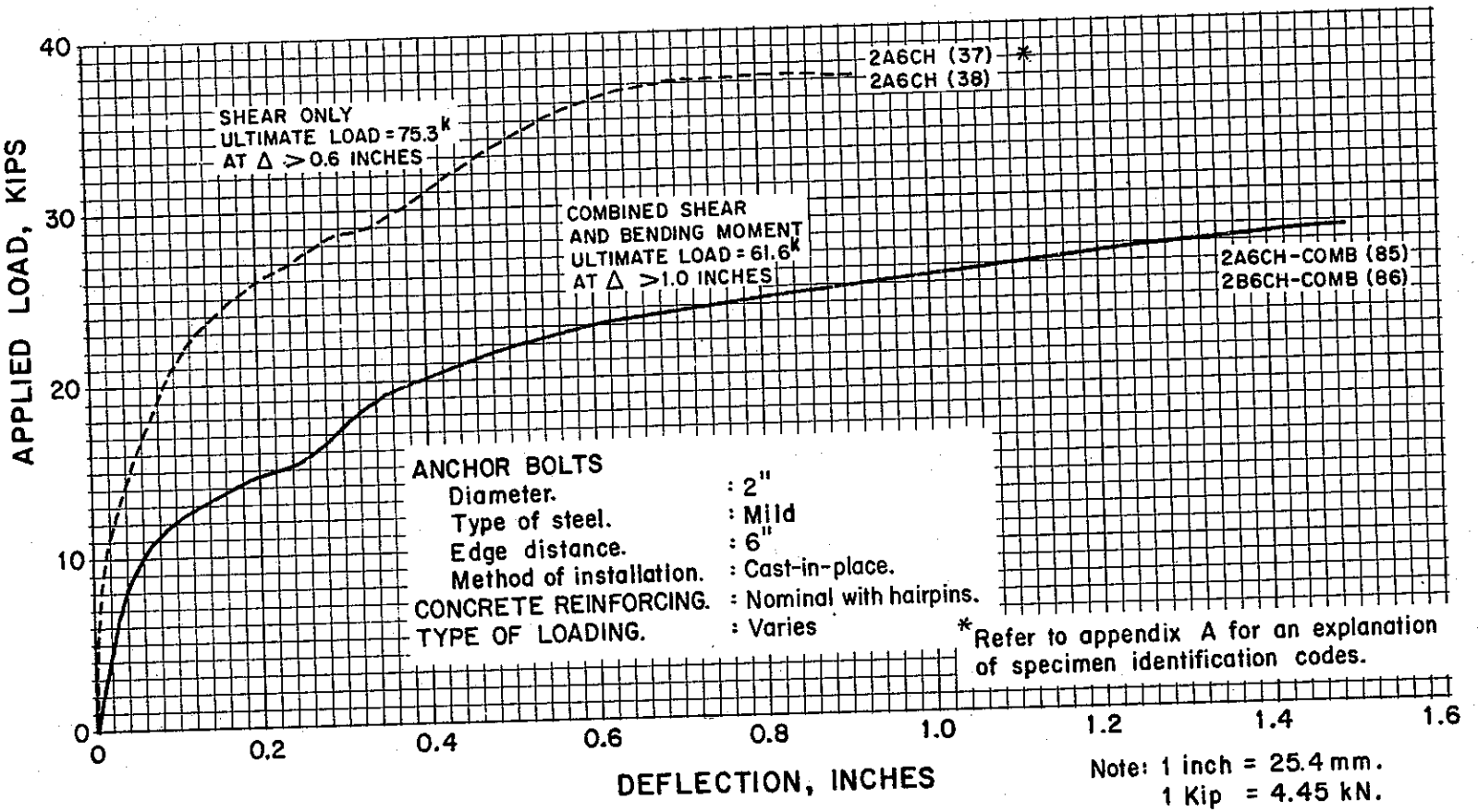

Figure 31. A comparison between the effects of pure shear and combined shear and bending moment loading on the lateral resistance of two-inch diameter anchor bolts.

remaining bolt failing the hairpin in tension. The 2-inch (50.8-mm) diameter bolt tests ended with failure of the hairpins. For the edge distances and bending moments under consideration it would seem that combined loading produces increased deflections while not affecting ultimate load capacity.

I. Efect of Cyclic Loading

The cyclic loading tests were conducted without stress reversal typically at a frequency of 1.5 cycles per second. The applied load was varied between pre-selected upper limits and nominal zero as shown in Figures 12 and 13, except for specimen 2B6CH-Cyclic. The applied cyclic loads for this specimen were ranged between two positive limits.

Reference to Figures 32 and 33, where modified cyclic data has been compared to corresponding uncycled tests, reveals no discernible difference in anchor bolt behavior due to cyclic loading up to deflections of 1 1/2 inches (38.1 mm). Plots of actual data obtained from load versus deflection tests for the six remaining cyclic tests conducted, Nos. 79, 80, 87, 88, 91, and 92, are shown in Appendices D-5, D-6, and D-7 for reference.

In Figure 34, a comparison is made between average loads and deflections from static and cyclic tests. Deflections at the points of initial cracking of the concrete are not shown in Figure 34 for the cyclic specimens as, due to the hysteresis effect, the determination of the deflections at the points of cracking is inexact. A comparison of the ultimate loads in Figure 34 indicates that ultimate load carrying capacity is not

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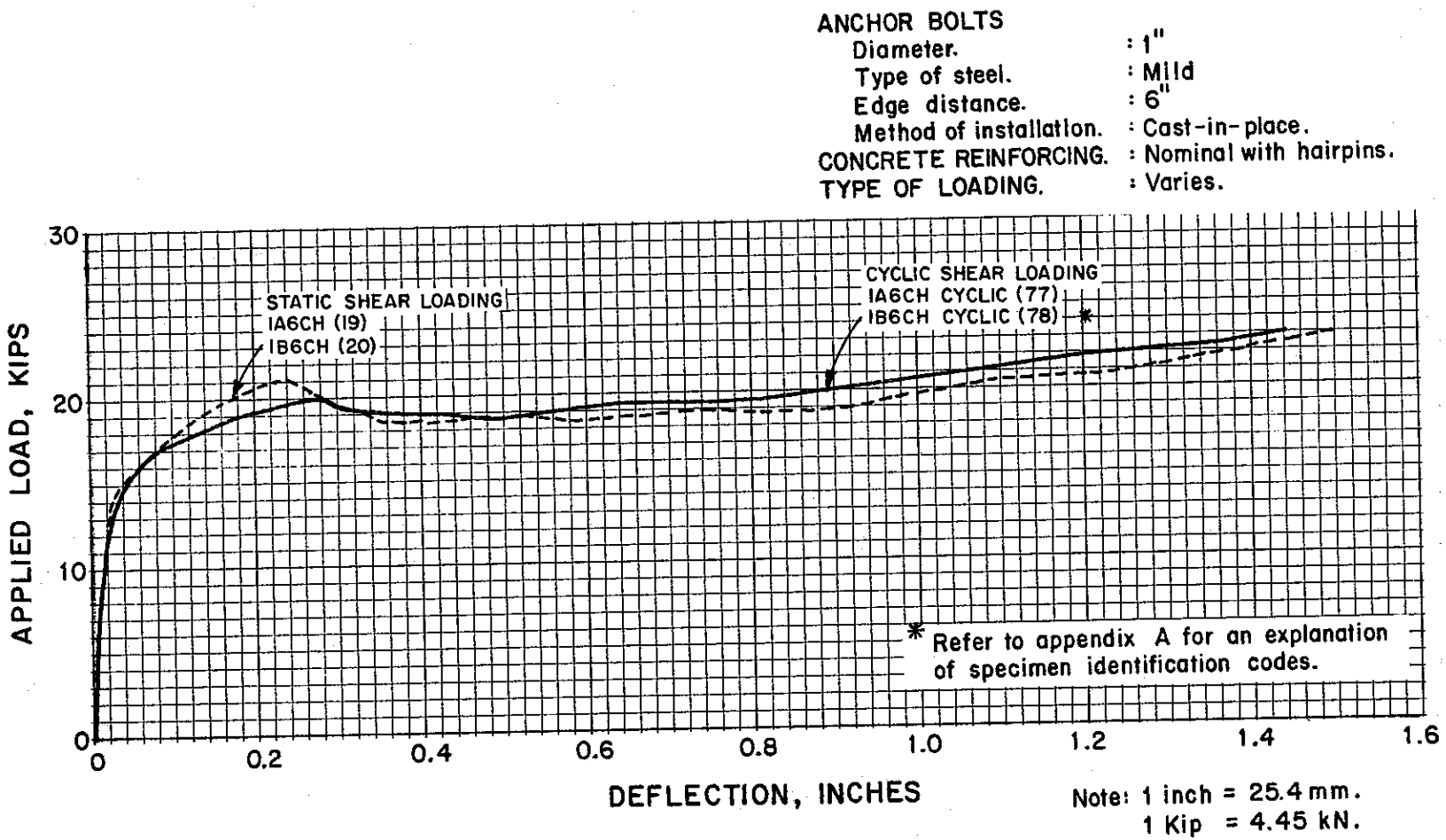

Figure 32. A comparison between the effects of static shear and cyclic shear loading on the lateral resistance of one-inch diameter anchor bolts.

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ANCHOR BOLTS
- Diameter. : 1"
- Type of steel. : High strength.
- Edge distance. : 6"
- Method of installation. : Cast-in-place.

CONCRETE REINFORCING. : Nominal with hairpins.
TYPE OF LOADING. : Varies.

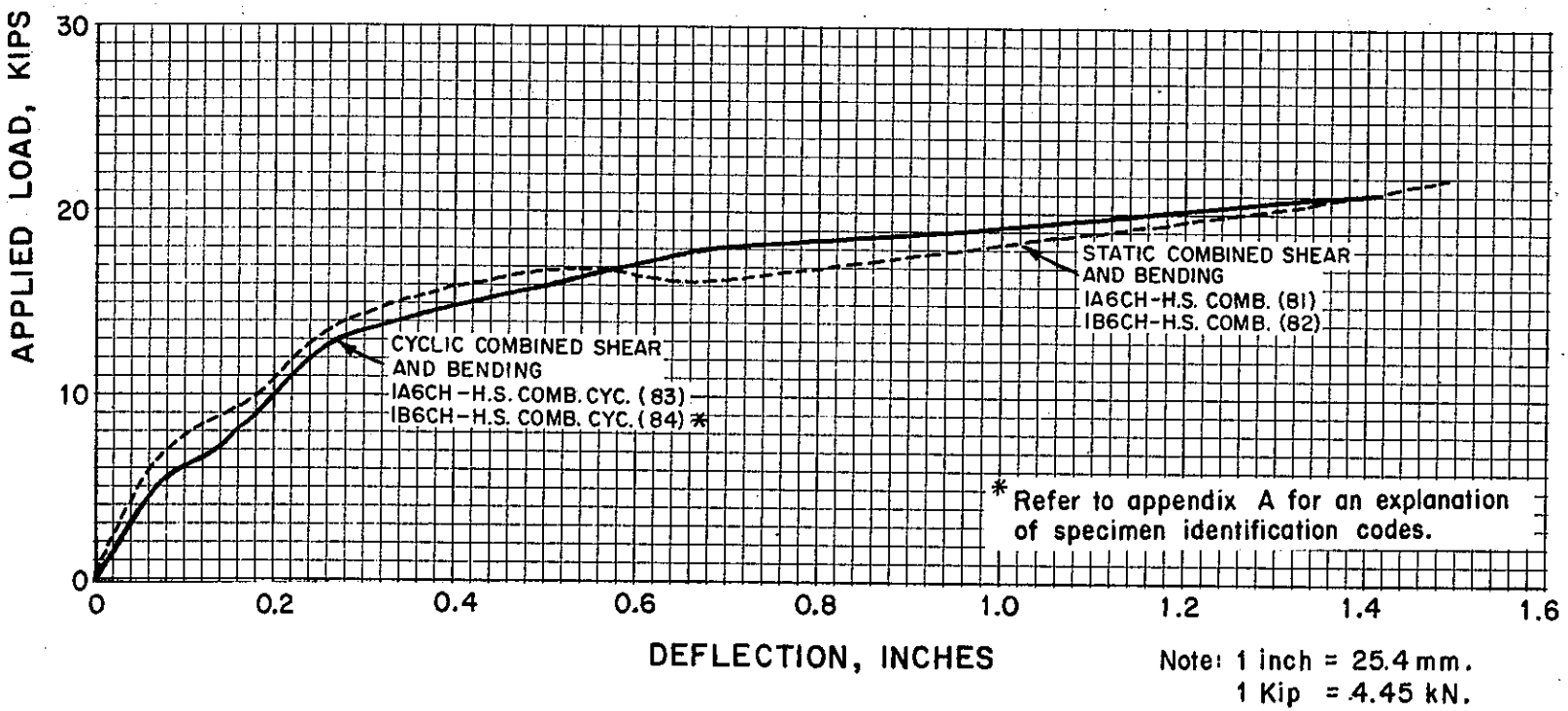

Figure 33. A comparison between the effects of static and cyclic combined shear and bending moment loading on the lateral resistance of one-inch diameter anchor bolts.

Specimen Identification Codes		Average Loads, kips, and Corresponding Average Deflections, inches					
Test Nos.	Anchor Bolt Ident. No.	P @ Δ = 0.05"	Δ = 0.05"	P Crack	Δ Crack	P Ult.	Δ Ult.
37,38	2^{C}_{D}6CH	30.4	0.05	25.1	0.030	75.3	>0.8
87,88	2^{A}_{B}6CH-Cyclic	——	——	18.7	——	66.3	<0.75
19,20	1^{A}_{B}6CH	15.5	0.05	18.5	0.015	33.6	>1.0
77,78	1^{A}_{B}6CH-Cyclic	——	——	13.7	——	38.1	>1.0
21,22	1^{A}_{B}6CN-22	17	0.05	——	——	21.0	0.17
79,80	1^{A}_{B}6CN-Cyclic	——	——	14.8	——	22.5	——
89,90	2^{A}_{B}6CH-H.S.-Comb.	16.5	0.05	15.8	0.047	61.8	>0.85
91,92	2^{A}_{B}6CH-H.S.-Comb.-Cyclic	——	——	15	——	67.7	>1.0
81,82	1^{A}_{B}6CH-H.S.-Comb.	4.7	0.05	13.8	0.28	38.5	>1.0
83,84	1^{A}_{B}6CH-H.S.-Comb.-Cyclic	——	——	13.5	——	30.4	>1.0

NOTES: 1. Refer to Appendices A-1 and A-2 for an explanation of above abbreviations.

2. 1 inch = 25.4 mm.
1 kip = 4.45 kN.

Figure 34. Comparison between average loads and deflections of static and cyclic tests.

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influenced by the application of between 300 and 400 repeated loadings at working stress levels. However, after 1000 repetitions of overload levels, i.e., maximum loads equal to about 2/3 of the ultimate static lateral resistance, a 7% reduction in load resistance occurred with specimen 2B6CH-CYCLIC. It is suspected that with increasing numbers of load cycles at the higher load levels, the restraining concrete would fracture sufficiently to allow individual chunks to fall away or be otherwise displaced. This would of course destroy the continuity of concrete between the bolt and the nominal reinforcing and thereby provide room for additional deflection. In the case of hairpin reinforcement it is probable that the hairpin yields at the apex where stresses are highly concentrated, resulting in plastic deformation.

J. Effect of Bolt Strength

High-strength anchor bolts conforming to ASTM Designation: A449 were used in the combined load test for both static and cyclic loading. A 6-inch (152.4-mm) edge distance was used for all tests.

Salient data from the static tests are tabulated in Figure 35. The load-deflection curves for these tests are shown in Figures 36 and 37.

The chart shows that for the edge distance in question, ultimate load capacity is not increased by the use of high-strength bolts.

A comparison of the divergent load-deflection curves for the 1-inch (25.4-mm) diameter bolts with the nearly coincident curves for the 2-inch (50.8-mm) diameter bolts indicates that high-strength bolts can be effectively used however to reduce bolt deflections under certain conditions. The governing criterion appears to be that edge distance which can develop the yield strength in shear for a mild steel bolt of a given diameter. Any larger edge distance

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Bolt Diameter (inches)	Average Loads (kips) and Corresponding Average Deflections (inches)											
	Mild Steel (ASTM A307)						High-Strength Steel (ASTM A449)					
	Test Nos.	P @ Δ = 0.05"	P Crack	Δ Crack	P Ult.	Δ Ult.	Test Nos.	P @ Δ = 0.05"	P Crack	Δ Crack	P Ult.	Δ Ult.
1	73,74	2.8	13.7	0.96	38	>1.0	81,82	4.7	13.8	0.29	38.5	>1.0
2	85,86	18.4	16.8	0.04	61.7	>1.0	89,90	16.5	15.8	0.04	61.8	≈1.0

NOTES: 1. Refer to Appendix A for complete information about above test numbers and abbreviations.

2. 1 inch = 25.4 mm.
1 kip = 4.45 kN.

Figure 35. Comparison between average loads and deflections of mild steel and high-strength steel anchor bolts.

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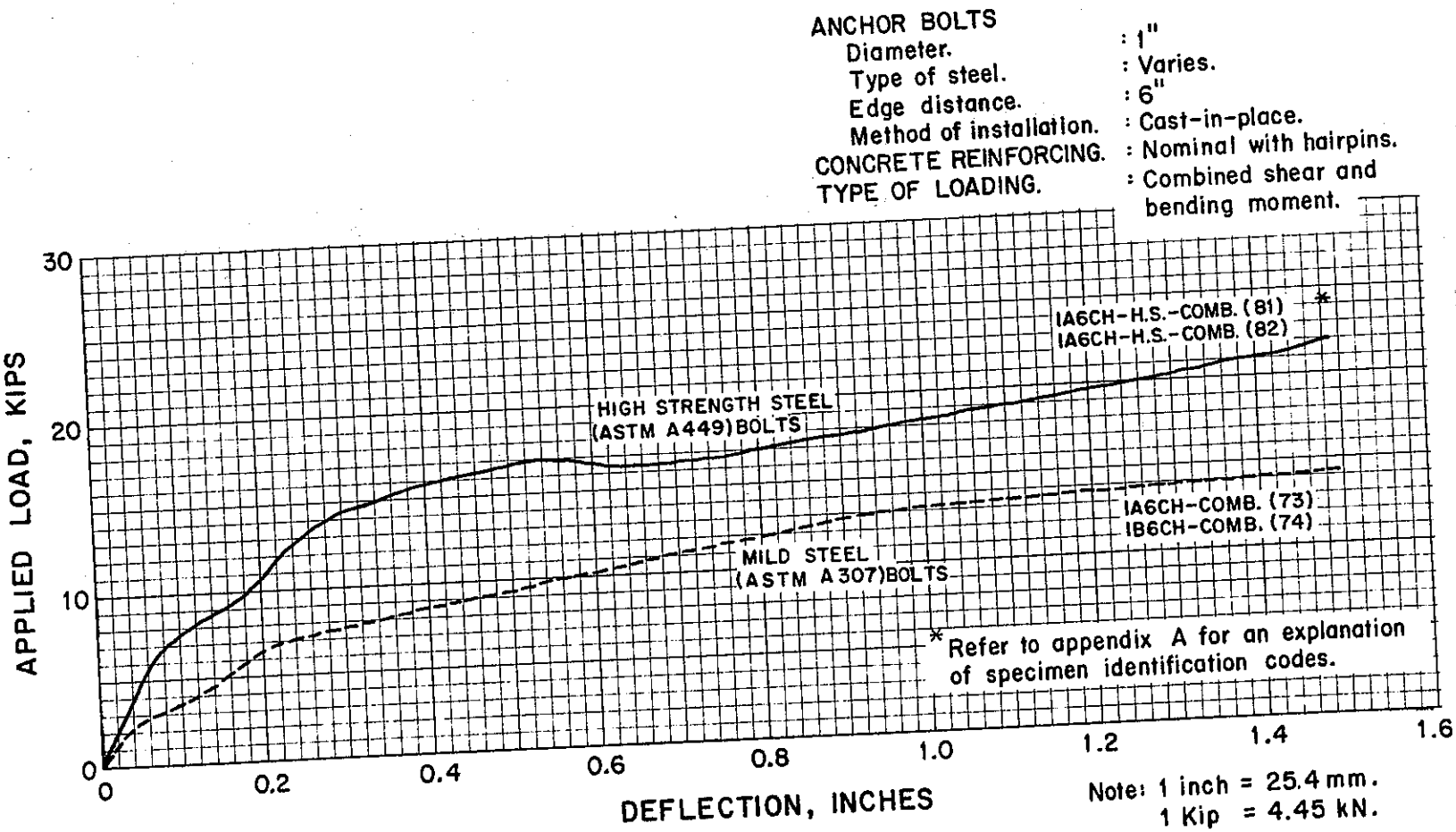

Figure 36. The effect of anchor bolt strength on the lateral resistance of one-inch diameter bolts.

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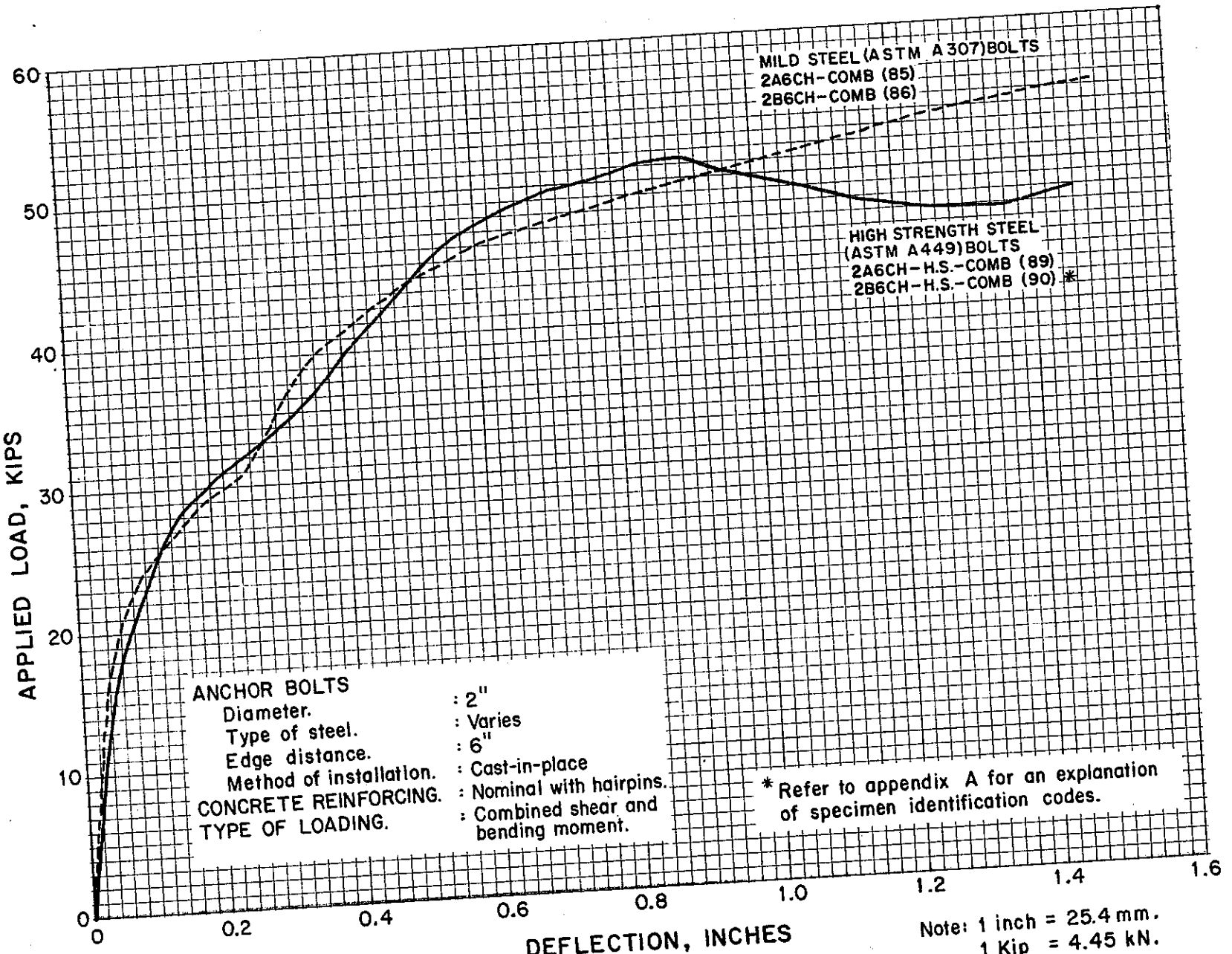

Figure 37. Effect of anchor bolt strength on lateral resistance of two-inch diameter bolts.

should then make possible the utilization of the greater yield strength of the high-strength bolt.

To realize the full potential of a high-strength bolt would of course require substantially greater edge distance and/or additional reinforcement.

K. Effect of Group Action

Group action, as it relates to anchor bolts, refers to the performance of a number of bolts considered to be acting as a unit compared with the performance which might be expected from such a group if their individual load carrying capabilities were purely additive. This phenomenon is demonstrated in Figure 38 for a given set of parameters. The average load-deflection curves for the bolt pair tests shown in Figure 38 are drawn to one-half vertical scale so that the ordinate represents the applied load per bolt.

As can be seen from this figure, a definite reduction in per-bolt load carrying capacity exists. This reduction varies with the spacing between the bolts. Plots of load versus deflection for the remaining pairs of five group tests, Nos. 59 and 60, 61 and 62, 67 and 68, 69 and 70, and 71 and 72, are shown in Appendix D-3 for information.

Figure 39 does not reveal any readily apparent trends with regards to the effect of edge distance for the range under study. The data points at a spacing to edge distance ratio of 2.0 do indicate however that the use of hairpin reinforcement mitigates the effects of close bolt spacing.

In all instances the mode of failure for the nominally reinforced specimens was splitting and tensile failure of the concrete. In all but one instance the hairpin reinforced bolt tests resulted

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ANCHOR BOLT PAIRS
Diameter. : 1"
Type of steel. : Mild
Edge distance. : 6"
Method of installation. : Cast-in-place
CONCRETE REINFORCING. : Nominal
TYPE OF LOADING. : Shear
SPACING BETWEEN BOLTS : Varies

* Refer to appendix A for an explanation of specimen identification codes.

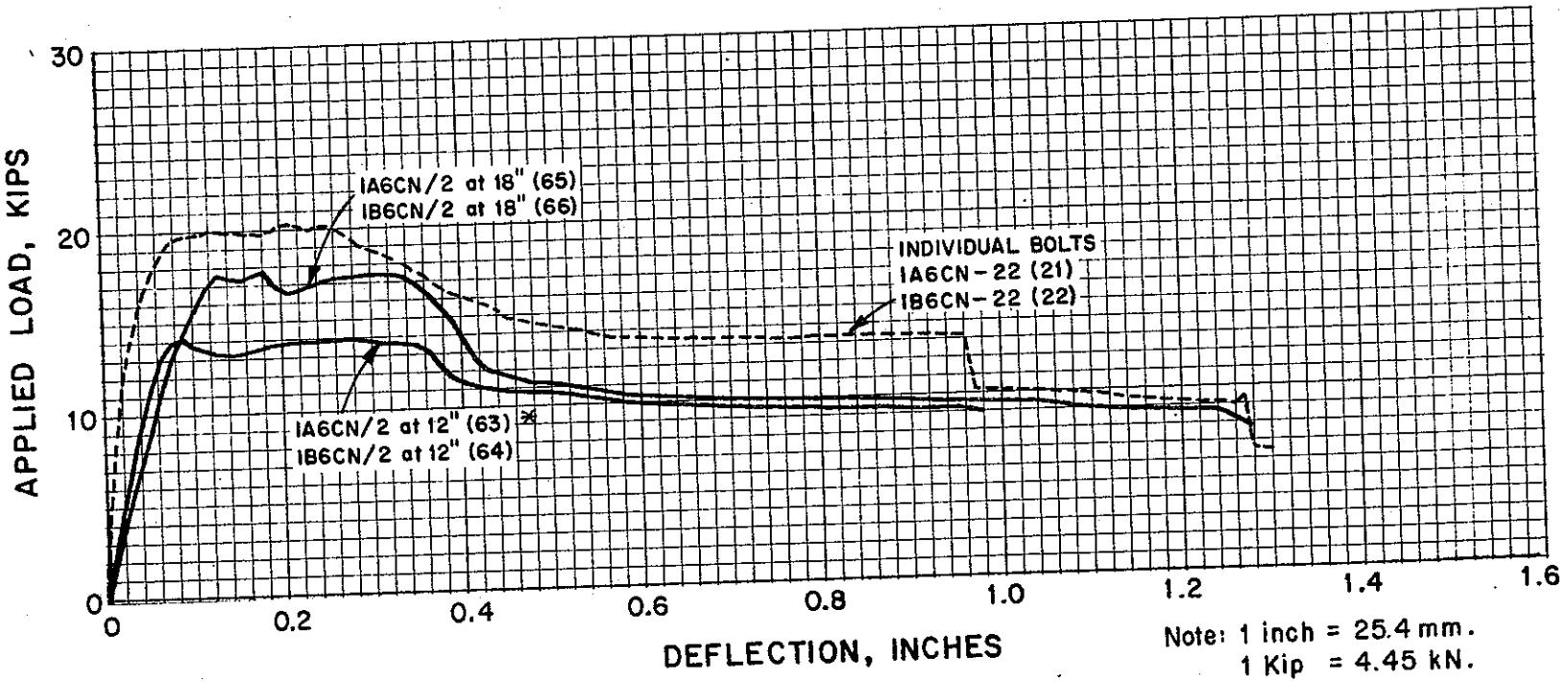
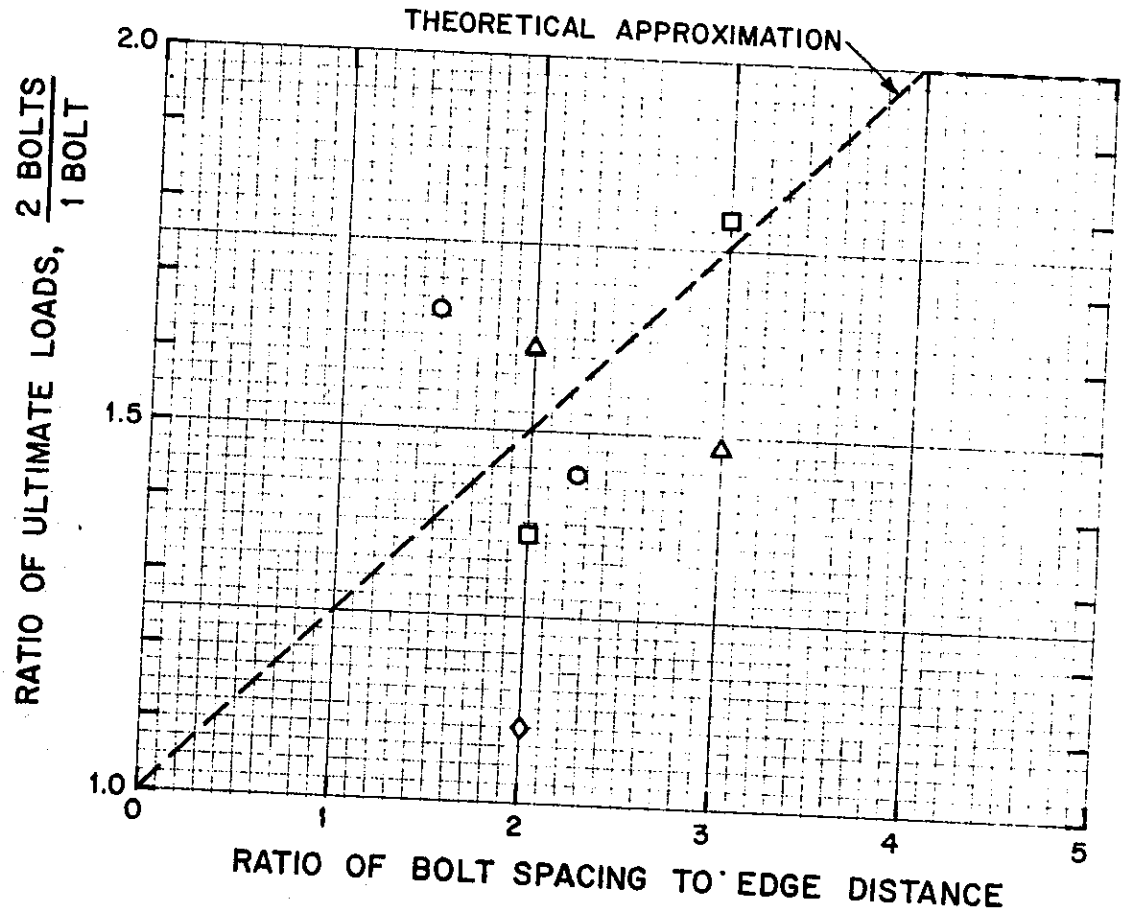


Figure 38. The effect of bolt spacing on the lateral resistance per bolt of one-inch diameter anchor bolt pairs.



SYMBOL	SPACING	EDGE DISTANCE	TYPE OF REINFORCEMENT
□	12", 18"	6"	NOMINAL
◇	16"	8"	NOMINAL
△	12", 18"	6"	NOMINAL WITH HAIRPINS
○	12", 18"	8"	NOMINAL WITH HAIRPINS

NOTE: EACH DATA POINT REPRESENTS AN AVERAGE OF TWO TESTS.

1 inch = 25.4 mm.

Figure 39. Relationship between ultimate load ratio of pairs of bolts to single bolts and spacing/edge distance ratio for one-inch diameter anchor bolts.

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in shear failure of the bolt or failure of the hairpin in tension or bond. Assuming that 1-inch (25.4-mm) bolts lack the necessary rigidity to take full advantage of hairpin reinforcement, it seems reasonable to average all test results for a given edge distance to bolt spacing ratio. Data points shown in Figure 39 depict these averages. The dashed line defines the curve shape expected from results of a theoretical approximation, with a maximum ultimate load ratio at a bolt spacing to edge distance ratio of 4.0. Because only a limited number of group tests were conducted and data was somewhat scattered, it was not possible to validate a design curve.

It was not feasible to test pairs of 2-inch (50.8-mm) diameter bolts but it is suspected that close spacing would have less influence on laterial resistance where hairpin reinforcement is used on this size bolt.

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VI. REFERENCES

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4. State of California, Department of Transportation, "Bridge Planning and Design Manual, Vol. I", Section 5-56, Structural Steel Design - Anchor Bolts, February, 1970.

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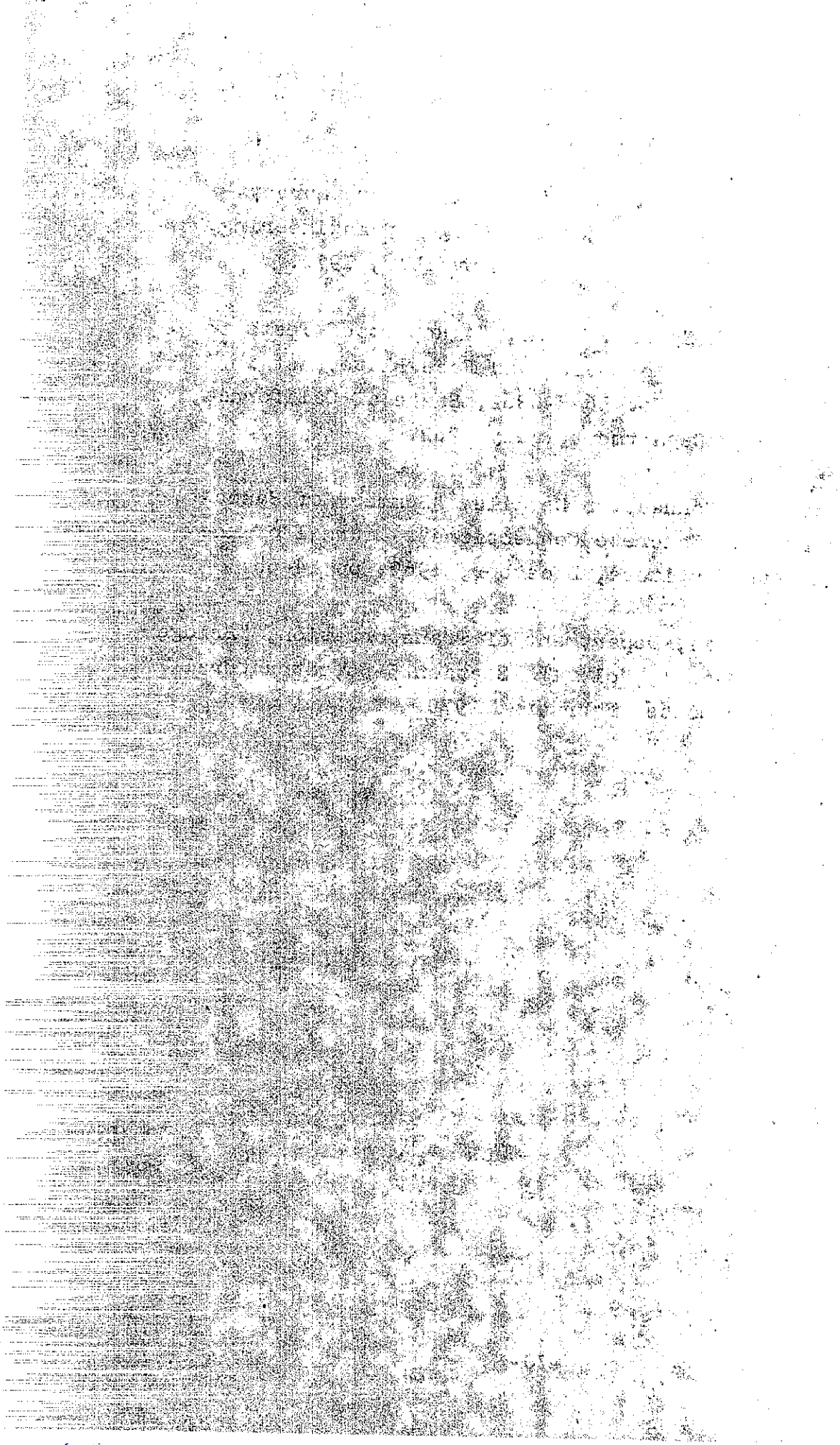

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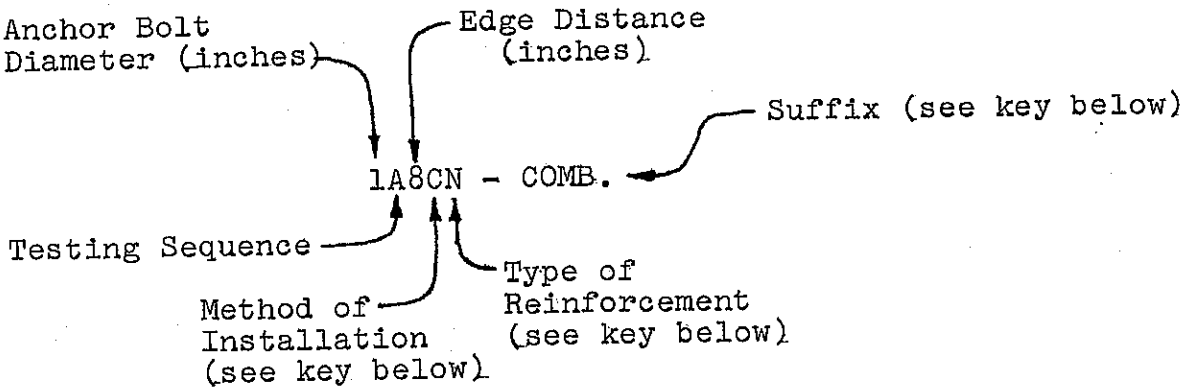
SPECIMEN IDENTIFICATION CODES



Explanation of Typical Anchor Bolt Identification Number

Method of Installation

C = Cast-in-place

S = Cannister (sleeve and mortar

D = Drilled hole and epoxy

Type of Reinforcement

N = Nominal reinforcing (#4 rebar @ 18 in.)

H = Nominal reinforcing with two hairpin rebars around anchor bolt

U = Nominal reinforcing with two vertical stirrups near anchor bolt.

Suffix

Note: Unless otherwise specified pure shear loading and mild steel anchor bolts are assumed.

CYCLIC = Cyclic loading

COMB. = Combined shear and bending moment loading

H.S. = High strength anchor bolts

2 @ 18 = Two bolts spaced 18 inches apart

22, 33, or 44 = Clear span distance (inches) between support beams

Note: 1 inch = 25.4 mm.

Appendix A-1. Key to abbreviations in the specimen identification code sections of the test information summaries.

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MATERIALS INFORMATION

- Concrete

  fc = Compressive strength of concrete, psi, at time of lateral shear tests.

- Anchor Bolt Steel

  fs YIELD = Stress (ksi) at the yield point in the anchor bolt steel.

  fs ULT. = Ultimate stress (ksi) in the anchor bolt steel.

TEST DATA

- Lateral Loads

  P at CRACK = Lateral load (kips) on the anchor bolt(s) when first cracks in the concrete block were visually observed.

  P at Δ = 0.05" = Lateral load (kips) on the anchor bolt(s) at a bolt deflection of 0.05 inches.

  P at 1st PEAK = The first peak lateral load (kips) on the anchor bolt(s) observed at a deflection of less than 0.5 inches.

  P at ULT. = Maximum lateral load sustained by the anchor bolt(s) during the course of the test.

- Deflections

  Δ at CRACK = The deflection (inches) of the anchor bolt(s), measured at the probe location, when the first crack in the concrete block was visually observed.

  Δ at 1st PEAK = The deflection (inches) of the anchor bolt measured at the probe location when the first peak in load at a deflection of less than 0.5 inches occurred.

  Δ at ULT. = The deflection (inches) of the anchor bolt(s), measured at the probe location, when the maximum lateral load on the bolt(s) occurs.

- Failure Modes

  C = Severe cracking of concrete.

  HP = Bond failure and/or tensile failure of hairpin reinforcement.

  B = Complete shear failure of anchor bolt.

- Ratio of Ultimate Loads

  P_2/P_1 = Ratio of ultimate lateral load resistance of bolt pairs to the ultimate lateral load resistance of individual bolts.

NOTE: 1 inch = 25.4 mm.
1 kip = 4.45 kN.

Appendix A-2. Key to abbreviations in the materials information and test data sections of the test information summaries.

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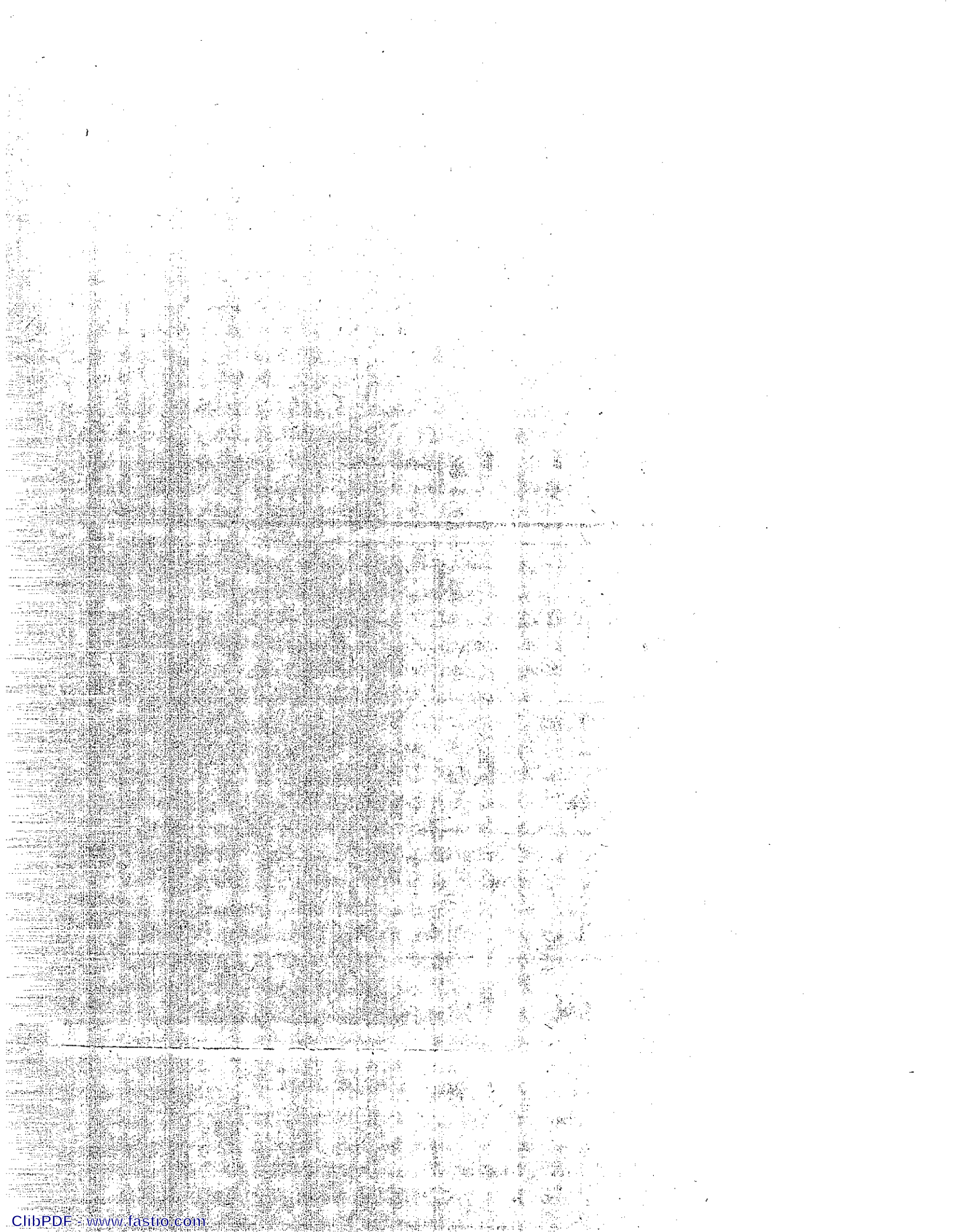
TE	ANCHOR BOLT STEEL			LATERAL LOAD, P (KIPS)				DEFLECTION, Δ (INCHES)			FAILURE MODES	GENERAL COMMENTS
AGE (days)	fs YIELD (ksi)	fs ULT. (ksi)	TYPE	P at CRACK	P at Δ=0.05"	P at 1st PEAK	P at ULT.	Δ at CRACK	Δ at 1st PEAK	Δ at ULT		
			ASTM A307	——	10.8	12.0	16.6	——	0.07	0.4	C	#4 hairpins
16	43	68	Hot	——	11.7	14.5	14.6	——	0.125	0.17	C	w/10 inch legs
			Drawn	——	10.0	13.5	26.3	——	0.10	>1.0	C,B	#4 hairpins
			Mild	——	12.4	18.0	24.9	——	0.16	>1.0	C,B	w/5 inch legs
			Steel	10.0	10.6	10.6	25.2	0.033	0.05	>1.0	C	#4 hairpins
15	40	62		8.9	11.0	11.0	25.2	0.022	0.05	>1.0	C	w/10 inch legs
14				——	14.0	16.4	16.5	——	0.11	0.12	C	
14	42	66		9.0	11.0	12.5	12.6	0.02	0.14	0.14	C	
19	40	62		8.9	10.5	10.7	11.7	0.022	0.065	0.37	C	
14	40	62		11.3	12.5	12.5	21.1	0.022	0.05	>1.0	C	
				13.0	13.5	14.1	16.8	0.044	0.08	>1.0	C	
				——	8.7	10.9	11.0	——	0.105	0.1	C	
15	42	66		——	4.5	9.6	9.7	——	0.15	0.12	C	
14				26.3	3.5	——	32.3	0.750	——	>1.0	B only	#4 hairpins w/11 inch
15	40	62		20.6	11.0	——	41.1	0.230	——	>1.0	C,B	legs
19				17.0	8.5	——	41.7	0.225	——	>1.0	C,B	← Bolt split cannister open
14				——	10.0	20.4	20.7	——	0.14	0.14	C	
15	42	66		——	7.0	15.4	15.5	——	0.165	0.165	C	
				20.0	16.0	20.3	30.9	0.215	0.235	>1.0	C,B	#4 hairpins w/10 inch legs
14	40	62		17.0	15.0	21.7	36.3	0.082	0.23	>1.0	C,HP	← Bolt 1/2 sheared
15				——	19.0	19.7	21.0	——	0.08	0.21	C	
15	43	68		——	15.0	21.0	21.0	——	0.12	0.12	C	
15				——	17.2	17.2	17.3	——	0.06	0.06	C	
15				——	16.5	19.8	19.9	——	0.1	0.1	C	
14	43	68		——	20.1	20.1	20.1	——	0.05	0.05	C	
15				——	17.2	18.3	18.6	——	0.07	0.07	C	
				21.5	12.5	—	39.0	0.228	—	>1.0	C	#4 hairpins
15	40	62		22.5	15.5	—	35.5	0.249	—	0.94	C,HP	w/10 inch legs
				——	12.5	—	32.4	——	—	>0.5	C	← Bolt 1/2 sheared
16	42	66		——	10.5	—	32.4	——	—	0.51	C	← Bolt 1/4 sheared
				——	10.5	—	26.8	——	—	0.45	B only	
16	42	66		17.5	12.0	—	26.2	0.16	—	0.57	B only	
				32.5	10.0	—	36.8	0.732	—	0.94	C	
16	40	62		30.5	14.5	—	37.7	0.462	—	0.75	C	



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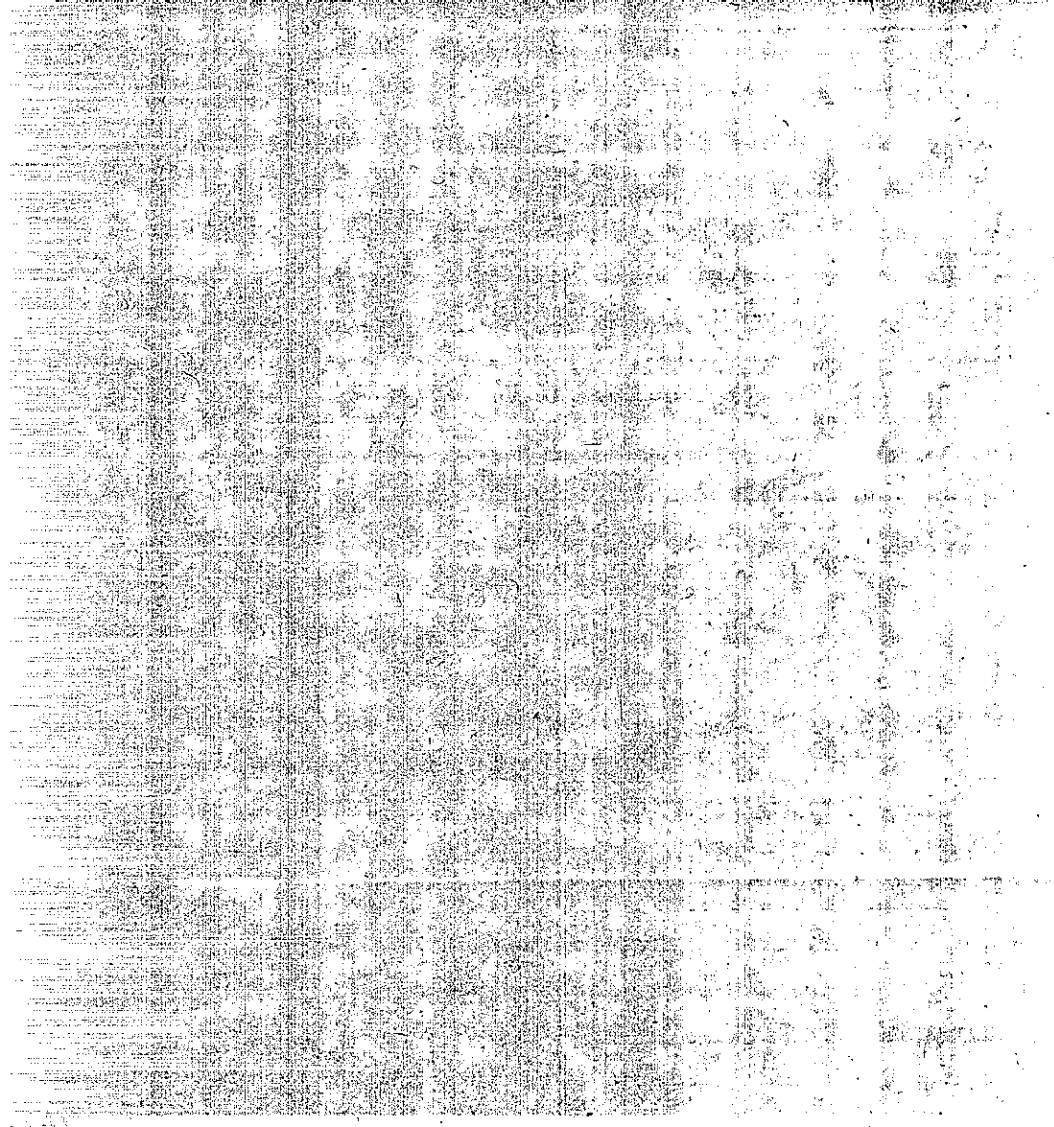
(days)	(ksi)	(ksi)		CRACK	Δ=0.05"	1st PEAK	ULT	CRACK	1st PEAK	ULT	MODES	COMMENTS
15	43	67	ASTM A307 hot drawn mild steel	23.3	31.0	44.5	46.8	0.025	0.22	> 0.7	C	#4 hairpins
15	43	67		21.5	31.5	45.0	46.2	0.017	0.19	0.61	C	w/10 inch legs
19	62	72	ASTM A307 cold drawn mild steel	30.2	32.3	——	73.3	0.042	——	0.7	C,HP	#5 hairpins
21	62	72		20.0	28.5	——	77.3	0.018	——	> 0.9	C,HP	w/14 inch legs
15	43	67	ASTM A307 hot drawn mild steel	21.6	24.6	26.3	26.3	0.02	0.19	0.19	C	
15				19.6	25.0	25.0	25.4	0.013	0.05	0.48	C	
16				15.4	18.6	20.8	20.8	0.026	0.19	0.19	C	
16				18.5	5.0	20.8	20.8	0.08	0.18	0.18	C	
16				29.0	44.0	87.9	87.9	0.023	0.48	0.48	C	#5 hairpins
16				31.5	45.0	84.5	84.5	0.03	0.35	0.35	C	w/14 inch legs
16				20.0	25.5	34.4	34.4	0.045	0.11	0.11	C	
16				22.5	32.6	34.7	34.7	0.024	0.065	0.065	C	
19				61.0	25.0	76.8	77.9	0.15	0.36	> 1.0	C	#5 hairpins
19				67.0	31.7	80.0	80.0	0.16	0.28	0.28	C	w/14 inch legs
16				49.2	46.8	55.1	55.1	0.056	0.077	0.077	C	
16				53.3	49.0	60.0	60.0	0.06	0.092	0.092	C	
20				51.0	23.0	——	69.0	0.273	——	0.55	C	
20				53.0	27.0	61.0	61.0	0.195	0.41	0.41	C	
20				61.0	26.2	——	91.7	0.3	——	0.83	C	#5 hairpins
20				58.0	32.5	——	91.3	0.22	——	0.67	C	w/16 inch legs
20				51.5	28.0	65.7	65.7	0.14	0.31	0.31	C	
20				53.0	39.0	59.2	59.2	0.087	0.16	0.16	C	

to Appendices A-1 and A-2 for explanation of above abbreviations.

= 25.4 mm.
= 4.45 kN.

ormation summary of tests conducted on individual two inch diameter anchor bolts.



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ays)	(ksi)	(ksi)	TYPE	a CRACK	a Δ=0.05"	a 1st PEAK	a ULT	Δ a CRACK	Δ a 1st PEAK	Δ a ULT	MODES	ULTIMATE LOADS	COMMENTS
7	40	62	ASTM A307 Hot drawn mild steel	30.0	26.0	30.0	49.7	0.09	0.09	> 1.0	C, Left B	1.61	#4 hairpins w/10 inch legs
7				30.0	8.0	30.0	58.2	0.22	0.23	> 1.0	C, Left HP	1.61	
6				28.0	18.3	35.5	43.7	0.083	0.19	> 1.0	C	1.48	
6				33.0	12.5	33.3	55.6	0.175	0.185	> 1.0	C, Right HP	1.48	
1				27.5	18.8	28.6	28.6	0.078	0.09	0.09	C	1.36	
6				21.0	24	28.5	28.5	0.039	0.098	0.098	C	1.36	
21				27.0	21.3	40.7	40.7	0.078	0.18	0.18	C	1.79	
23				28.0	14.5	34.4	34.4	0.081	0.12	0.12	C	1.79	
26				40.0	14.5	45.5	60.9	0.21	0.34	> 1.0	C, Right HP	1.66	#4 hairpins w/10 inch legs
26				43.0	19.5	43.5	62.7	0.25	0.28	> 1.0	C, Right B	1.66	
26				47.0	29.7	49.3	53.4	0.25	0.31	> 1.0	C, Right B	1.44	
27				35.5	27.0	35.5	53.8	0.14	0.14	——	C, Left HP	1.44	
26				25.0	22.5	32.2	32.2	0.065	0.19	0.19	C	1.10	
23				38.5	27.0	39.3	39.3	0.1	0.11	0.11	C	1.10	

Appendices A-1 and A-2 for explanation of above abbreviations.

loads shown above represent the total load on both bolts.

25.4 mm.
4.45 kN.

rmation summary of tests conducted on pairs of one inch diameter anchor bolts.

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14	40	62	ASTM A307 hot drawn mild steel	13.2	2.5	—	38.0	1.02	—	>1.0	C,B	#4 hairpins w/10 inch legs
15	40			14.2	3.0	—	38.0	0.9	—	>1.0	C,H.P.	
15	40			—	4.7	—	20.5	—	—	>1.0	B only	Failure occurred in the threaded region of the bolt.
15	40			—	4.0	—	19.7	—	—	>1.0	B only	
15	40			13.5	—	—	40.1	—	—	>1.0	C,B	#4 hairpins w/10 inch legs
16	40			14.0	—	—	36.0	—	—	>1.0	C,HP	
16	40			14.5	—	—	24.0	—	—	>1.0	C	
16	40	62		15.2	—	—	21.0	—	—	0.25	C	
15	88	124	ASTM A449 High Strength Steel	14.5	5.1	—	38.0	0.32	—	>1.0	C,HP	#4 hairpins w/10 inch legs
15	88			13.0	4.3	—	38.9	0.25	—	>1.0	C,HP	
16	88			13.0	—	—	31.0	—	—	>1.0	C,HP	
19	88			14.0	—	—	29.7	—	—	>1.0	C,HP	
21	43	67	ASTM A307 hot drawn mild steel	18.0	20.3	—	59.3	0.04	—	>1.0	C,HP	#5 hairpins w/14 inch legs
21	43	67		15.5	16.5	—	64.0	0.04	—	>1.0	C,HP	
21	62	72	ASTM A307 cold drawn mild steel	19.2	—	—	72.8	—	—	>1.0	C,HP	
22	62	72		18.2	—	—	59.7	—	—	>0.5	C,HP	
23	71	105	ASTM A449 High Strength Steel	14.5	16.3	—	58.9	0.04	—	0.85	C,HP	
23	71			17.0	16.6	—	64.7	0.055	—	>1.0	C,HP	
22	71			15.0	—	—	68.4	—	—	>1.0	C,HP	
23	71	105		15.0	—	—	67.0	—	—	>1.0	C,HP	

Appendices A-1 and A-2 for explanations of above abbreviations.

= 25.4 mm.
4.45 kN.

mation summary of tests conducted on individual one and two inch diameter
r bolts subjected to cyclic and combined loading.

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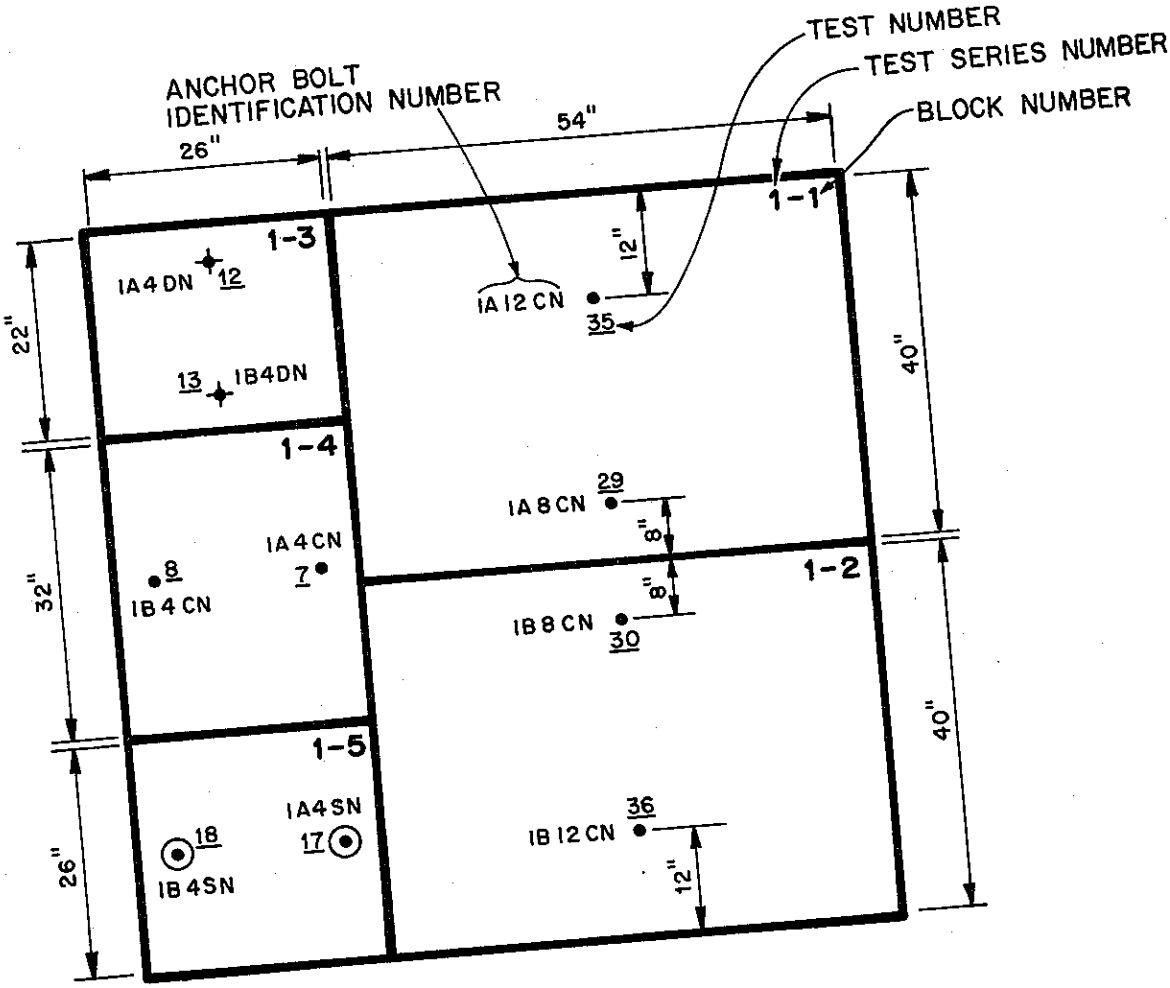

PLAN VIEW

SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● – CAST-IN-PLACE
- ⊙ – CANNISTER AND MORTAR
- ✦ DRILLED HOLE AND EPOXY

NOTE: ALL BLOCKS IN TEST SERIES 1 ARE 24 INCHES DEEP. BOLTS INSTALLED IN ALL TEST SERIES 1 SPECIMENS ARE ONE INCH DIAMETER.
SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.
1 INCH = 25.4mm.

Appendix B-1. Dimensions and layout of blocks in test series 1.

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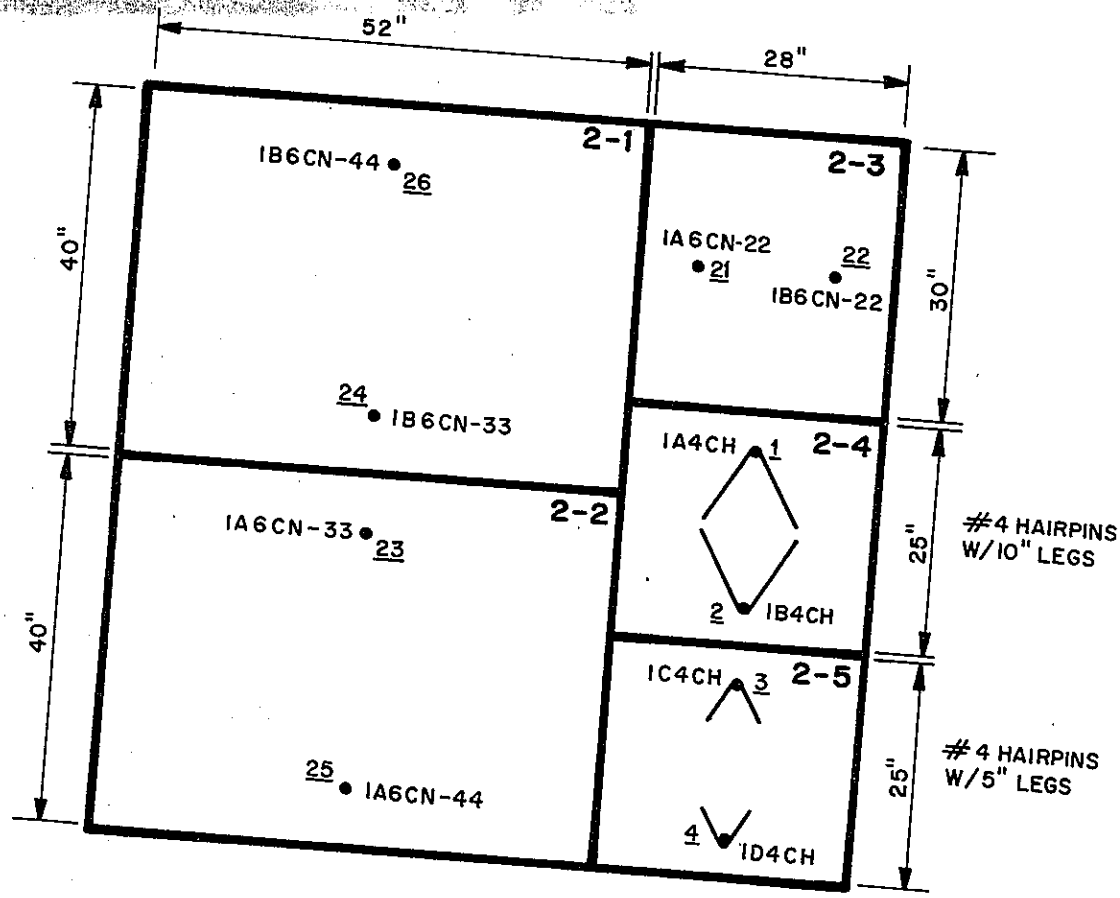

PLAN VIEW

SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● - CAST-IN-PLACE
- ⊙ - CANNISTER AND MORTAR

NOTE: ALL BLOCKS IN TEST SERIES 2 ARE 24 INCHES DEEP.
BOLTS INSTALLED IN ALL TEST SERIES 2 SPECIMENS ARE ONE INCH DIAMETER.
SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.
1 INCH = 25.4 mm.

Appendix B-2. Dimensions and layout of blocks in test series 2.

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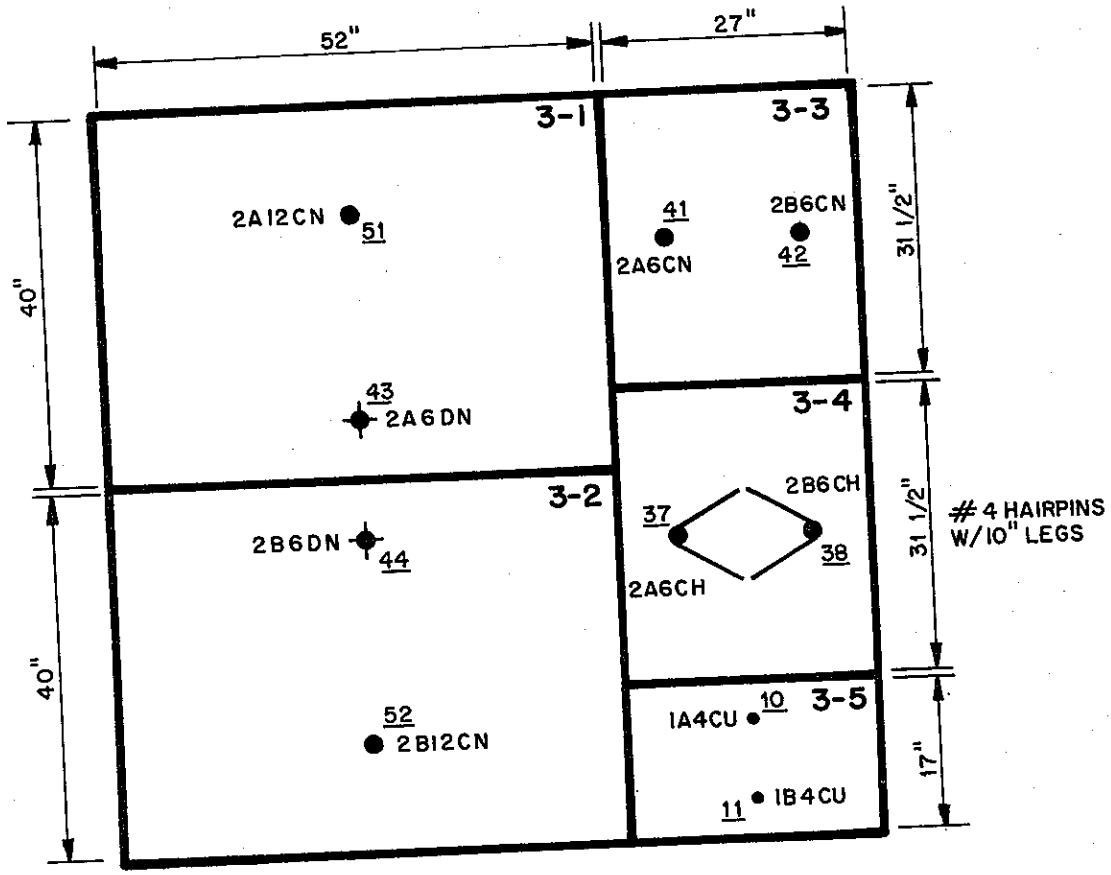

PLAN VIEW

SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● - CAST-IN-PLACE
- ⊙ - CANNISTER AND MORTAR
- ✦ DRILLED HOLE AND EPOXY

NOTE: ALL BLOCKS IN TEST SERIES 3 ARE 24 INCHES DEEP.

SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.

1 INCH = 25.4 mm.

Appendix B-3. Dimensions and layout of blocks in test series 3.

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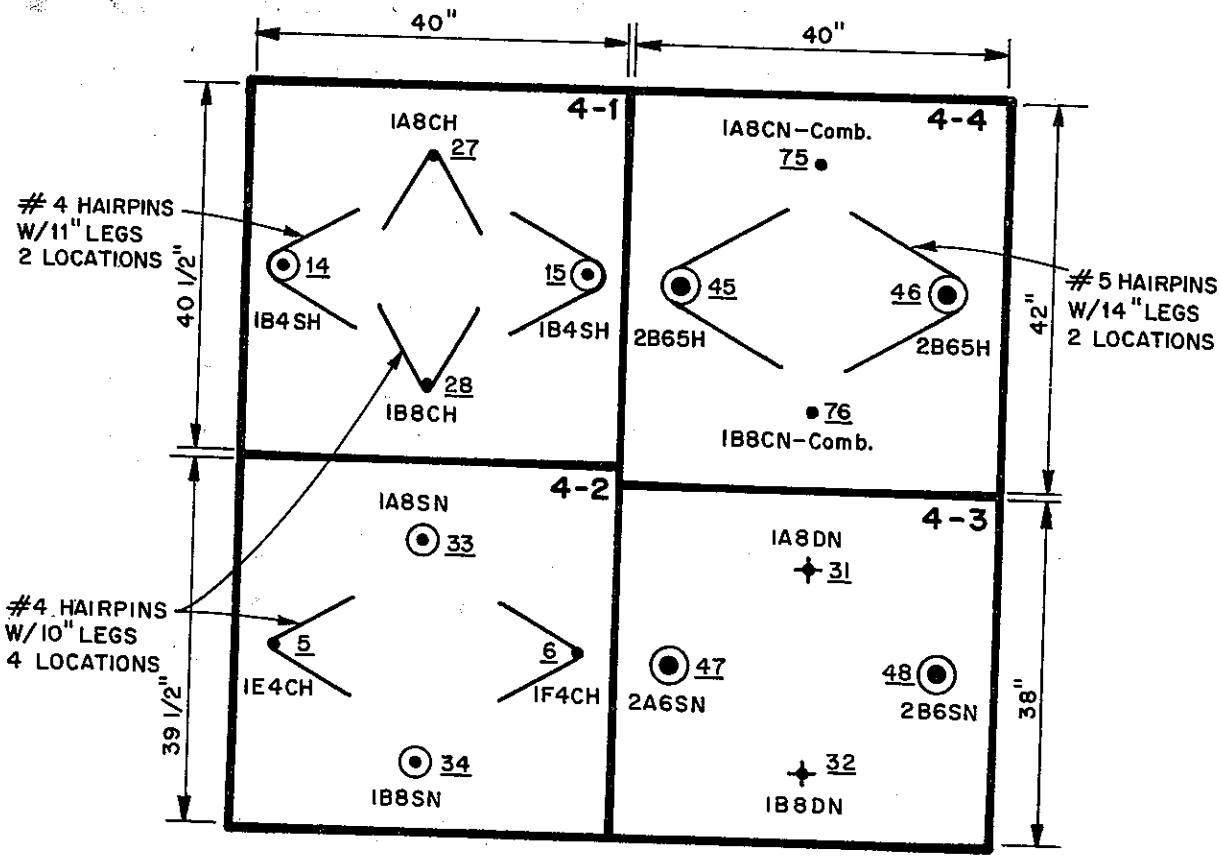

PLAN VIEW

SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● - CAST-IN-PLACE
- ⊙ - CANNISTER AND MORTAR
- ✦ DRILLED HOLE AND EPOXY

NOTE: ALL BLOCKS IN TEST SERIES 4 ARE 24 INCHES DEEP.

SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.

1 INCH = 25.4 mm.

Appendix B-4. Dimensions and layout of blocks in test series 4.

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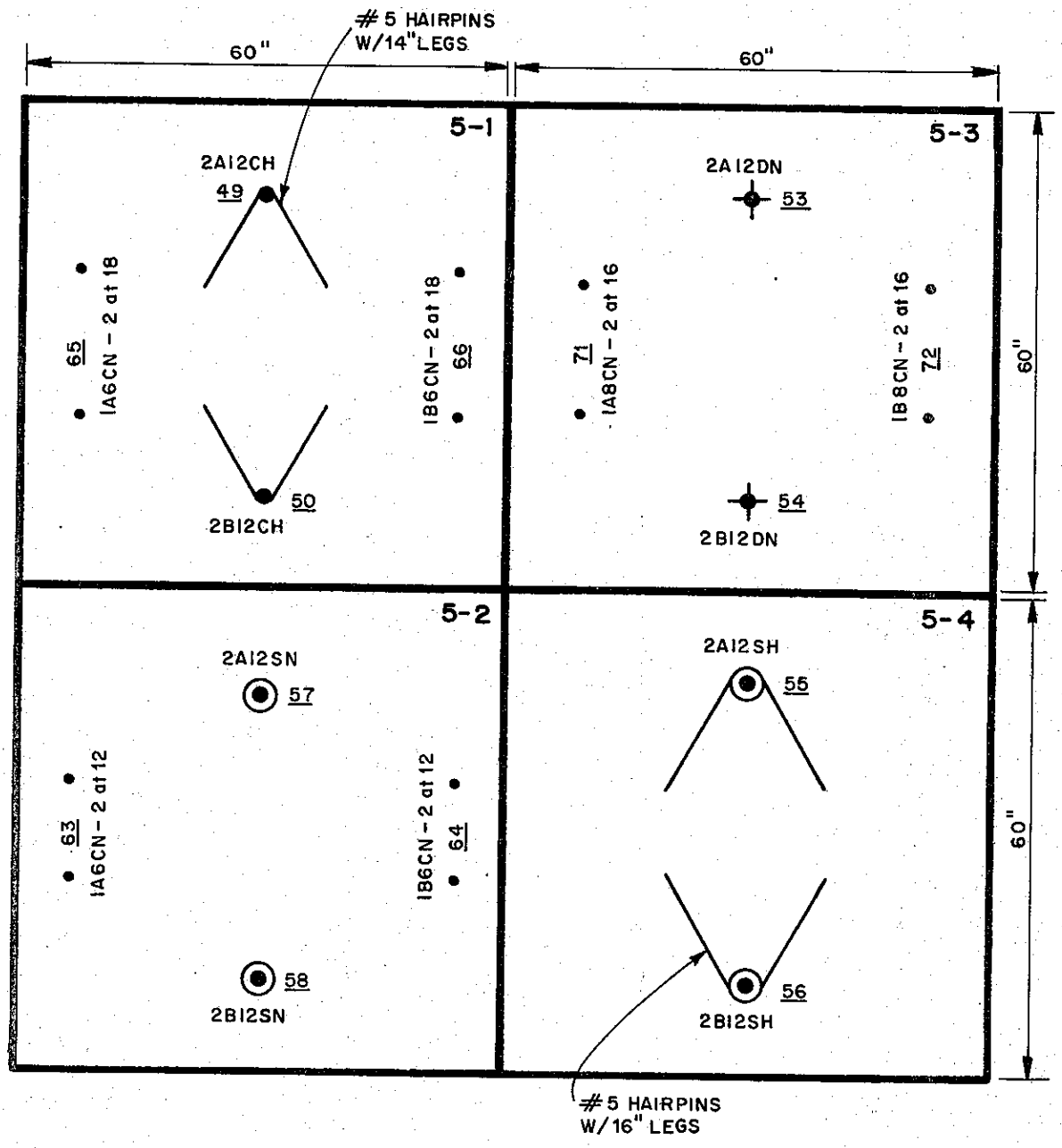


PLAN VIEW

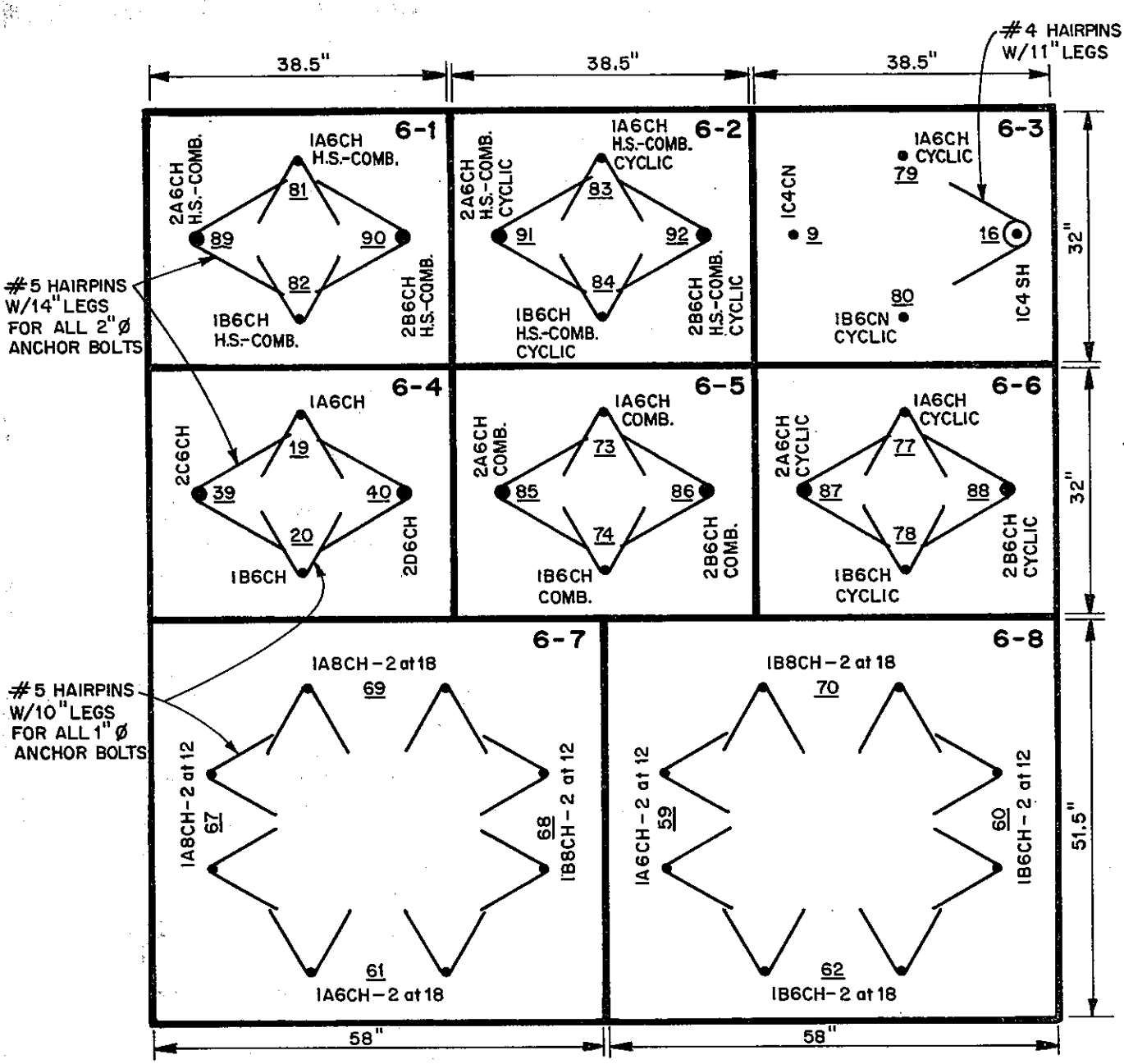
SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● - CAST-IN-PLACE
- ⊙ - CANNISTER AND MORTAR
- ✦ DRILLED HOLE AND EPOXY

NOTE: ALL BLOCKS IN TEST SERIES 5 ARE 24 INCHES DEEP.
BOLTS INSTALLED IN ALL TEST SERIES 1 SPECIMENS ARE ONE INCH DIAMETER.
SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.
1 INCH = 25.4 mm.

Appendix B-5. Dimensions and layout of blocks in test series 5.

ClibPDF - www.fastio.com



PLAN VIEW

SYMBOLS DESCRIBING TYPE OF BOLT INSTALLATION:

- ● - CAST-IN-PLACE
- ⊙ - CANNISTER AND MORTAR
- ✦ DRILLED HOLE AND EPOXY

NOTE: ALL BLOCKS IN TEST SERIES 6 ARE 24 INCHES DEEP.
BOLTS INSTALLED IN ALL TEST SERIES 1 SPECIMENS ARE ONE INCH DIAMETER.
SEE APPENDIX A FOR A COMPLETE EXPLANATION OF SPECIMEN IDENTIFICATION CODES AND TEST DATA.
1 INCH = 25.4 mm.

Appendix B-6. Dimensions and layout of blocks in test series 6.

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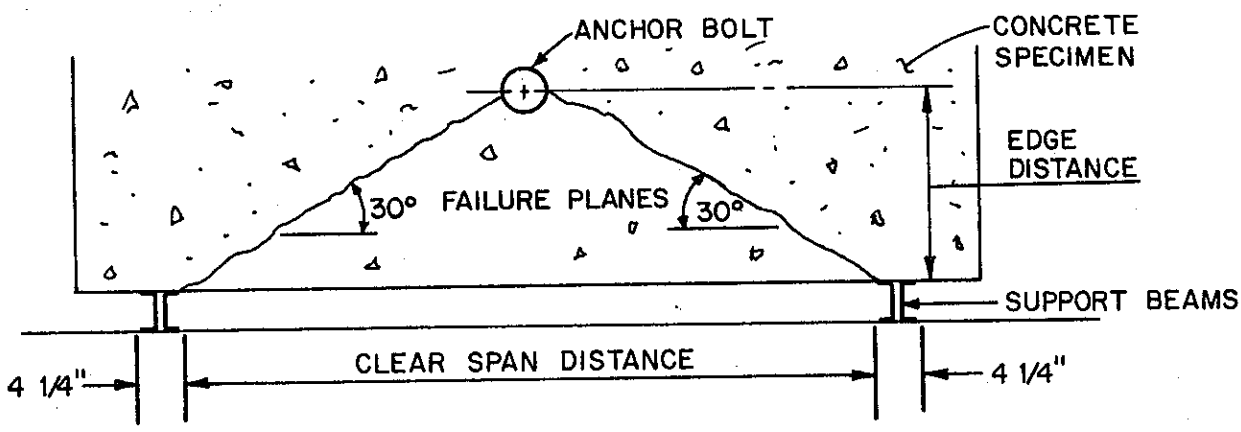

TYPICAL FRONT VIEW OF CONCRETE TEST SPECIMEN

BOLT OR SLEEVE DIAMETER (INCHES)	EDGE DISTANCE (INCHES)	CLEAR SPAN DISTANCE (INCHES) BETWEEN SUPPORT BEAMS
1	4	15
	6	22
	8	29
	12	43
2	6	23
	12	44
3	4	17
	6	24
	8	31
	12	45
5	6	26
	12	47

Note: 1 inch = 25.4 mm.

Appendix C-1. Clear span distances between support beams.

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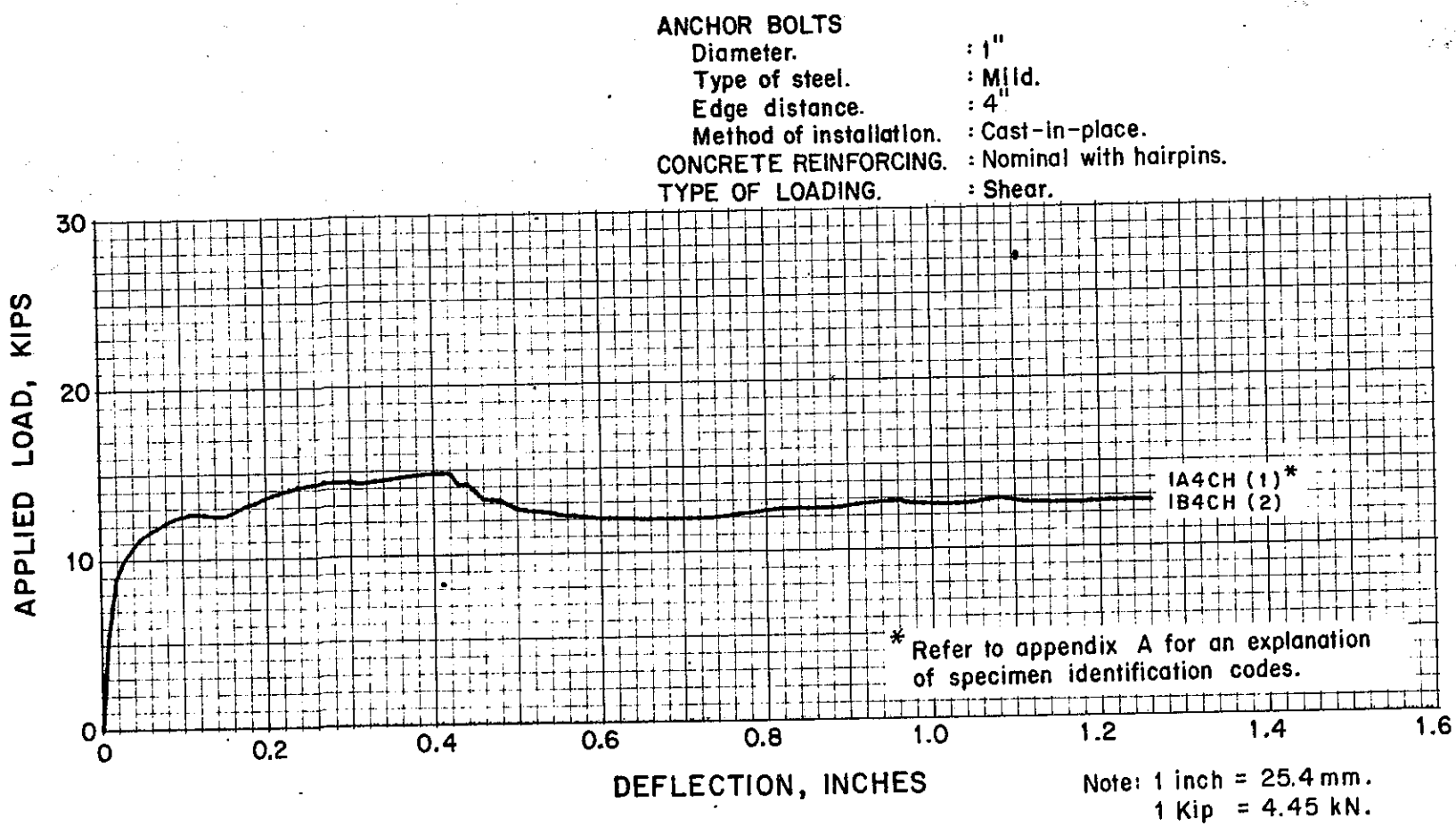

Appendix D-1. Load-deflection plot average of tests 1A4CH (1) and 1B4CH (2)

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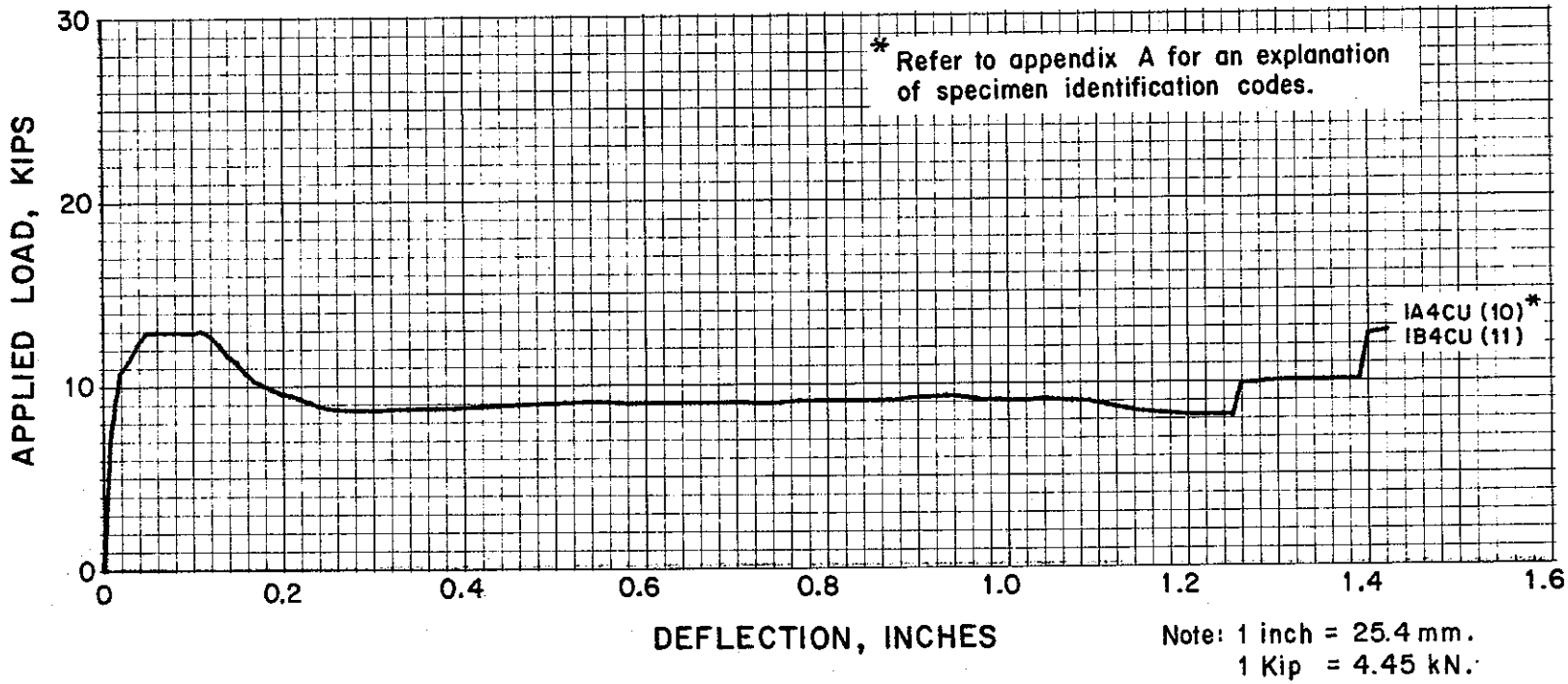
ANCHOR BOLTS
Diameter. : 1"
Type of steel. : Mild.
Edge distance. : 4"
Method of installation. : Cast-in-place.
CONCRETE REINFORCING. : Nominal with stirrups.
TYPE OF LOADING. : Shear.



Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Appendix D-2. Load-deflection plot average of tests IA4CU (10) and IB4CU (11)

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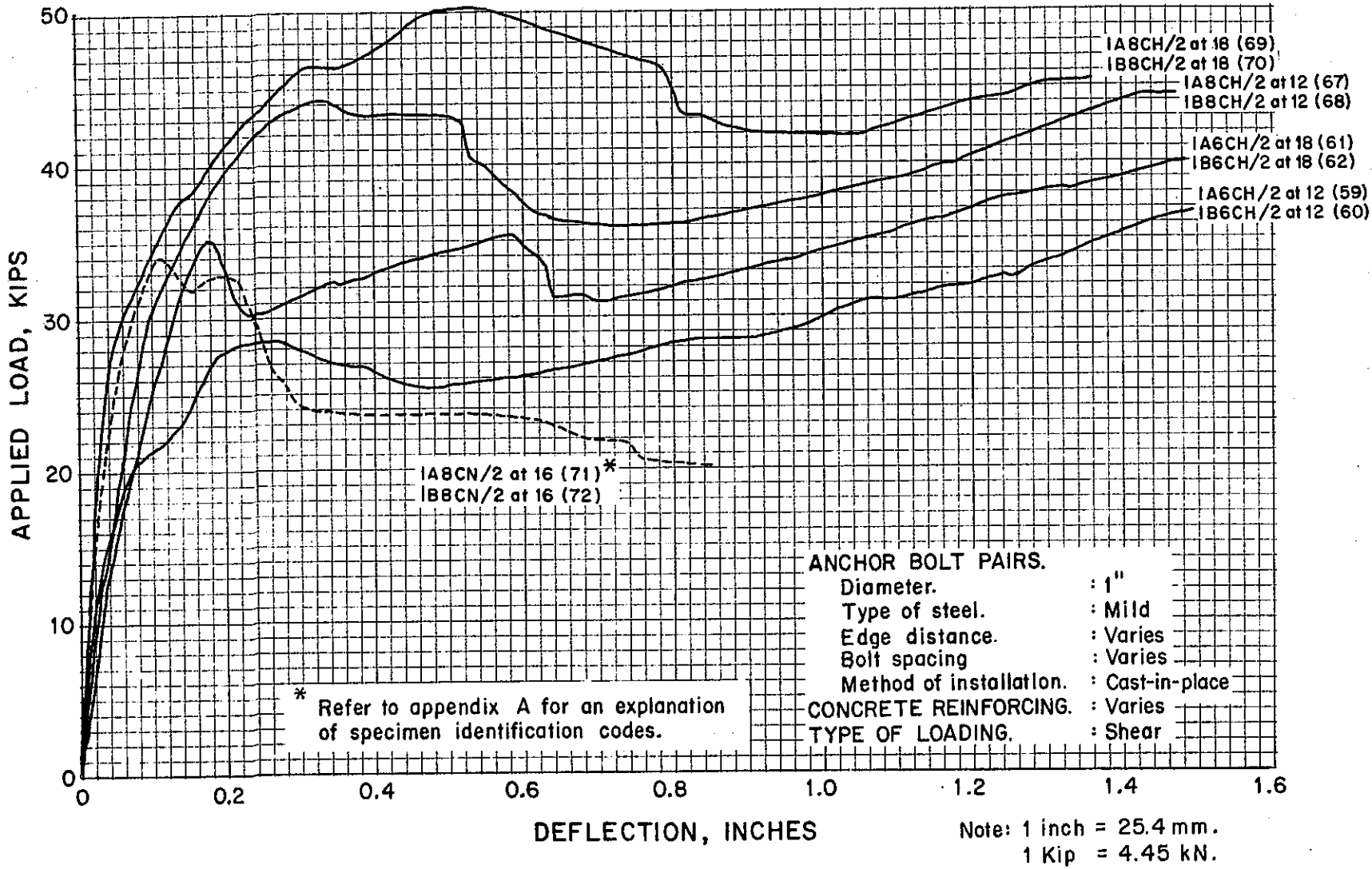

Appendix D-3. Load-deflection plot averages of bolt pair tests as shown.

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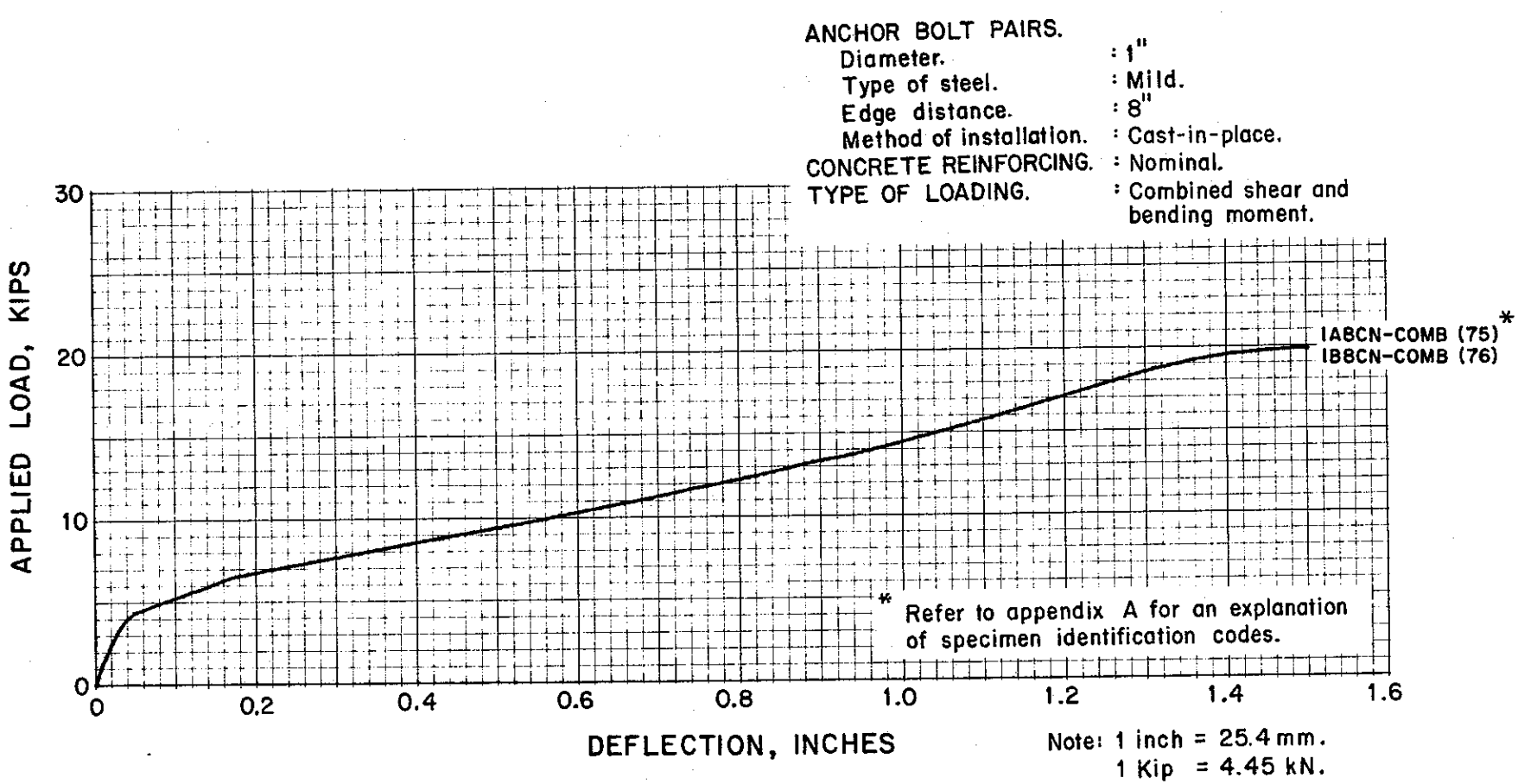

Appendix D-4. Load-deflection plot average of tests IA8CN-COMB (75) and IB8CN-COMB (76).

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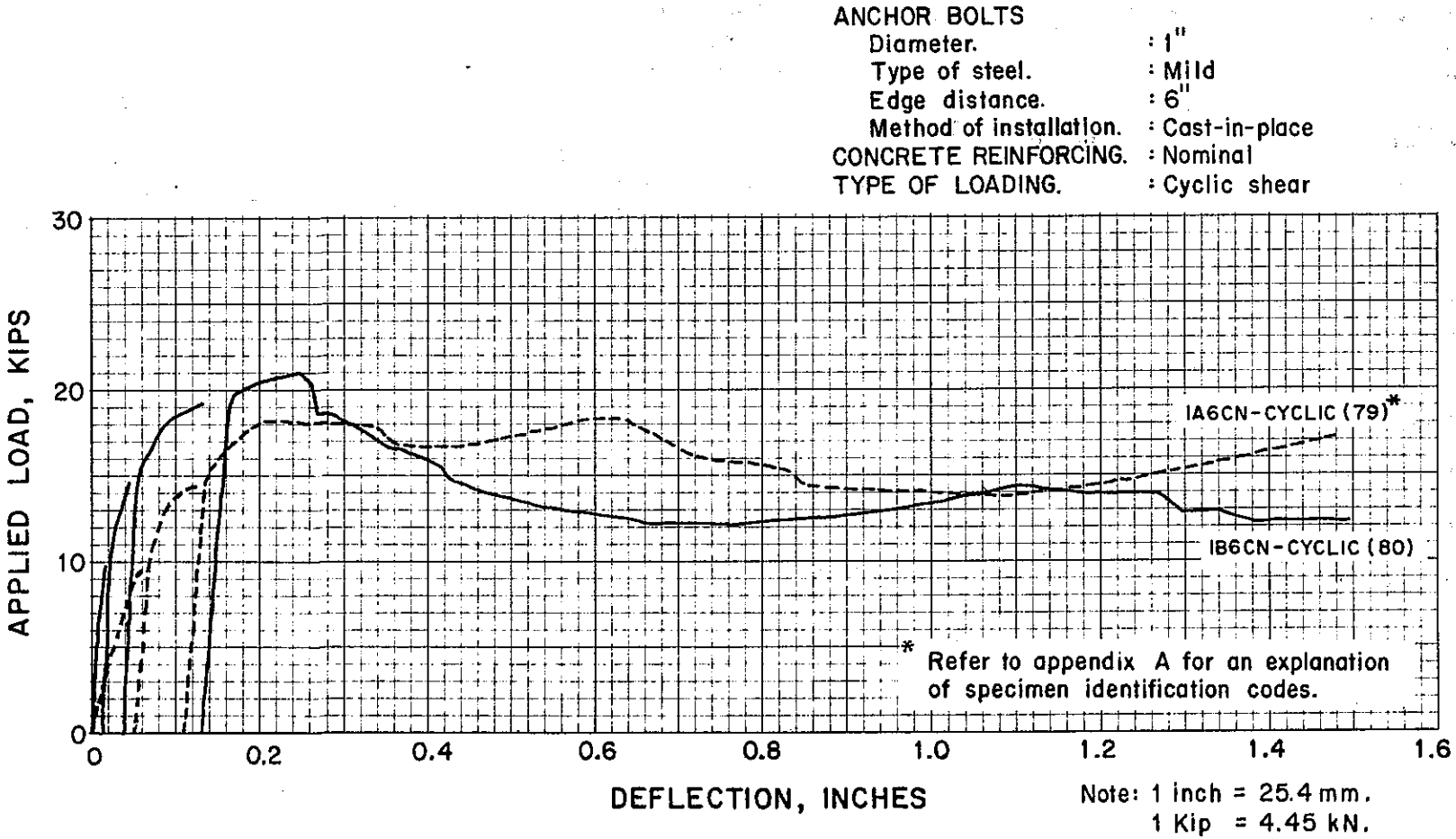

Appendix D-5. Load-Deflection plots of cyclic tests IA6CN-CYCLIC (79) and IB6NC-CYCLIC (80)

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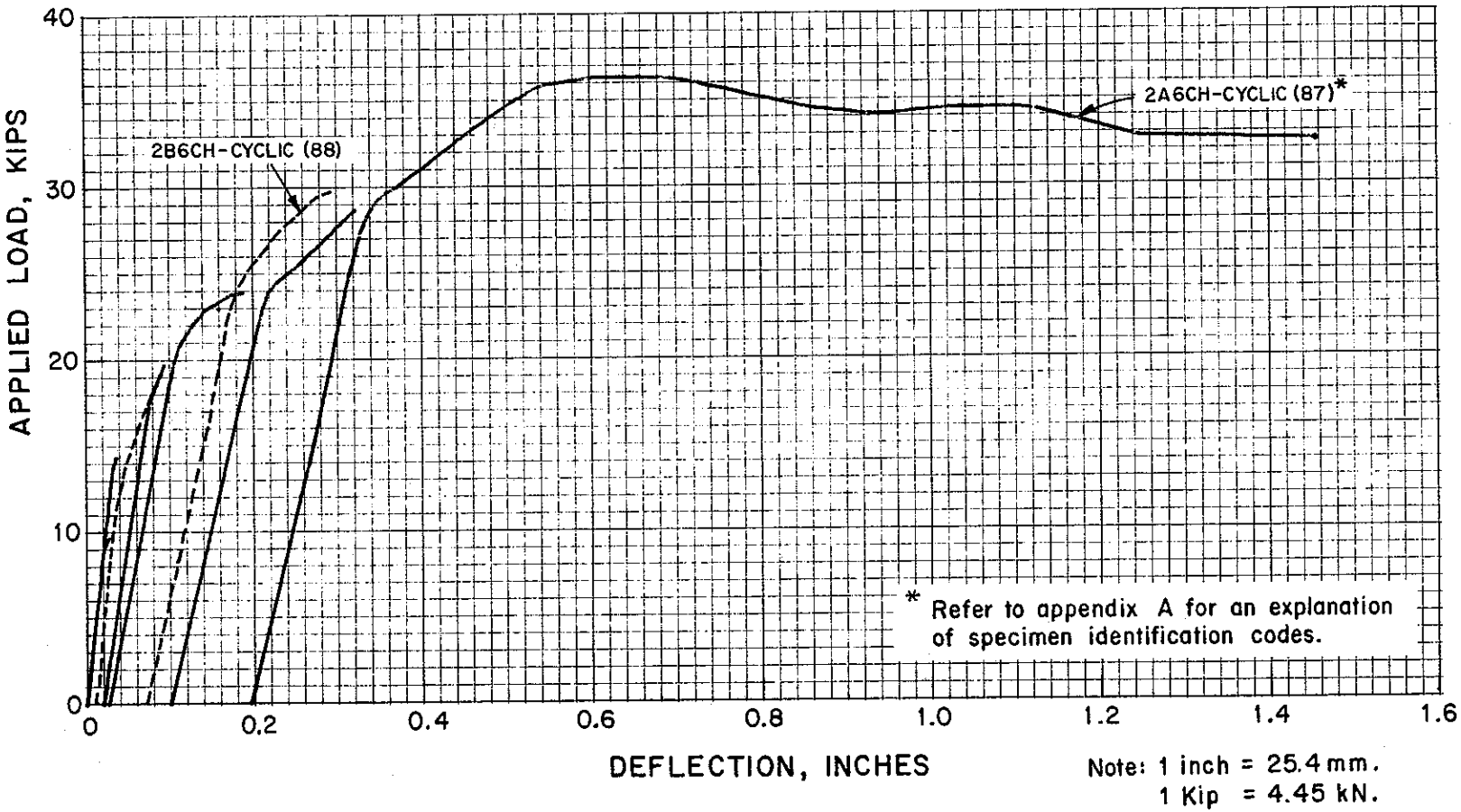
ANCHOR BOLTS
Diameter. : 2"
Type of steel. : Mild
Edge distance. : 6"
Method of installation. : Cast-in-place
CONCRETE REINFORCING. : Nominal with hairpins
TYPE OF LOADING. : Cyclic shear



Note: 1 inch = 25.4 mm.
1 Kip = 4.45 kN.

Appendix D-6. Load deflection plots of cyclic tests 2A6CH-CYCLIC (87) and 2B6CH-CYCLIC (88).

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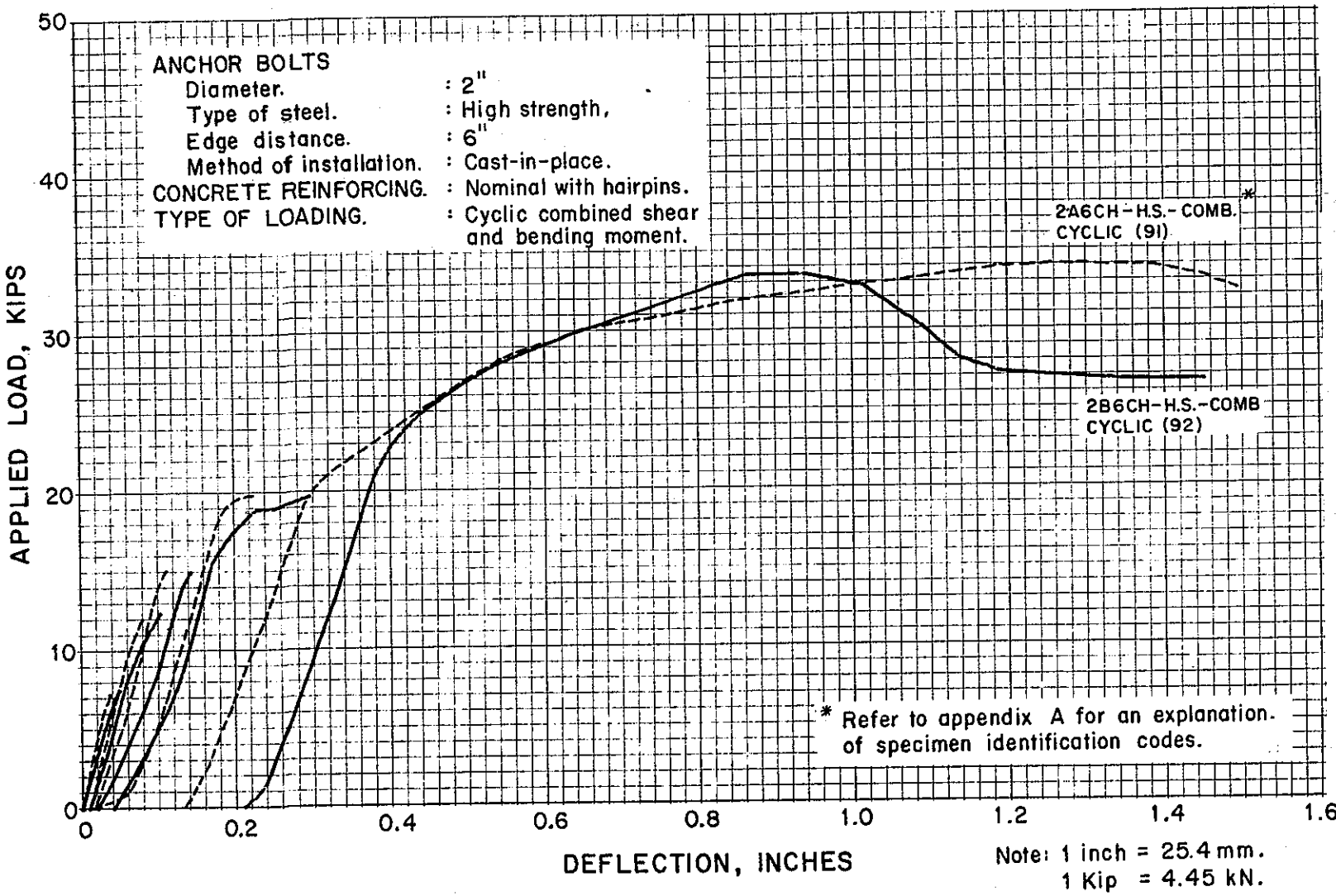

Appendix D-7. Load-deflection plots of cyclic tests 2A6CH-H.S.-COMB CYCLIC (91) and 2B6CH-H.S.-COMB CYCLIC (92)