BEHAVIOR OF STEEL TO CONCRETE CONNECTIONS INCORPORATING ADHESIVE FILLERS

by

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THESIS

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of

MASTER OF SCIENCE IN ENGINEERING

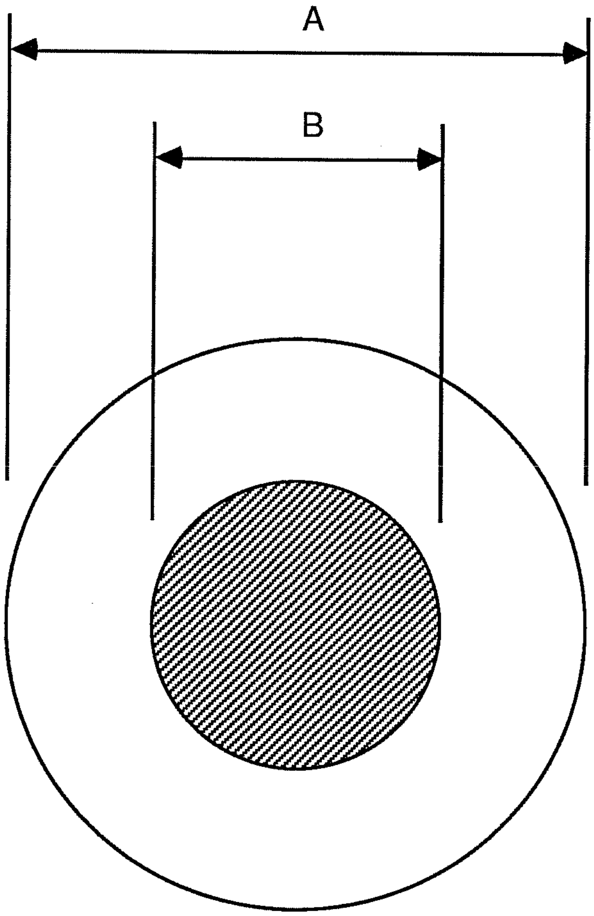
THE UNIVERSITY OF TEXAS AT AUSTIN
May 1988

ABSTRACT

Seventeen specimens were constructed and tested to investigate the load-deformation behavior of steel-to-concrete bolted shear connections. Three hole clearances were investigated, ranging from the standard 1/16-in. clearance to 5/16-in. oversize. Structural adhesive was used to fill the void created between the connecting rod and hole. Specimens were tested with no adhesive fillers, with the voids only partially filled with adhesive, and with the voids completely filled with adhesive. The nuts on some specimens with adhesive fillers were tightened by hand to investigate the effect of variation in bolt preload. It was found that connections with oversize holes and a completely filled rod-hole void were stiffer, stronger, and had more deformation capacity than connections with standard size holes and no adhesive filler. It was also found that bolt preload was not critical when using adhesive fillers.

at Austin (Grant No. CEE-82-1205). The major part of the research involved tests on a two-thirds scale model of a two-story, two-bay reinforced concrete frame. The unstrengthened frame was first damaged, then strengthened by wing walls and failed by lateral loading. The damaged frame was then retrofitted with a steel bracing system and tested again.

Distinguishing features of this research were the substantial size of the model, and the cooperative effort between the university and a private engineering design group, H. J. Degenkolb and Associates of San Francisco, California. Other projects in this program include investigations of the interface shear capacity of concrete surfaces, the use of epoxies for grouting reinforcing dowels, and the behavior of steel-to-concrete connections.



A = HOLE DIAMETER

B = NOMINAL BOLT DIAMETER

CLEARANCE = AMOUNT OF OVERSIZE = A - B

Fig. 1.1 Definition of "clearance" and "oversize"

CHAPTER 2
BACKGROUND

2.1 Introduction

In this chapter a general overview of repair and strengthening motivations and methods is presented. Steel bracing techniques are reviewed using findings from previous research, and methods and problems associated with steel-to-concrete connections are presented. Connections incorporating adhesives are then discussed along with previous research in this area. The last section deals with design and behavior of steel-bolted connections, including behavior in shear, problems with multiple-bolt connections, and research concerning oversize holes.

2.2 Repair and Strengthening

Due to an increasing understanding of the behavior of structural systems under seismic loading, methods of repair and strengthening have emerged as a viable alternative to demolition and reconstruction. Structures may be strengthened for a variety of reasons:

1) to repair a damaged structure to at least its original strength, and ideally to an improved level of resistance to lateral loading
2) to modify an existing building to meet more stringent code requirements

3) to allow for new occupancy or usage while maintaining adequate safety
4) to correct errors in design or construction
5) to allow for additional construction.

Buildings best suited for seismic retrofitting generally possess adequate vertical load resistance, but lack sufficient lateral strength. Retrofitting techniques must be economically feasible, easily constructed, and should not create new areas of weakness. The amount and location of existing damage must be carefully assessed, along with an analysis of failure modes and amount of remaining strength. Proper selection of a retrofitting system includes evaluation of its goals: strength, ductility or a combination of both.

Current retrofitting techniques include column strengthening, infilled walls, wing walls, and steel bracing systems (Fig. 2.1). In general, existing elements are modified for increased ductility, and new elements are added for increased strength.

2.3 Steel Bracing Techniques

Steel bracing systems may be designed to carry all lateral forces, leaving only vertical loads to be borne by the existing structure. This procedure is best suited for multistory frames in need of strengthening at every story [16]. Some advantages of steel bracing include:

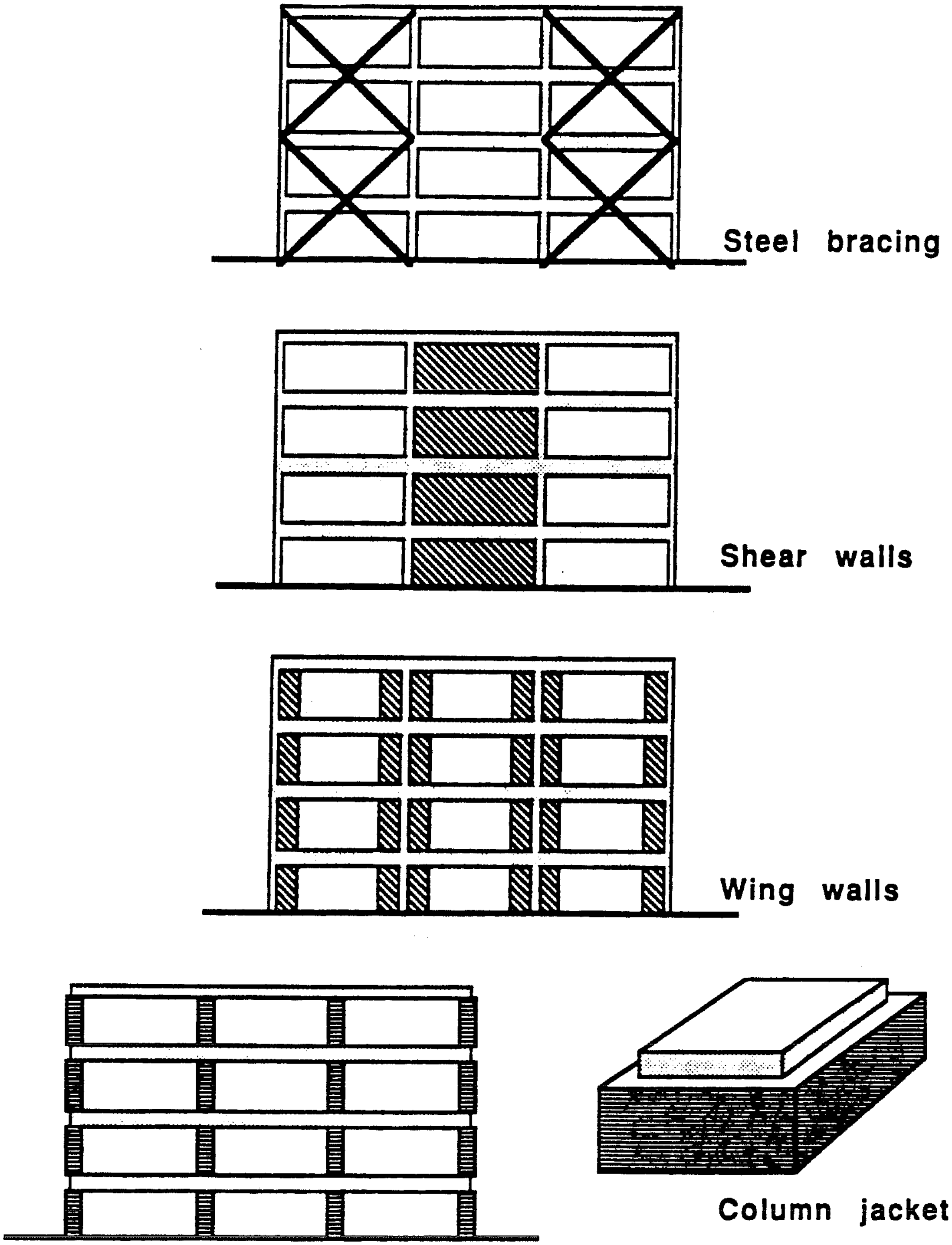


Fig. 2.1 Typical retrofitting techniques [5]

1) The system is constructed from the exterior, thereby reducing disruption and loss of accessibility during construction.
2) The level of strength and stiffness can be controlled by adjustment of member size and location.
3) The system can provide improved ductility and damping.
4) Local force concentrations can be reduced using a uniform distribution of bracing.
5) The additional mass is small. This eliminates the need for costly foundation improvements, and avoids increases in lateral forces.

The major disadvantage of this retrofitting scheme is its high cost. Although components are prefabricated, material is expensive and construction is labor-intensive [5]. This system is best utilized in conjunction with other techniques.

2.3.1 Previous Research Involving Steel Bracing Techniques. The Japanese have conducted extensive research in the area of repair and strengthening. One arrangement of steel bracing, tested by Kawamata [17], was used to strengthen an eight-story building in Sendai, damaged in the 1978 Miyagi-ken-Oki earthquake. Extensive damage was partially due to spandrel walls at one end of the building. The increased stiffness at that end attracted most of the lateral forces and the columns were failed in shear. Once the existing members were repaired, eccentric steel cross bracing was installed externally on two sides of the structure (Figs. 2.2 and 2.3).

Research at The University of Texas at Austin includes testing of various retrofitting techniques involving a two-thirds scale, two-story, two-bay reinforced concrete frame. The frame, using working-stress techniques, had deep spandrel beams and slender columns, typical of construction in the California area during the 1950's and 1960's. The substantial size of the model reduced problems associated with testing small scale specimens.

The unstrengthened frame was evaluated under cyclic lateral loading, and again after the addition of reinforced concrete piers (wing walls). After the removal of the wing walls, the damaged frame was retrofitted with a steel bracing system and was tested to failure under cyclic lateral loading.

The diagonal steel bracing consisted of 6-in. deep wide flange sections with welded connections. Testing was temporarily halted when the welded connections failed prematurely. The connections were redesigned and the welds replaced before testing continued. The system successfully resisted lateral loads up to the point of brace buckling, well past the current UBC design loads. Jones [16] observed that the better the quality of the welded connections, the better the behavior of the entire system.

Related research by Roach [23] confirms that steel members connected to existing concrete generally fail due to inadequate

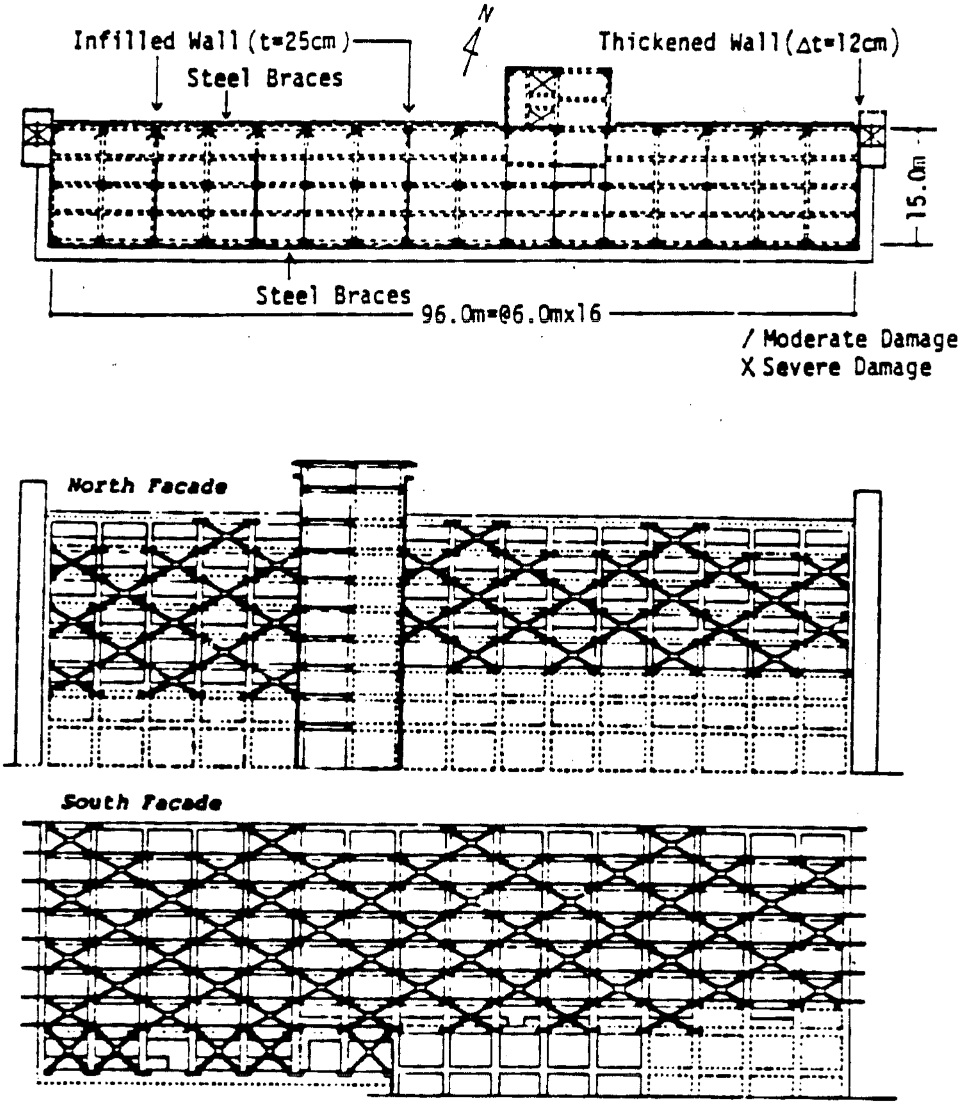


Fig. 2.2 Sendai School, Japan; plan and elevation [5]

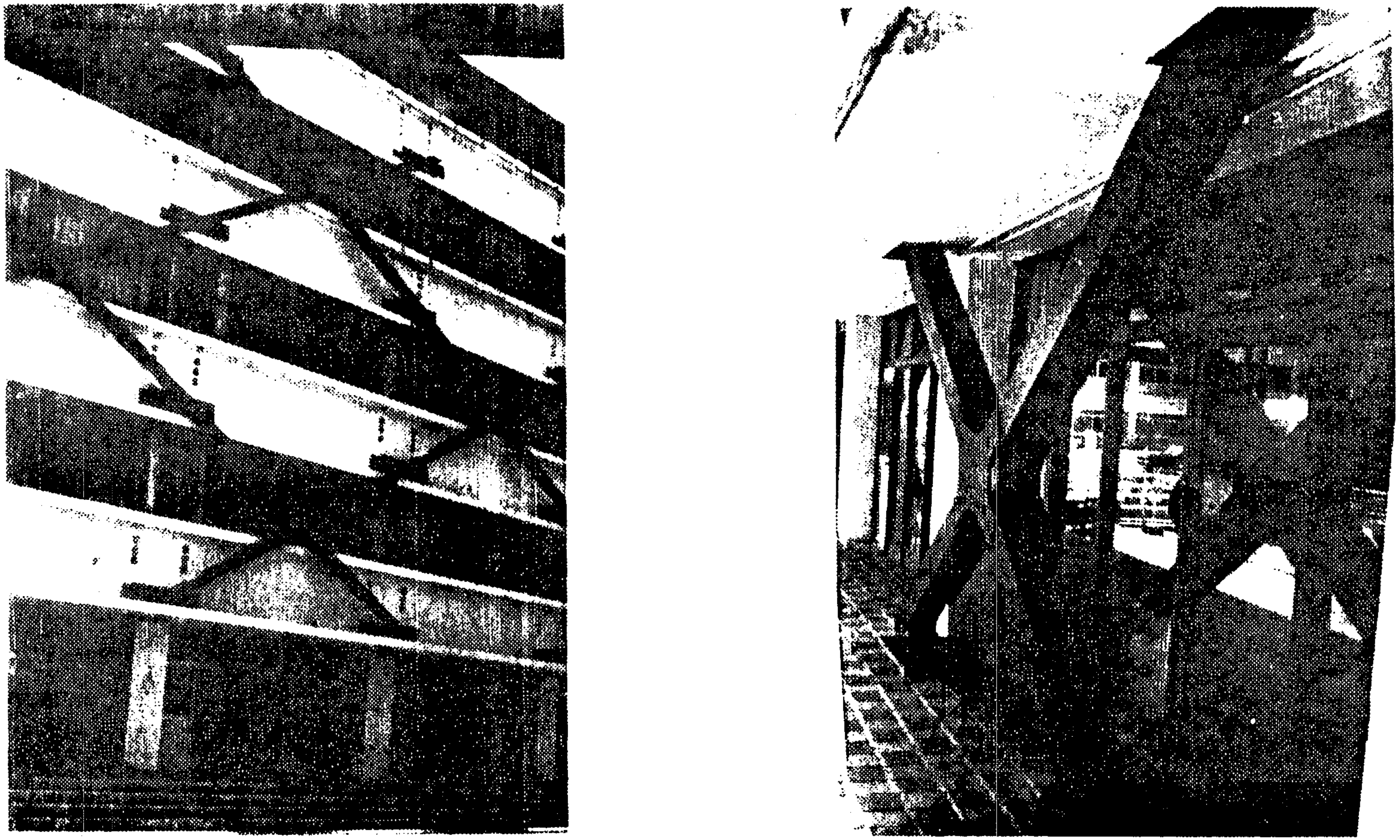


Fig. 2.3 Sendai School, Japan; steel bracing [5]

connections. Since such a failure is brittle, connections must be designed so that members are allowed to reach capacity in order to achieve ductility in the system. In addition, the performance of most anchor bolt systems is very dependent on installation procedures [19]. As a result, the frequent failure of connections under seismic load is often difficult to analyze. Was the connection incorrectly designed, was the bolting system itself deficient, or was the connection improperly installed?

2.3.2 Steel-to-concrete connections. Current methods of connecting steel members to concrete include expansion anchors, post-tensioned brace-to-frame connections, and adhesive-grouted rods or bolts. Studies by Luke [19] and Chon [11] revealed good performance of properly installed adhesive anchors.

Assuming that the rod or bolt is anchored sufficiently, problems are then limited to the method of attachment of the steel member to the anchors. Friction-type connections (near ultimate) as well as bearing-type connections experience slip into bearing. This slip usually consists of a series of small or minor slips, followed by one large or major slip. Problems associated with slip include the following, all of which are worsened in the presence of stress reversals or fluctuations:

1) Slip can cause harmful stress redistribution.
2) Slip may cause violation of deflection limitations.
3) Slip may cause cramping, fretting and fracture [8].
4) Slip intensifies fatigue problems.

The ductility of multi-fastener connections may also be limited by the deformation capacity of the end fasteners. As discussed in sub-section 2.5.3, this problem worsens with increasing joint length, and may result in brittle failure.

The frequent failure of connections in a steel bracing scheme may also be attributed in part to what Bickford [8] describes as "load intensifiers." These include:

1) shock and impact
2) mismatched surfaces
3) nonuniform preloads in the fasteners
4) slip problems caused by poor fit of bolts in holes
5) prying action.

Bickford also observes that the rate of connection failure is accelerated by:

1) lack of adequate damping in the connection
2) loosening of the nuts due to vibration or slip movement
3) leakage and corrosion
4) fatigue
5) galling or other material damage incurred during assembly.

Several authors [8,22,25,30] suggest that the addition of structural adhesives to connections would minimize these effects. The adhesive could be used not only as a bonding agent between surfaces, but also as a filler between the bolt and hole, essentially reducing the hole diameter.

2.4 Connections Using Adhesives

Semerdjiev [25] contends that a combination-type joint, such as a bolted connection incorporating adhesives, has advantages over connections using either bolts or adhesive independently. Structural adhesives are particularly suited to withstand stresses imposed by cyclic loading or impact, and can be obtained with varying degrees of flexibility and strength. Advantages of using adhesives in connections include the following:

1) In the presence of vibration, adhesives can prevent loosening of mechanical connectors, and can also damp the vibrations.
2) In joints subjected to impact or cyclic loads, adhesives can provide flexibility and damping without cracking or damage, thus significantly improving fatigue resistance.
3) Adhesives can effectively seal against liquids or gases that might otherwise undermine effectiveness of a joint.
4) Adhesives transmit stresses more uniformly than mechanical fasteners, thereby reducing stress concentrations.

When using adhesives, the following limitations should be considered:

1) Some adhesives are subject to creep under long-term static loading.
2) Extreme heat (fire, etc.) may induce debonding.
3) If adhesion is to be fully utilized, costly surface preparation may be required.
4) A bonded structure would be more difficult to dismantle.

Although generally more expensive, organic adhesives such as epoxies and polyesters have higher compressive and tensile strengths than do traditional cement grouts, and can add a substantial adhesion component [11]. Dowels grouted with these materials displace less when loaded in tension than do those grouted with traditional cements [19].

2.4.1 Previous Research Involving Steel-to-Concrete Connections Using Adhesives. Wiener [30] investigated the effects of including structural epoxy adhesive in the interface between steel and concrete in a typical steel-to-concrete connection. He evaluated the load-deflection characteristics of connections in which adhesive was used as a grout, and also as a bonding agent for the interface. His test specimens consisted of a concrete block into which threaded rods were anchored using adhesive. Various steel sections were then attached to the face of the block, sometimes using an adhesive interface, and the connection was cycled to failure in shear (Fig. 2.4).

Variables considered by Wiener included the number of bolts, the type and size of the connected steel sections, and the use or omission of adhesive at the interface. In constructing the steel-to-concrete connections with adhesive at the interface, some of the adhesive was inadvertently extruded, filling the void between the bolt and plate hole. Subsequent testing revealed significantly improved performance of the bonded connections, partially attributed to the adhesive "bearing pad" which had been extruded into the bolt hole. The load-slip envelopes in Fig. 2.5 illustrate this superior behavior in all stages of loading. Concerning the effects of the additional adhesive, Wiener concludes the following [30]:

1) Elastic capacity was increased by a factor of 2.
2) Ultimate capacity was increased by 13 percent.
3) There was greater connection stiffness in both the elastic and large slip ranges.
4) Adhesive extruded into bolt holes distributed loads more uniformly among bolts. When no adhesive was included, the end bolts of a multi-bolt connection accepted a greater portion of the load and generally failed before the remaining bolts achieved full capacity.

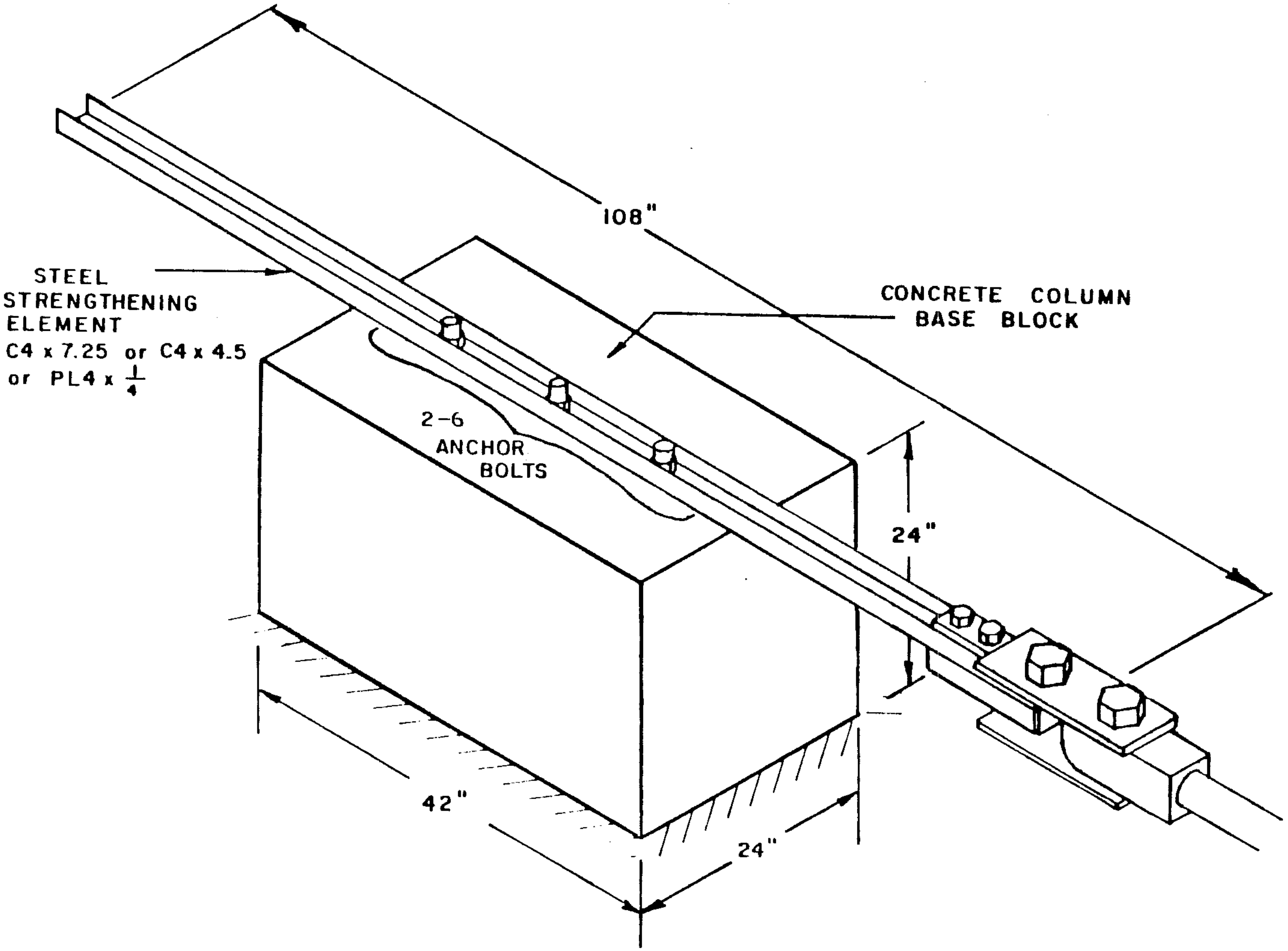


Fig. 2.4 Test configuration from previous research on steel to concrete connections using adhesives [30]

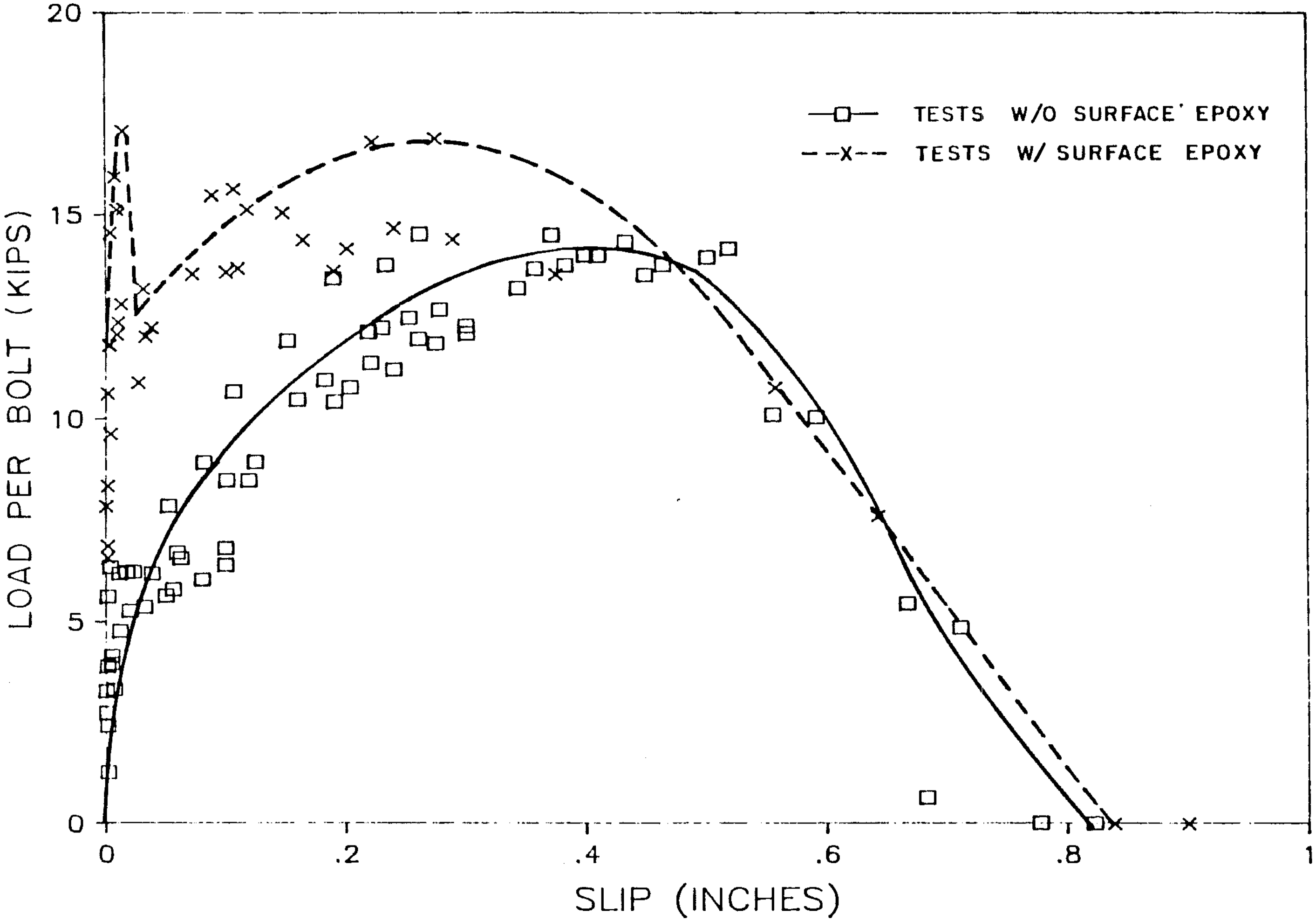


Fig. 2.5 Results from previous research on steel to concrete connections using adhesives [30]

5. Adhesive extruded into bolt holes greatly reduced bearing deformations in the plates, and reduced frictional slip by more than half.

Wiener also recommends that all steel to concrete bolted connections be designed bearing rather than friction connections [30].

A 1958 case study by Ritchie [22] involved the use of a cold-setting resin mixture to improve joint efficiency. Ritchie used the resin to fill the void between the bolt and hole, thereby reducing slip. The author also describes the advantages of using an adhesive interface to restrict rotation. His test specimens consisted of lap joints using a single 5/8-in. bolt in a punched hole with 1/16-in. clearance. Ritchie offers the graph shown in Fig. 2.6 to illustrate the improved efficiency.

Even after interface debonding, slip was still less than for a fitted hole. Obviously, improved resistance to rotation resulted from the adhesive interface, but was still maintained after debonding, due to the irregular contact surface.

After the occurrence of what were referred to as "sagging and distortion" problems in a truss-type bridge in the area, the use of adhesive was tested on an identical bridge constructed nearby. The single span was 95 feet long with a 3-in. camber at midspan. Ritchie notes that "The bridge had been in position for 18 months and retained all of its initial camber," implying no significant joint slip [22].

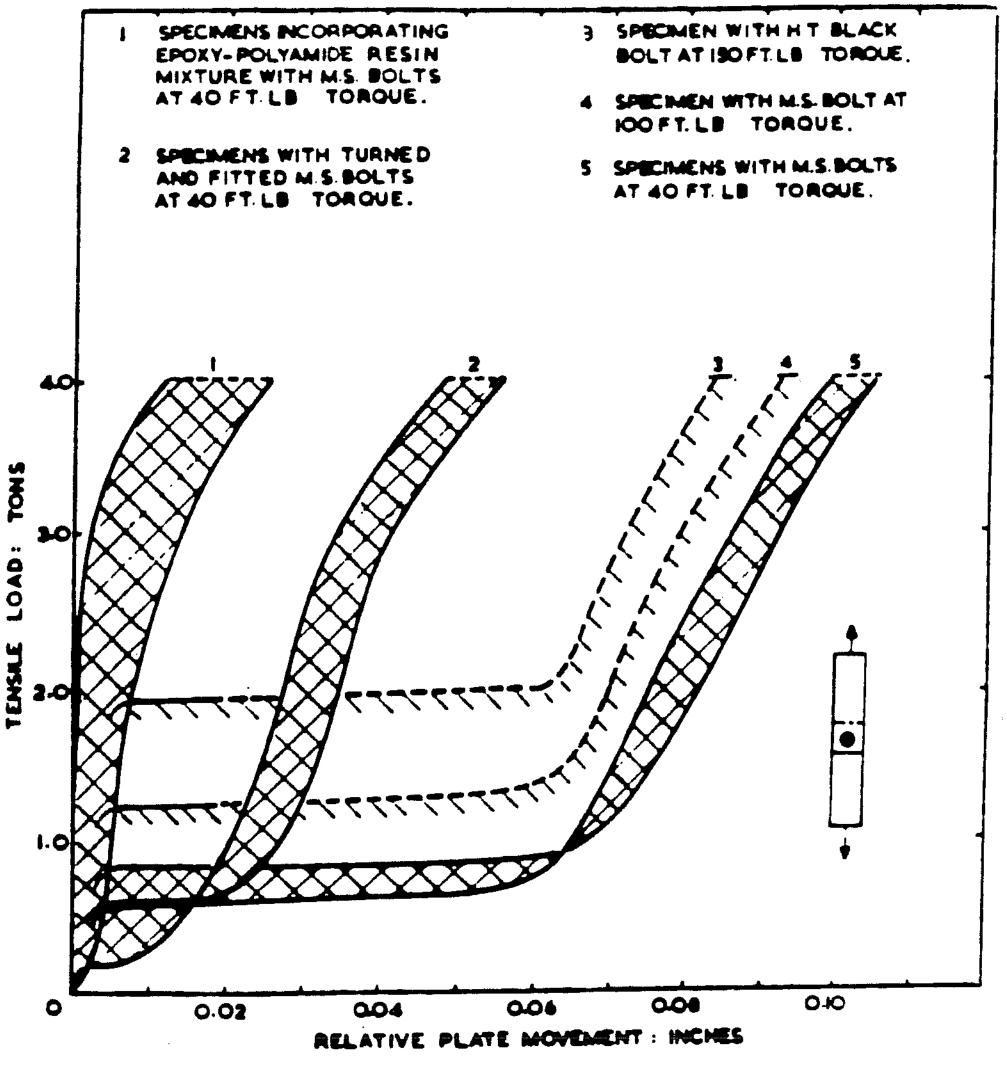


Fig. 2.6 Results of previous research on adhesive fillers in bolted connections [22]

2.5 Bolted Connections

High-strength connectors generally consist of A325 and A490 steel bolts. A325 bolts are made of tempered medium carbon steel; and A490 bolts, of tempered alloy steel. A325 bolts less than 1 inch in diameter have a specified minimum ultimate tensile strength of 120 ksi; those over 1 inch, 105 ksi. Specified minimum ultimate tensile strengths of A490 fastener range from 150 ksi to 170 ksi.

2.5.1 Types of Bolted Connections. Bolted connections are currently designed as friction type (slip-resistant) or bearing type.

Bearing connections transfer load by bearing of the bolt against the sides of the hole. In a friction connection, load is transferred by friction between the connected parts. This frictional force is influenced by factors such as surface preparation and coefficients of friction, but depends primarily on the clamping force provided by the high-strength bolts. Any relative movement (slip) of the connected parts represents failure of this type of connection. To achieve uniformity in clamping force, bolts are tightened well past yield, to around 70 or 80 percent of their ultimate tensile strength.

2.5.2 Behavior of Bolted Connections in Shear. Typical results of a shear test of high-strength bolts are shown in Fig. 2.7. In general, shear strength is about 62 percent of tensile strength [18], and (like tensile strength) decreases with increasing ductility. Higher-strength steel bolts can provide greater clamping force and higher

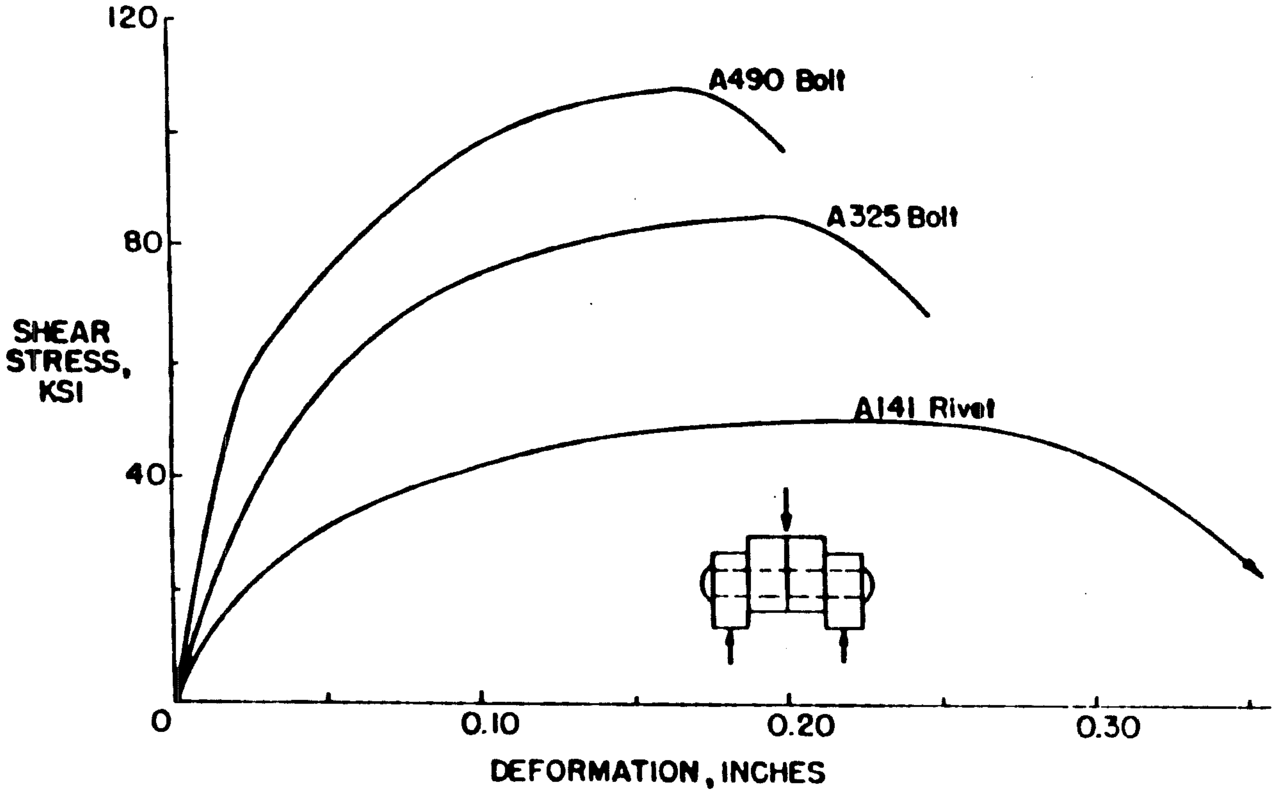


Fig. 2.7 Typical stress-deformation plot for high strength bolts loaded in shear [29]

ultimate shear strength, permitting more compact joints with fewer bolts.

Research at Lehigh University by Wallaert [29] revealed that the ultimate shear strength of high-strength bolted connections was unaffected by the preload (initial tension) of the bolts. This is due to the fact that near failure, pre-tension is dissipated by shear deformation, and frictional resistance is therefore negligible. Wallaert also noted the following relevant points:

1) Loading rate did not affect the load-deformation curve.
2) Shear resistance was proportional to the bolt area in the shear plane.
3) Bolt diameter did not affect ultimate stress, but larger bolts displayed greater deformation capacity.
4) The type of steel used in the connected parts did not affect shear strength.
5) Bolts tested in a tension jig showed a 10 percent lower shear strength than those tested in compression, due to the prying action that developed in tension.

2.5.3 <u>Behavior of Multiple-Bolt Shear Connections.</u> Testing indicates that longer joints do not efficiently carry design loads. In bearing or friction connections loaded to near ultimate, slip occurs bringing some bolts into bearing. As these bolts deform in shear, more bolts come into bearing and deform, until ideally all bolts are in bearing. At this point, since relative deformation between the connected elements is greatest at the ends, the end bolts must have large deformation capacity to continue to distribute the load. Usually the end bolts are unable to accommodate this amount of deformation and fail long before each bolt has reached its shear strength. This initiates an "unbuttoning effect," and the connection fails [10]. This phenomenon worsens with increasing joint length. It can therefore be concluded that the shear strength of bolted connections is usually limited by the deformation capacities of the individual bolts, and not by their strengths [13].

2.5.4 Oversize Holes in Bolted Connections. Misalignment between connected parts causes costly delays and can even require refabrication. Some fabricators require preassembly before shipping, but this is not possible when connecting to existing members. Causes of misalignment may include:

1) improper manufacturing
2) inadequate tolerances
3) distortions caused by cutting, welding or handling.

Oversize holes alleviate misalignment problems, and also permit erection adjustments.

Early studies involving friction connections indicated no loss of slip resistance using a 1/16-in. clearance (hole diameter 1/16-in. in excess of bolt diameter). Hence this clearance was permitted by early specifications [2].

The popularity of high-strength bolts prompted studies by Chesson and Munse [10] and German investigators, of the effects of loss of bolt preload and of the inclusion of washers, with holes having up to 1/8-in. clearance. It was found that a long-term loss of preload of about 10 percent could be expected, and that minimum preload could be achieved with or without washers. The omission of washers did, however, result in damage (galling) to the connected elements. Similar studies in Japan, South Africa and the Netherlands verify these findings.

Research at Lehigh University by Allen and Fisher [2] involved hole clearances of up to 5/16 in. Their study examined the effect of oversize and slotted holes on the following:

1) loss of bolt preload after installation
2) differences in slip resistance
3) standard tightening techniques
4) effect of including washers.

Their specimens were all designed as slip-resistant, since a slip of the magnitude normally associated with oversize holes would have been unacceptable in a bearing connection. The only tests specifically involving bearing were with slotted holes, to measure plate and bolt shear strength.

It was found that oversize holes caused a significant reduction in slip resistance of a connection due to the lower clamping force imparted by the bolts. This reduction is caused by reduced contact area immediately adjacent to the bolt, where clamping pressure is normally greatest.

Connected elements also experienced extensive damage after conventional tightening of the nut. With hole clearances of up to 3/16 in., the use of hardened washers under the nuts allowed the minimum preload to be achieved without severe plate galling. Holes with 5/16-in. clearance experienced a loss of preload due to dishing of the washer. Ultimate strength of connections was unaffected by oversize holes [18].

In addition to these test results, a theoretical maximum hole diameter was calculated using the allowable bearing stress on the connected plates. Combining the above results, the authors offered a table of allowable hole clearances which forms the basis of the current AISC specification concerning oversize hole limitations [4]. Although minimum preloads can be attained with standard tightening procedures, connections using oversize holes show reduced slip resistance. The combined effects of reduced preload, reduced clamping force due to less contact area, and smaller slip coefficients, result in a reduction of about 15 percent in slip resistance for connections with the recommended oversize holes [18].

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Introduction

In this chapter, the development of the test specimens is presented and the specimens are described. The variables tested are explained along with the nomenclature used for test identification. Materials and construction procedures are reviewed. The data acquisition system and instrumentation are described next, along with a typical testing procedure.

3.2 Specimen Description

A typical specimen is shown in Fig. 3.1. The base element was a plain concrete cube measuring 12 in. on each side. A single 5/8-in. diameter threaded rod was cast in place through the center and protruded 1.5 in. from two opposite faces of the block. Two 12-in by 10-in., 1/2-in. thick steel plates were then attached to the specimen using the exposed threaded rods. Threads were included in both shear planes. The holes in the plates were drilled 2 in. from the plate edges so that when attached, the lower edges of the plates would extend about 2 in. below the bottom face of the block. Assembled in this manner, the top face of the block could be loaded in compression with the reaction being provided by the plates extending from the bottom. The specimen was so loaded until shear failure occurred at the connections.

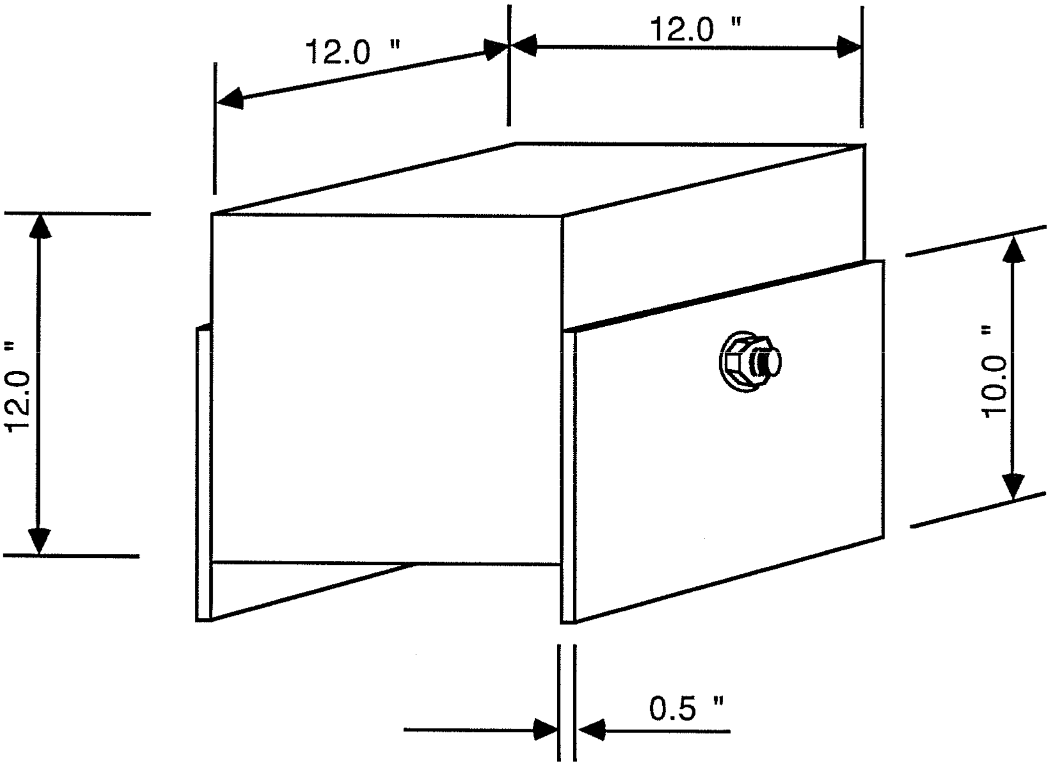


Fig. 3.1 Typical test specimen

3.3 Test Variables

Test variables included hole clearance, rod position in the hole, and the inclusion of structural adhesive in the void between the rod and the hole.

3.3.1 Hole Clearance. Three hole clearances were considered:

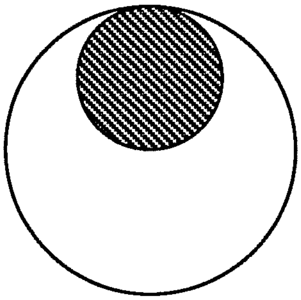
1) 1/16-in. clearance (standard size hole; 11/16-in. diameter
2) 3/16-in. clearance (current maximum oversized hole for slip resistant connections; 13/16-in. diameter)
3) 5/16-in. clearance (15/16-in. diameter hole).

3.3.2 Rod Position in the Hole. As shown in Fig. 3.2, rod position was varied in the hole from:

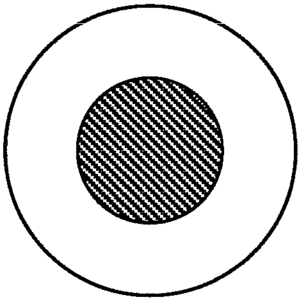
1) top of hole
2) center of hole
3) bottom of hole.

3.3.3 Structural Adhesive Fillers. The use of structural adhesives to fill the void between the rods and holes was investigated. Two types of application were considered:

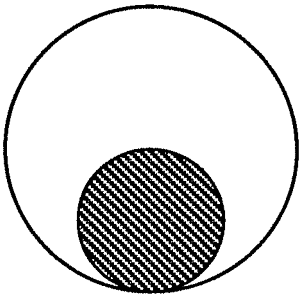
1) with the void only partially filled with adhesive
2) with the void completely filled with adhesive.



Top of Hole



Center of Hole



Bottom of Hole

Fig. 3.2 Rod position in hole

Connections involving standard-size holes without adhesive were compared with those involving oversize holes with adhesive. Connections involving hand-tightened nuts were compared with those involving conventionally-tightened nuts.

3.4 Specimen Development

Selection of the test specimen shown in Fig. 3.1 involved several factors:

1) The specimen should adequately represent the connection of a new steel member to existing reinforced concrete.
2) Deformation of the rods should be prevented, except near the connection.
3) Failure should occur at the connection, rather than by plate buckling or damage to the concrete.
4) Load should be distributed equally between the two connections on each specimen.
5) Load and deformation (slip) should be measured accurately.
6) Because the rod positions in the holes would have to be varied while keeping the top face of the block parallel to the bottom edges of the plates, the specimen should be small and light enough to move by hand.

7) Parts to be connected should be held securely in position for the application of adhesive and tightening of the nuts.

8) The effects of a bonded interface should be minimized.

The use of a single cast-in-place threaded rod resulted in two bolted connections located symmetrically on opposite faces of the block. The use of a single rod would eliminate embedment and pullout problems. The symmetrical shear loading would assure an equal load distribution between the two connections. The relatively small size of the specimen facilitated the use of a 600 kip universal testing machine, and allowed for ease of handling.

3.4.1 <u>Hole Clearance.</u> The three hole clearances mentioned above were selected for two reasons. First, the same clearances had been used in the previous tests [2] that formed the basis for current AISC code limitations on oversize holes. Second, holes drilled into existing concrete for grouting connecting rods customarily have a clearance of 1/4 in. A clearance of 5/16 in. in a prefabricated steel section would allow the steel section to be held in position on the existing concrete member and used as a template for drilling anchor holes into the concrete. An adhesive such as epoxy could be used to grout the rods, while simultaneously filling the void between the rod and plate hole. This procedure would not only eliminate alignment problems, but would also produce significant savings in time and cost when connecting steel to concrete [30].

3.4.2 Rod Position in the Hole. To fully examine the effects of using oversize holes in field applications, the position of the rod in the hole was varied among 3 locations: top, center and bottom. These were intended to represent the worst, typical, and best cases respectively. Potential slip would be the greatest with the rod at the top of the hole, and least with the rod resting at the bottom of the hole, placing the connection immediately in bearing.

3.5 Test Identification and Nomenclature

A total of seventeen tests were performed. Tests and corresponding specimens are differentiated as follows: The first letter of the name indicates the hole clearance in sixteenths of an inch. A "1" indicates a 1/16-in. clearance, a "3" represents a 3/16-in. clearance, and so on. The second letter indicates the rod position in the hole: "T" for top, "C" for center, and "B" for bottom. The letter "E" is included in the third position if adhesive (epoxy) was used, and excluded if no adhesive was involved. An "H" is included in the next position for those tests in which the nuts were tightened by hand. For tests in which the void between rod and hole was completely filled with adhesive, names are followed by "- I".

For example, "Test 3CEH-I" would indicate a hole clearance of 3/16 in. (13/16-in. diameter hole), rod centered in the hole, adhesive included, nuts hand tightened, and the void between the rod and hole completely filled with the adhesive. "Test 5T" would indicate a hole clearance of 5/16 in. (15/16-in. hole diameter), rods at the top of the hole, no adhesive, and the nuts tightened to 140 foot-pounds. Replicate tests were differentiated by a number immediately following the word "Test". For example, "Test2 1B" would indicate the second test of a connection with 1/16-in. clearance, rods at the bottom of the holes, no adhesive, and nuts tightened to 140 foot-pounds.

Tests were conducted in three groups. The first group involved standard size holes with no adhesive. The second group involved oversize holes with the void partially filled with adhesive. The last group involved oversize holes and a completely filled void between rod and hole.

3.6 Materials

3.6.1 Concrete. Because only a small amount of concrete was needed for the specimens, they were cast using part of a load of concrete ordered for another project, sponsored by the Texas State Department of Highways and Public Transportation (Texas SDHPT). Because of this, the concrete used conformed to Texas SDHPT class C [27], which has a minimum specified 28-day compressive strength of 3600 psi. Three cylinders tested at 7 days attained an average strength of 4370 psi, and the average strength of three cylinders tested at 28 days was 5430 psi.

3.6.2 Threaded Rods, Nuts, and Plates. Threaded rods were 5/8-in. A193-B7, similar in strength to A325 high-strength bolts. Rods were continuously threaded. Heavy hex 5/8-in. nuts were used with hardened washers as specified in the current AISC code for oversize holes [4]. Plates were A36 steel, 1/2-in. thick, precut to 12 by 10 inches. The 1/2-in. plate thickness was chosen to prevent plate buckling and to minimize apparent slip caused by plate-hole deformation.

3.6.3 Adhesive. The adhesive used in all tests was Sikadur 31 Hi-Mod Gel, a 2-component, solvent-free, moisture-insensitive, high-modulus, high-strength, structural epoxy paste adhesive. It has a compressive modulus of elasticity of 8.3×10^5 psi. Its 7-day compressive strength is 12,000 psi at 70 degrees F., and its shear strength at 14 days is 3,400 psi. This gel has a working pot life of 30 minutes at 70 degrees F.

3.7 Construction of Specimens

3.7.1 Formwork. Formwork for the blocks consisted of two troughs approximately 12 feet long by 12 inches wide, divided into twelve equal compartments. Forms were constructed using 3/4-in. AC plywood and structural 2 x 4's. The sides of the forms were clamped face to face for drilling rod holes prior to assembly to ensure that the cast-in-place rods were parallel to the top faces of the blocks. The completed forms are shown in Fig. 3.3.

3.7.2 Plate Drilling. When drilling the holes in the plates, it was essential that the lower edges of the plates be parallel and the holes aligned. The plates were clamped together in pairs while resting on end on a flat surface, then drilled as one. All edges of the plates were filed to present a uniform bearing surface.

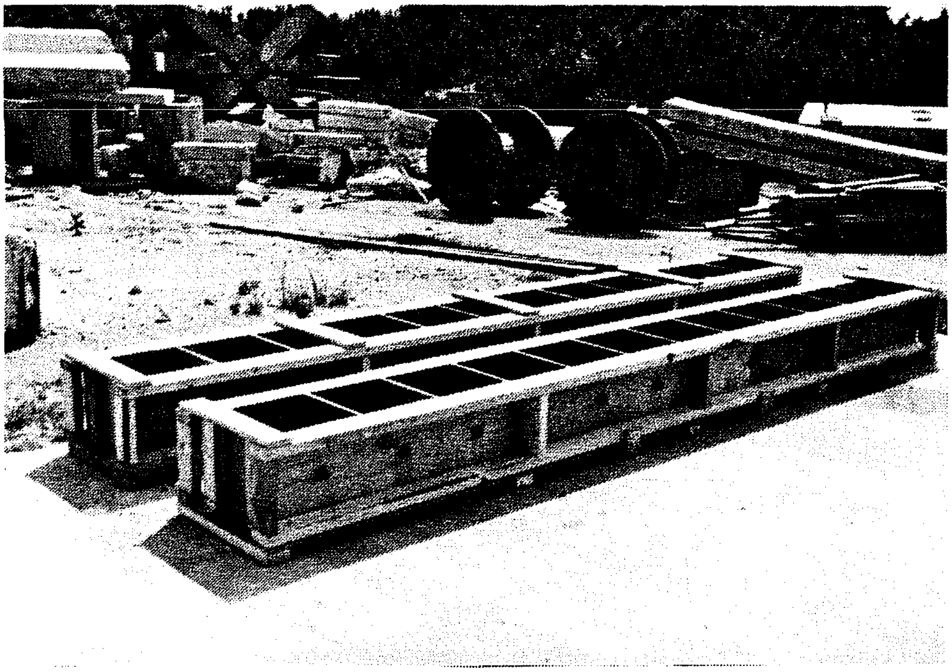


Fig. 3.3 Completed formwork

3.7.3 Mixing of Adhesive. The two-component epoxy required a 2-to-1 mixing ratio by volume. Generally used in large-volume applications, the adhesive is shipped in packs of two containers, the intention being to mix the entire contents for an accurate ratio. For mixing the small quantities required for this study, large graduated syringes such as the one shown in front of a 6-in. diameter cylinder mold in Fig. 3.4 were used. Each component was placed in a separate syringe, air and excess material were extruded to leave the desired volume in each syringe, then both components were placed in a container for mixing. The components were mixed using a hand drill and wire stirrer for at least three minutes and until all streaking disappeared, as specified by the manufacturer. The adhesive was then placed in a third syringe for application to the specimens.

3.7.4 Plate Positioning. Several problems were encountered in positioning the blocks and rods in the specified position for plate attachment. The top face of the block and the lower edges of the plates had to be kept parallel, while maintaining the specified position of the rod in the holes. A system consisting of four wooden wedges, a flat steel table, large clamps made of threaded rods and 2 x 4's, and a level was used effectively.

For specimens in which the void between rod and hole was only partially filled with adhesive (see sub-section 3.7.6), the bare block was placed on a flat steel table previously leveled to horizontal. The block was then lifted to a suitable height and supported by a wedge at

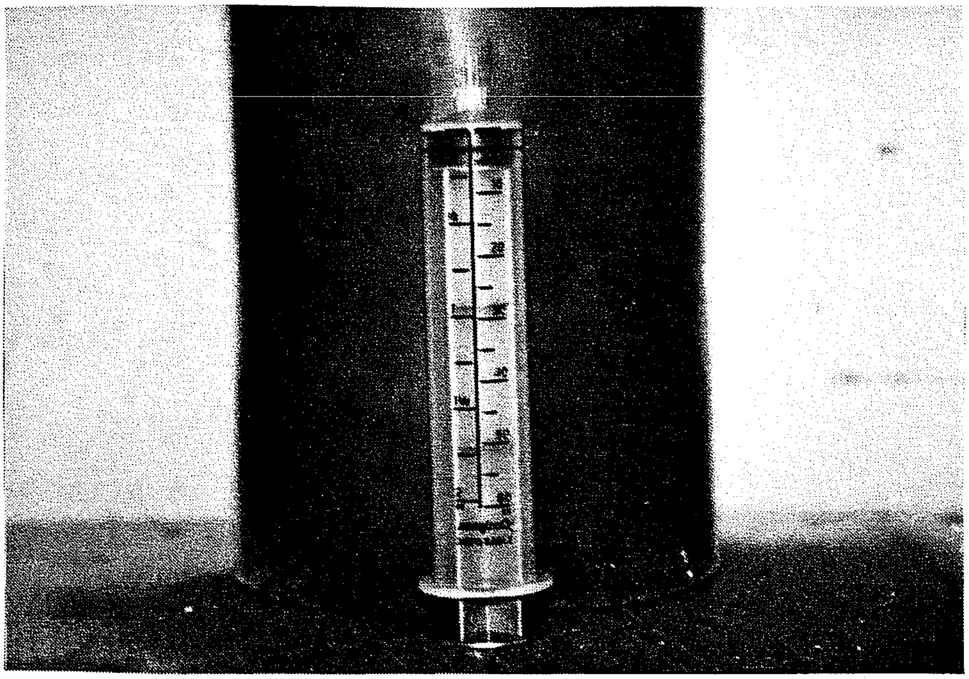


Fig. 3.4 Graduated syringe used for adhesive application

each corner. The height of the block was adjusted using the wedges until the rod reached the appropriate position (Fig. 3.5). The plates were then placed in position. With the plates also supported by the table, the top of the block was adjusted to level, and the plates were set firmly in place with the clamp. This process was repeated until all specimens for the first and second groups of tests were ready to be bolted after application of adhesive (Fig. 3.6).

Specimens in which the void between rod and hole was completely filled with adhesive (see sub-section 3.7.7), were assembled in a slightly different fashion. Due to problems with seating and adhesive application procedures discussed in sub-sections 3.7.5 and 3.7.6, these specimens were assembled separately on a steel seating plate. Resting on the seating plate, the bare block was positioned with wedges like previous specimens. Then, instead of clamping the plates for later application of adhesive, the adhesive was applied, the plates positioned, and the nuts torqued in one continuous operation for each specimen.

3.7.5 Seating of Specimens in the Testing Machine. After curing it was found that the plates on some specimens for the first and second groups of tests were not perfectly aligned with the base of the testing machine and a slight rocking motion could be felt. All specimens with partial adhesive fillers were ready for testing. To alleviate this problem, aluminum channels about 1-in. across, were filled with hydrastone and placed under each plate, eliminating the rocking (Fig. 3.7).

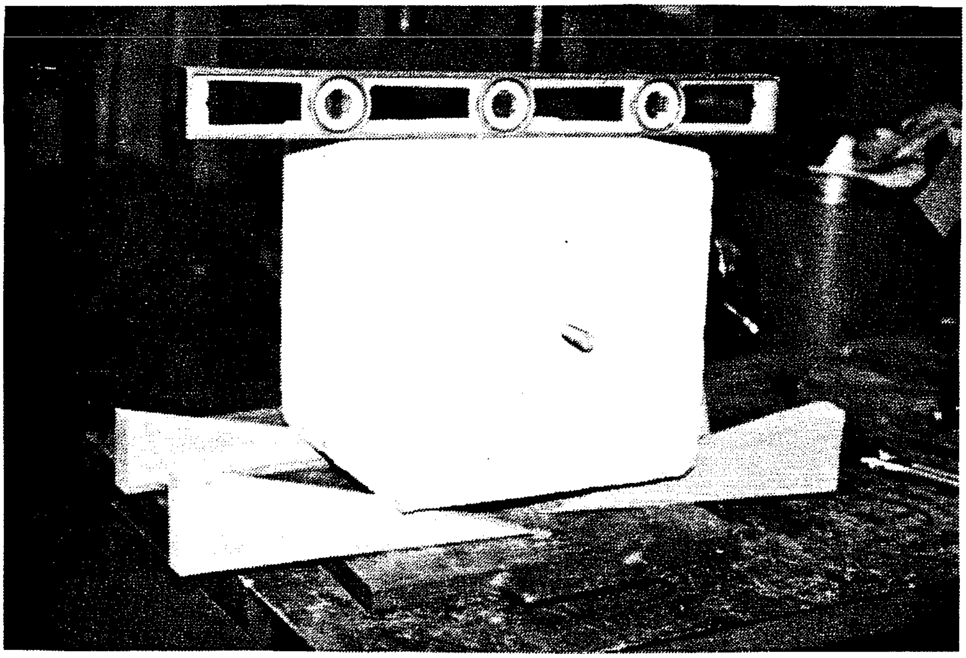


Fig. 3.5 System used for plate positioning

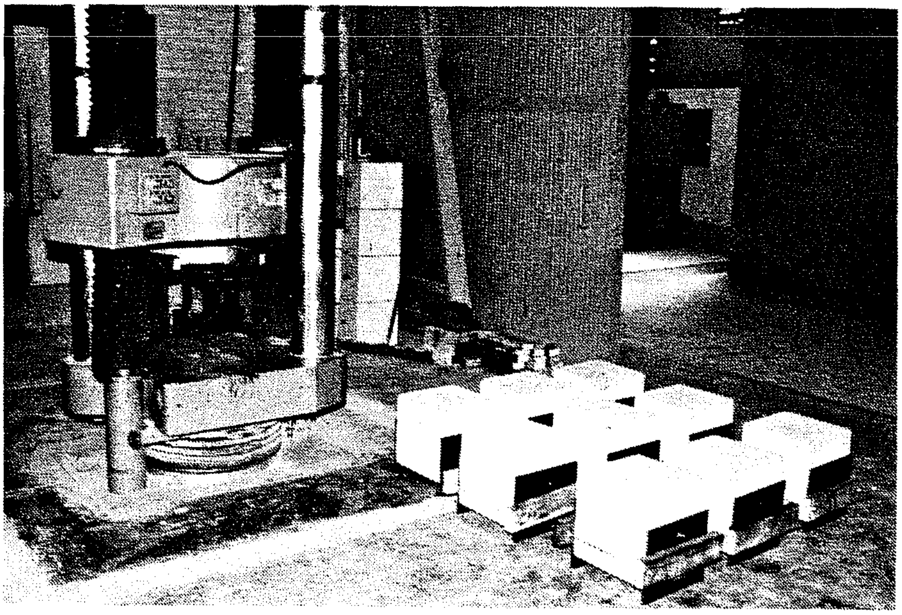


Fig. 3.6 Specimens ready for adhesive application beside universal testing machine

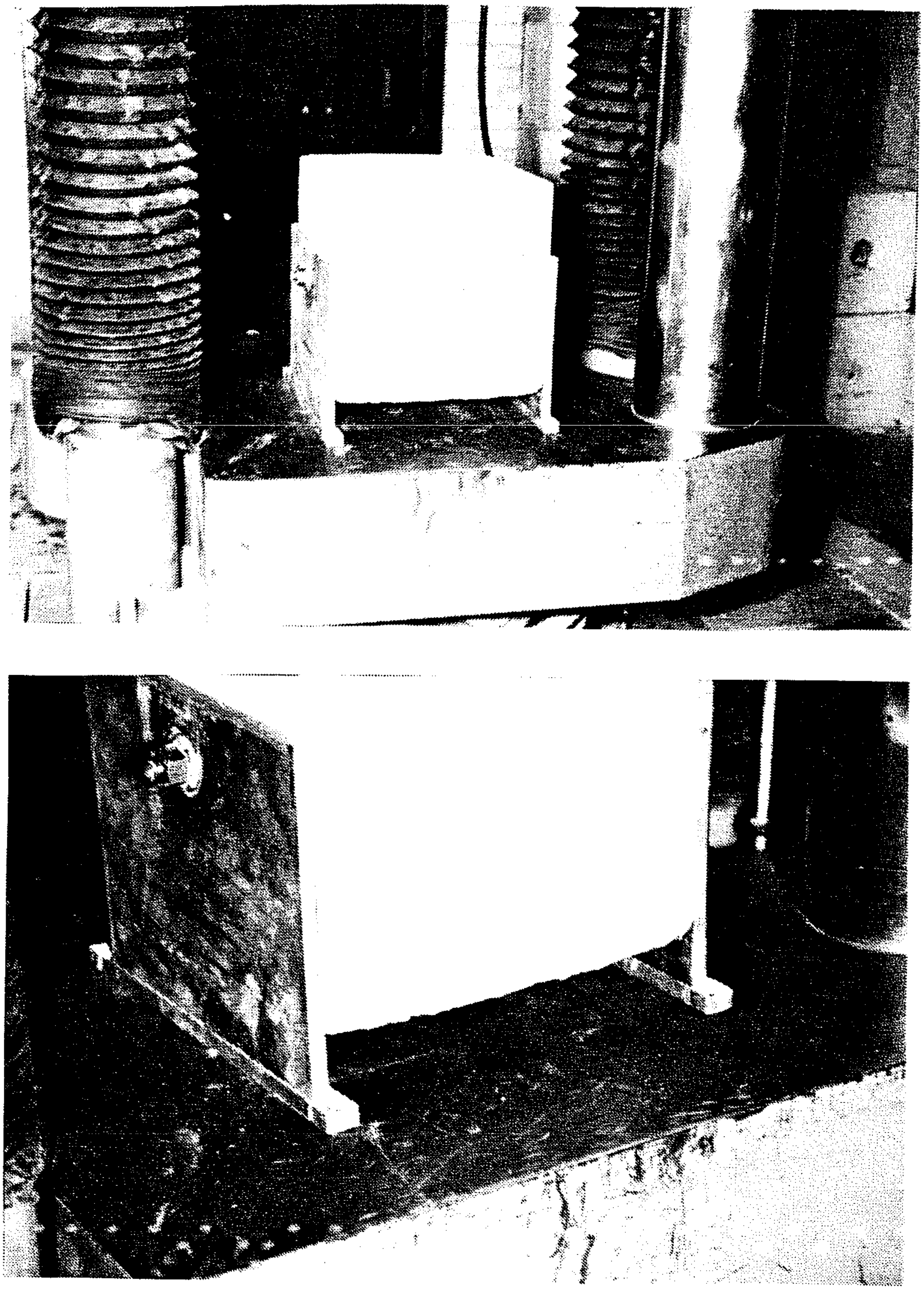


Fig. 3.7 Specimen seated in aluminum channels and hydrastone

Subsequent specimens with complete adhesive fillers were assembled on a steel "seating plate" about 1-in. thick and 16-in. square, which was in turn placed on the base of the testing machine to support the block during testing (Fig. 3.8).

3.7.6 Application of Adhesive - Partially Filled Void. Since bond between concrete and steel was not required, no surface preparation was performed. This probably also better represents unfavorable field conditions.

For specimens with a partial adhesive filler, the mixed adhesive was injected from the outside of the hole using a syringe (Fig. 3.9). This procedure was intended to prevent the adhesive from entering the interface between concrete and steel, and to avoid any effects of adhesion between surfaces. Since all specimens had been previously positioned and clamped, it was possible to apply the adhesive to all specimens in a single operation.

After this group of tests, it was noted that the injected adhesive did not completely fill the void between the rod and hole (Fig. 3.10).

3.7.7 Application of Adhesive - Completely Filled Void. To completely fill the void between rod and hole for the third group of tests, the adhesive was applied generously to the base of the exposed rod and surrounding concrete, the plates were pushed into position, and the nuts were attached. In this procedure, the adhesive was extruded out of the

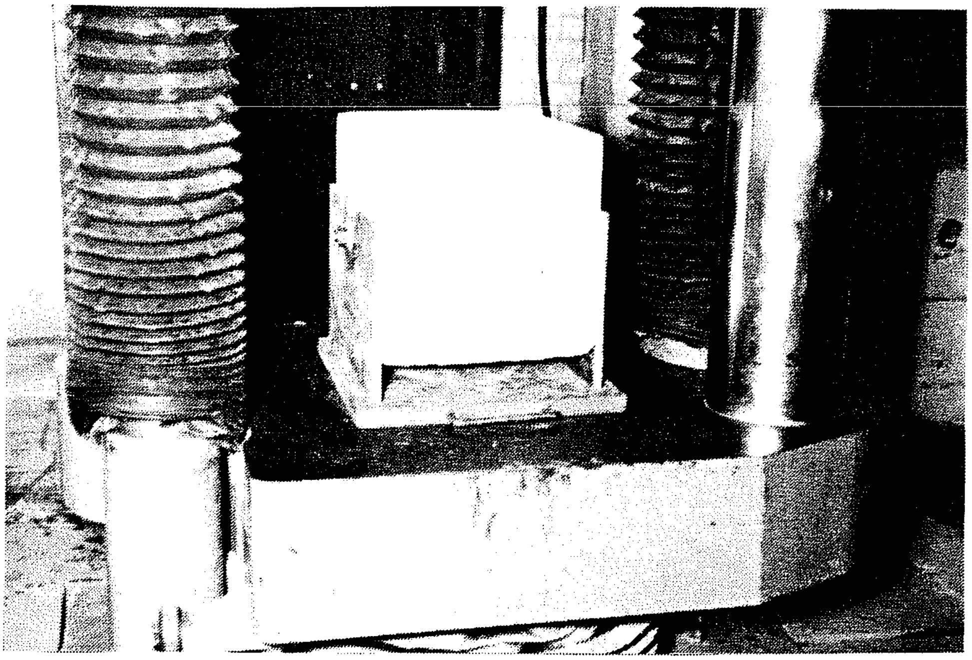


Fig. 3.8 Specimen seated on seating plate

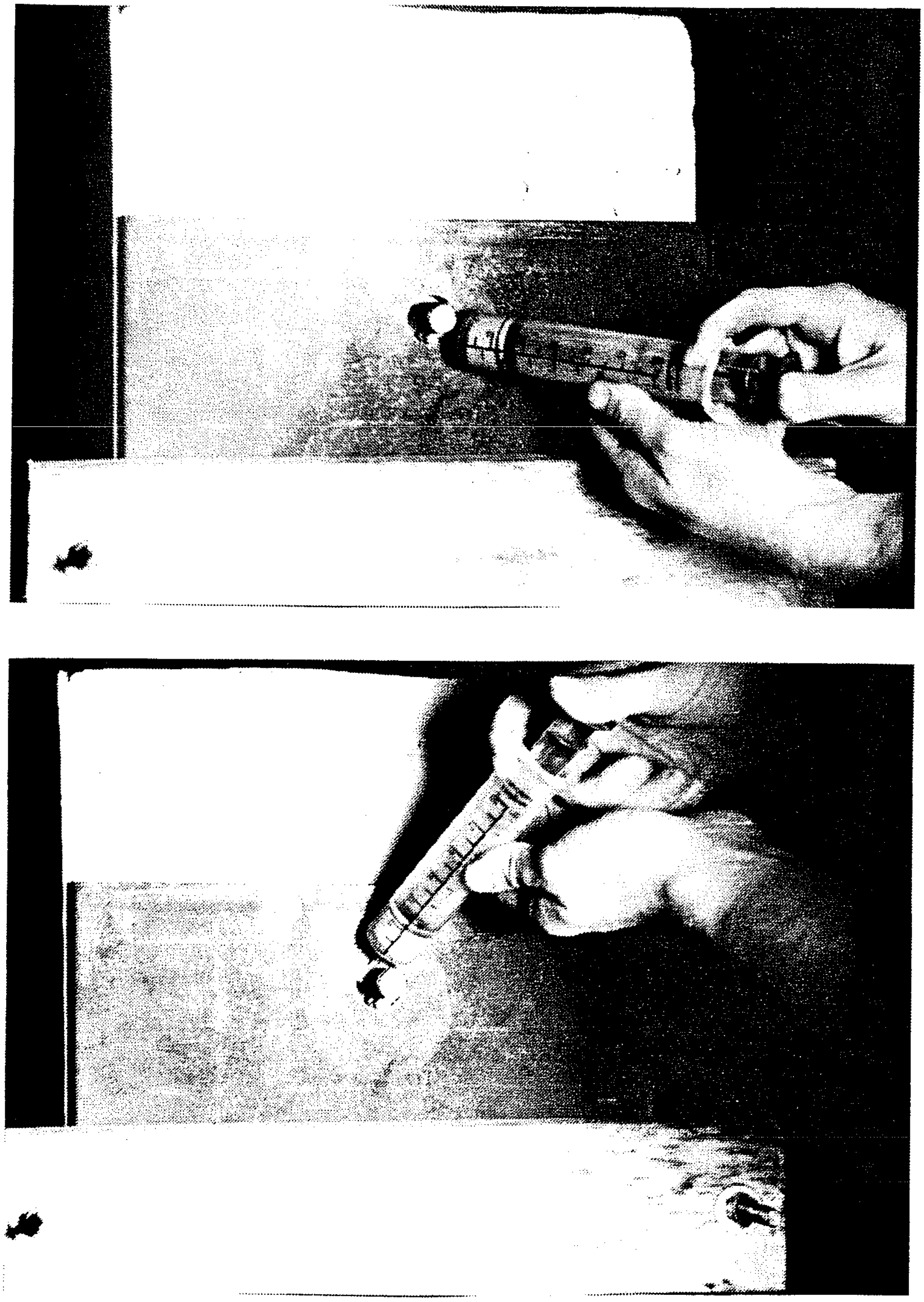


Fig. 3.9 Injection of adhesive

Fig. 3.10 Failure surface showing partial adhesive filler

hole around the rod completely filling the void. Some bonding at the interface was expected. This simulated a more realistic field application (Figs. 3.11 through 3.13).

Since the working pot life of the hi mod gel was 30 minutes at 70 degrees F., assembling more than two specimens at a time was impractical. It was decided that the graduated syringes allowed a close enough control over mixing ratios to mix the adhesive for each specimen separately. This procedure was verified by the manufacturer.

3.7.8 Tightening the Nuts. After application of the adhesive and positioning the plates, the nuts were applied and tightened to a value of 140 foot-pounds as measured by a torque wrench. For specimens in which the effect of hand tightening the nuts was to be assessed, an ordinary adjustable hand wrench was used. The resulting torque was estimated to be about 75 foot-pounds.

3.7.9 Curing. All specimens involving adhesive were cured for the manufacturer's recommended seven days. All tests were performed on the eighth day after application of adhesive.

3.8 Instrumentation and Data Acquisition.

3.8.1 Measurement of Displacements. Since the 600-kip universal testing machine used in all tests applies compressive loads by raising the lower base section relative to the stationary upper head, displacement was measured in terms of the upward movement of the base relative to the floor. Two 1-in. linear potentiometers were fixed at

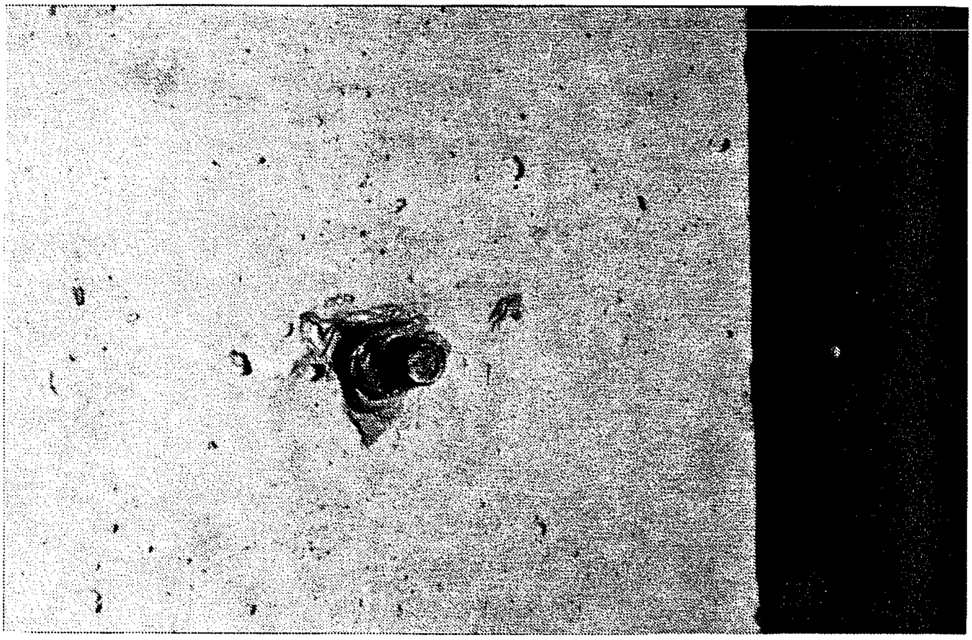


Fig. 3.11 Adhesive applied to base of rod

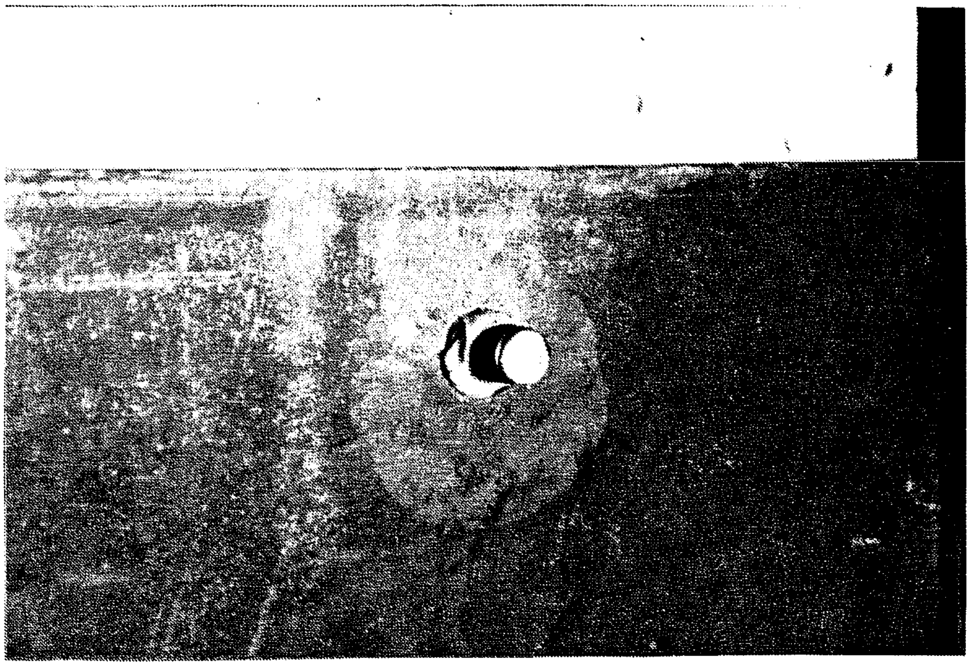


Fig. 3.12 Plate in position with extruded adhesive

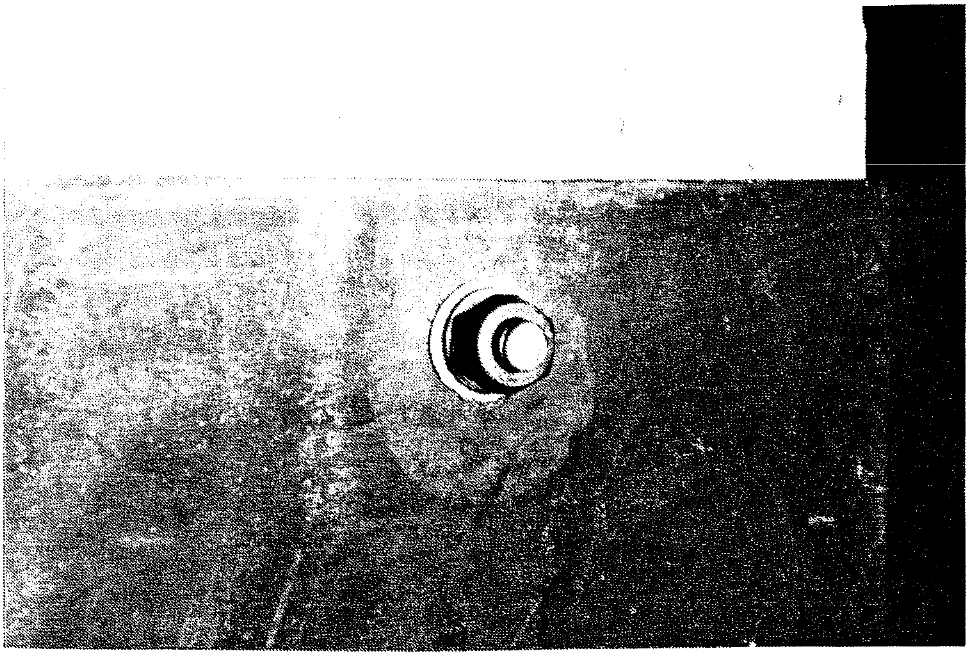


Fig. 3.13 Adhesive confined in hole void by washer and nut

opposite corners of the base, to account for any variation of the base from level, and to provide verification of results. Values obtained from the two measurements revealed that the base did indeed remain horizontal during testing. Using a Vishay Precision Amplifier, an excitation voltage of one volt (amplified 10 times) was supplied to one potentiometer, and 10 volts (unamplified) was supplied to the other. This was done to check for electrical "noise" or other variations due to amplification or equipment. Since no significant discrepancies were observed, the two values obtained from the potentiometers were averaged.

3.8.2 Data Acquisition. Data was collected using a Hewlett-Packard 7090A Measurement Plotting System and HP VECTRA microcomputer. The plotter accommodated three channels of input. In this case, channels 1 and 2 were used for the potentiometers, and channel 3, for the load (Fig. 3.14). Voltage values were stored in an internal buffer, loaded into a comma-separated-value file in the HP VECTRA, and finally converted to inches and kips using a SuperCalc 4 spreadsheet program.

3.9 Testing Procedure

Specimens were placed on the lower platform of the 600-kip machine. As mentioned earlier, the first and second groups of specimens were set into aluminum channels and hydrastone, while the third group of specimens were seated on a steel plate to provide a solid reaction with

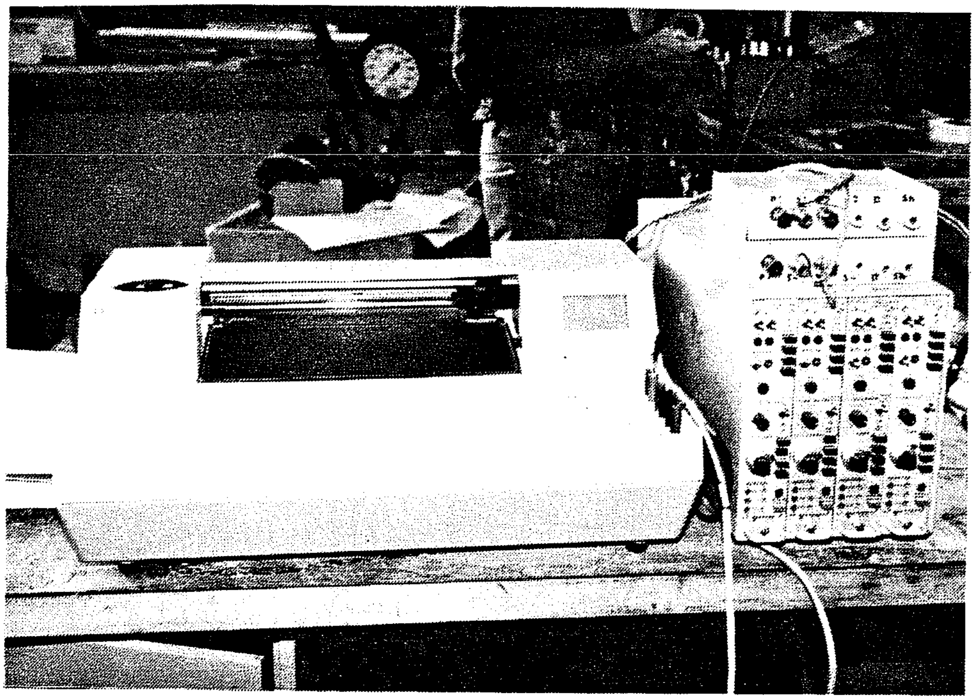


Fig. 3.14 HP three-channel plotter and Vishay amplifier

the base for each test. The 10-in. diameter upper circular head was lowered onto the specimen, and the specimen was centered.

The three-channel plotter would receive data only for a pre-specified time frame. Within this time frame the plotter would record 1000 data points. To record a maximum number of relevant data points, it was advantageous to extend each test to the full duration of the pre-specified time frame, but in no case to exceed that duration.

Loading was controlled by a hand valve, and accurate control of loading rate was impractical. The three-channel plotter was pre-set to a total maximum test time of three minutes. Since the time to failure varied from test to test, a loading rate of 15 to 20 kips per minute was maintained by adjusting the hand valve during the test. Allen [2] has shown that the load-deformation response of bolts tested in shear is unaffected by load rate. Loading continued until one or both connections failed in shear.

CHAPTER 4

TEST RESULTS

4.1 Introduction

In this chapter, results of all tests are presented graphically with observations and comments. Results are then compared using average values from tests with no adhesive, tests with partially filled voids, and tests with completely filled voids. Actual values from tests with hand-tightened nuts are compared with average values from the standard tests. Discussion of results is presented next, along with applications to repair and strengthening.

4.2 Typical Data

As discussed in Section 3.9, the data acquisition system recorded 1000 data points over a preset time period, Three minutes in this case. Since the number of points recorded before failure varied from test to test, data were manipulated in the SuperCalc 4 spreadsheet program to include only pertinent data points. The first point of the test was taken to be one point before the first positive increase in load values; the last, to be the point of rod fracture. This process eliminated data recorded during seating of the specimen against the loading mechanism, as well as data recorded after the connection failed. This allowed comparison of results in a common graphical format, shown on the following pages. The fewest number of data points in any test was 655; the greatest was

984. Even the fewest number of points were sufficiently dense to produce a smooth curve.

4.3 Tests Without Adhesive

Six specimens were tested without adhesive to establish baselines to which the specimens with adhesive could be compared. All specimens in these tests had holes with the standard 1/16-in. clearance.

4.3.1 Slip Tests. Two tests (Test 1T and Test 1CH) were performed to reveal the approximate loads at major slip, and did not involve loading to failure. Results from these tests are shown in Figs. 4.1 and 4.2. In Test 1T (140 ft-lbs torque), a major slip of approximately 0.07 in. occurred at about 20 kips accompanied by a loud cracking sound. The connection with hand-tightened nuts slipped approximately 0.05 in. at 7 kips, with no audible noise.

4.3.2 Tests to Failure. Two tests (Test 1B and Test2 1B) were conducted with the rod seated at the bottom of the hole. The results are shown in Figs. 4.3 and 4.4. The bolts failed at an average deformation of 0.22 in. at an average ultimate load of 40.0 kips, which corresponds to an ultimate strength of 88.6 ksi on the root area of the threaded rods. These curves are very similar to those obtained by Wallaert and Fisher from double shear tests involving A325 high-strength bolts [29].

The remaining two specimens were the same as those of the slip tests described in section 4.3.1, except that these specimens were loaded to failure. Results are shown in Figs. 4.5 and 4.6. Specimen2 1T

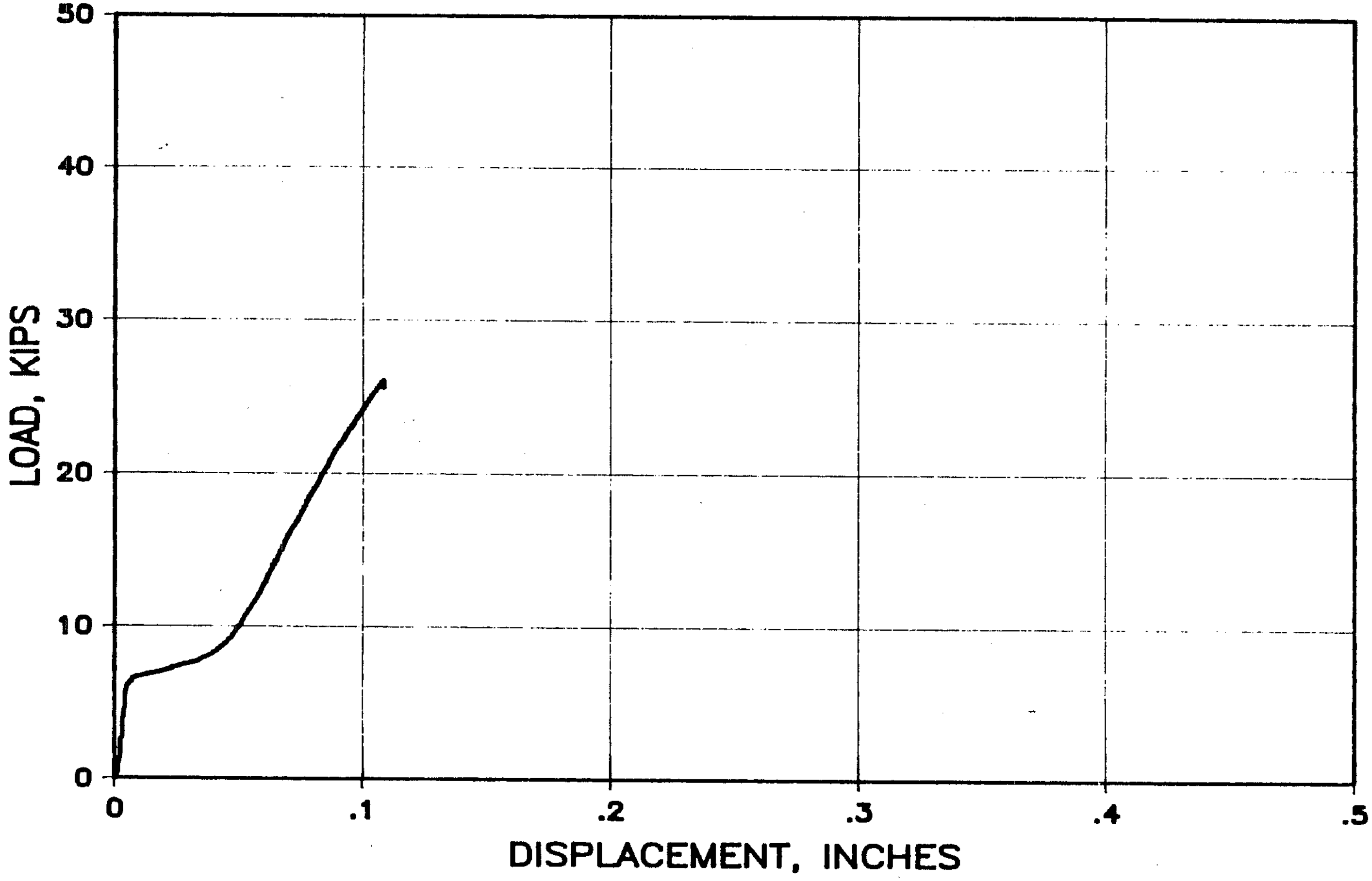


Fig. 4.1 Load-displacement plot, Test 1CH

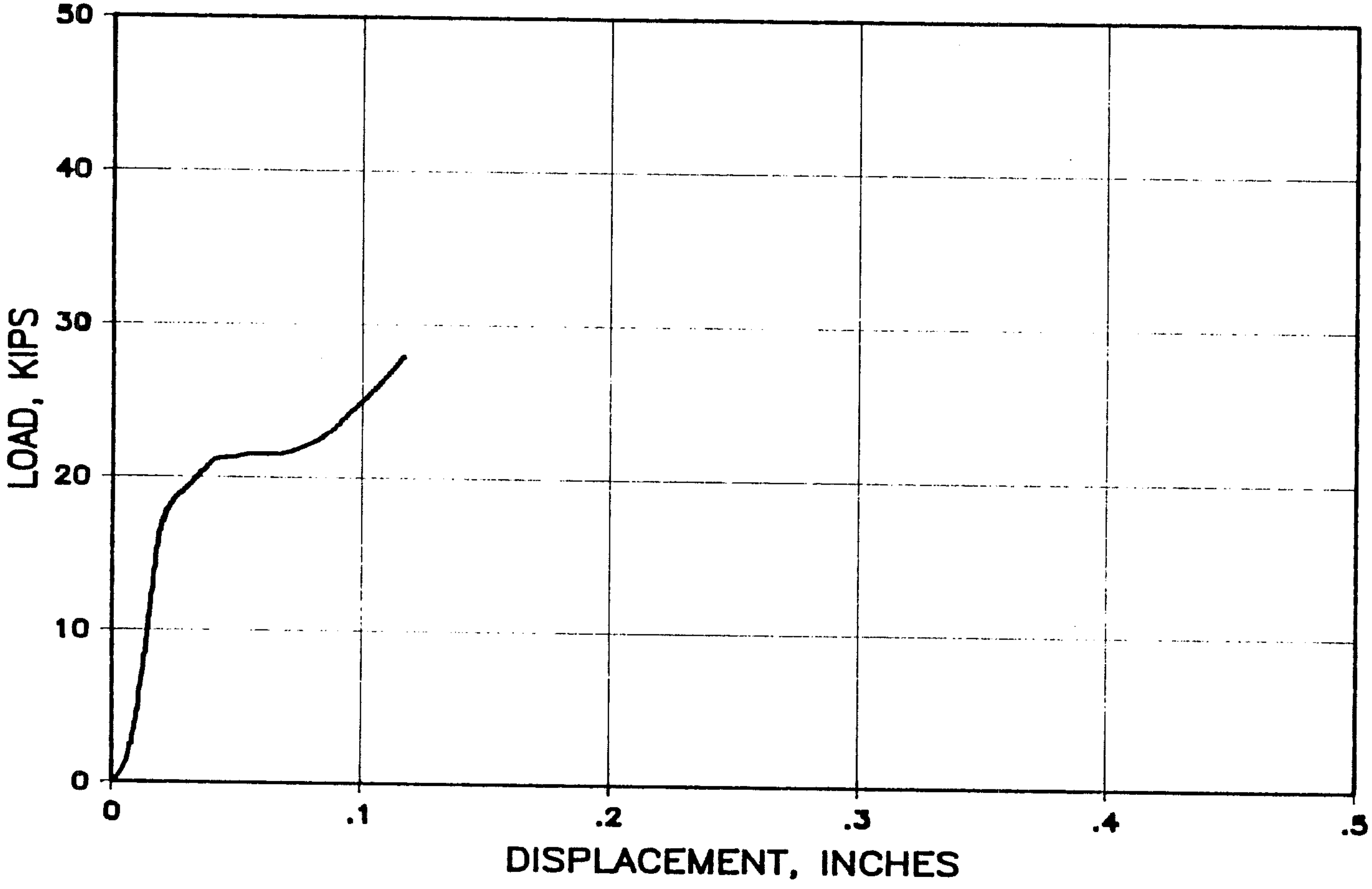


Fig. 4.2 Load-displacement plot, Test 1T

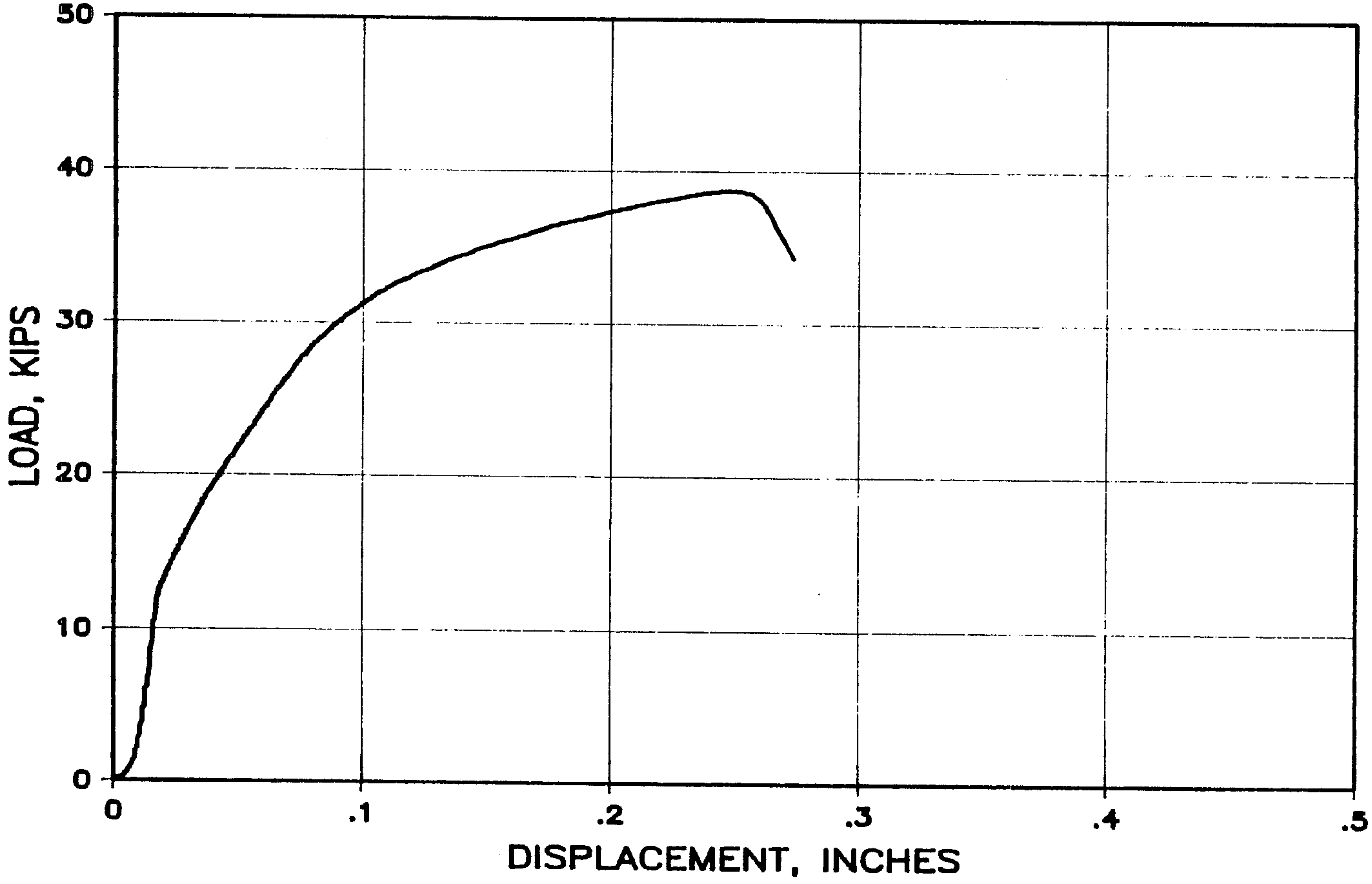


Fig. 4.3 Load-displacement plot, Test 1B

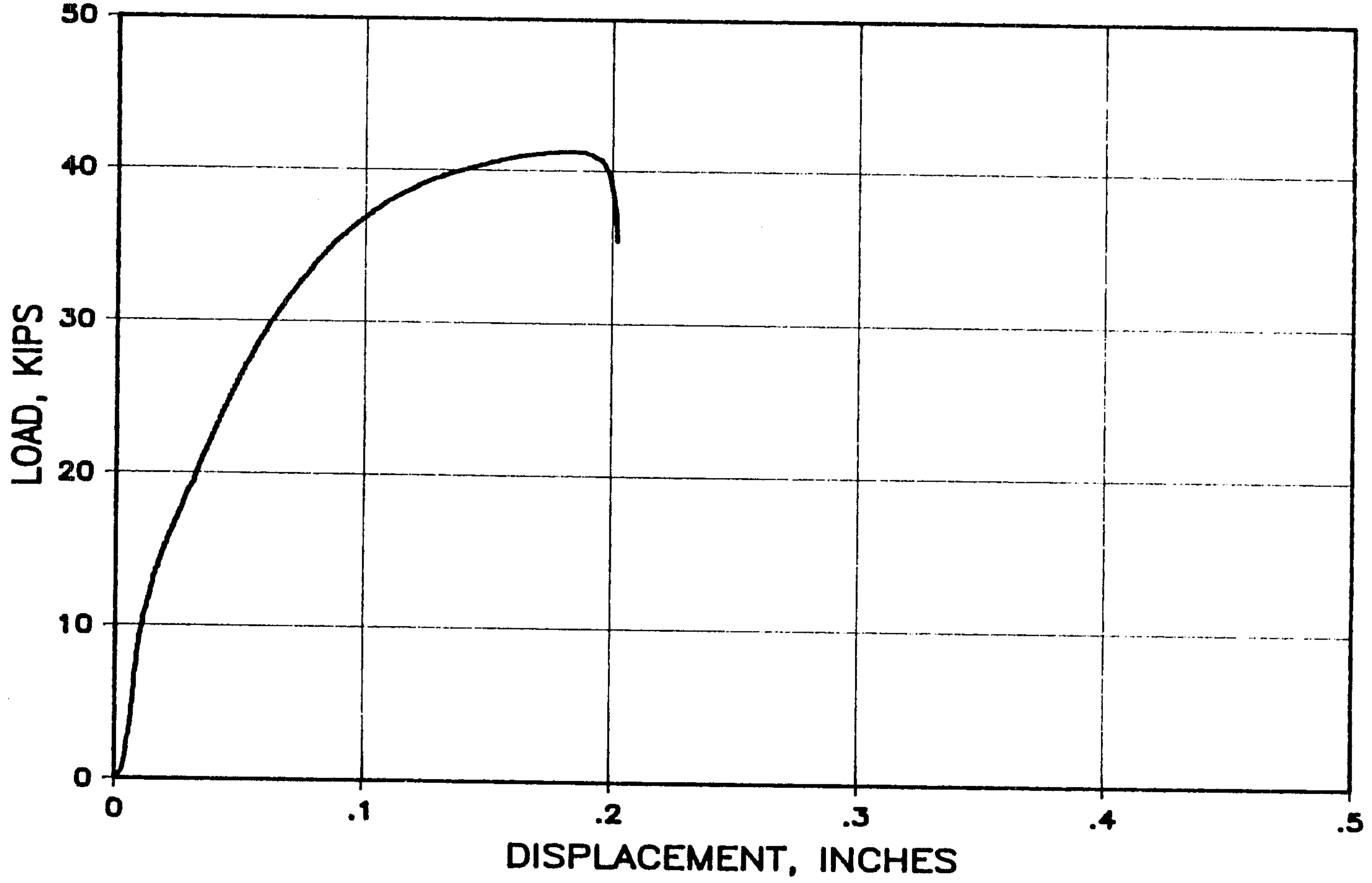


Fig. 4.4 Load-displacement plot, Test2 1B

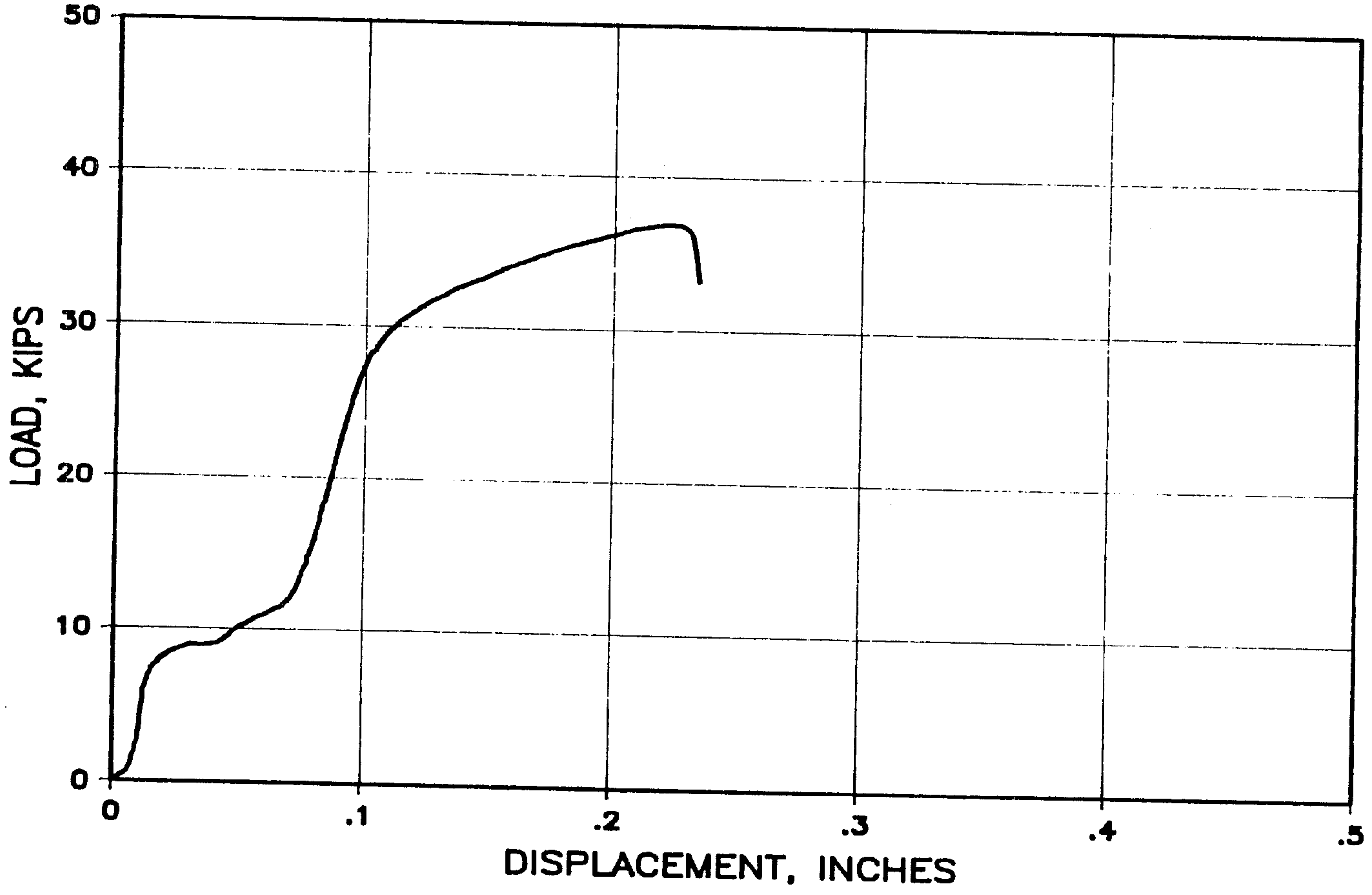


Fig. 4.5 Load-displacement plot, Test2 1CH

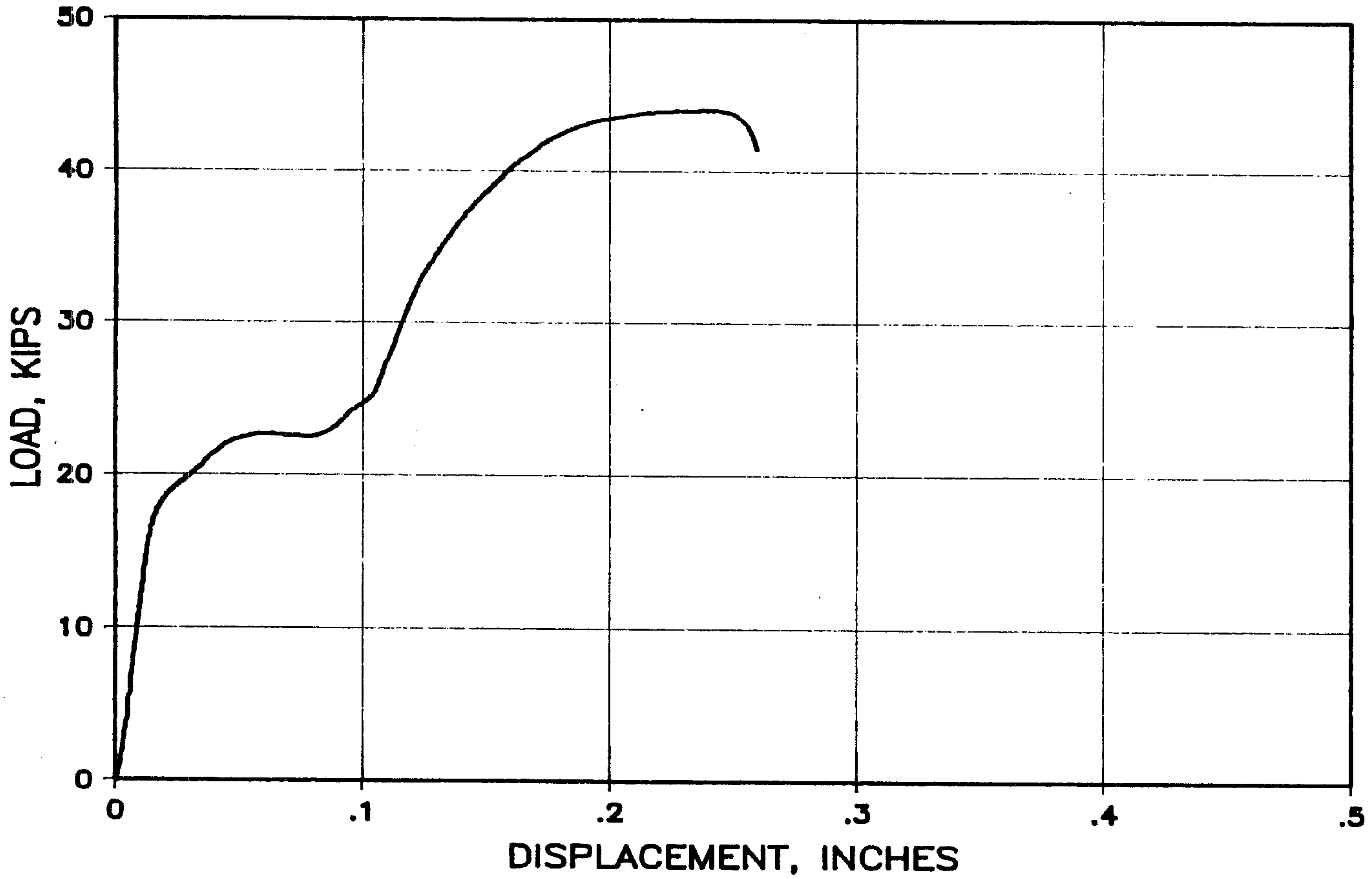


Fig. 4.6 Load-displacement plot, Test2 1T

achieved the highest load of any specimen without adhesive, (44.0 kips), at an ultimate deformation of 0.24 in. The major slip of about 0.1 in. occurred at slightly above 20 kips, and was again accompanied by a loud cracking sound. Specimen2 1CH failed at the lowest load of any specimen (36.9 kips), but with a typical deformation, 0.23 in. Major slip of about 0.06 in. occurred at 8 kips, with no audible noise.

4.4 Tests Involving A Partially Filled Void

As discussed in sub-section 3.7.6, in this series of tests the adhesive was injected into the rod-hole void from the outside, and no bond was created between steel and concrete. Upon dismantling the specimens, it was noted that the adhesive did not extend completely into the void, and some space was left between concrete and adhesive (Fig. 3.10).

4.4.1 1/16-Inch Clearance. Specimen 1CE was the only one with a standard size hole and adhesive. Compared to specimens without adhesive, the test results (shown in Fig. 4.7) reveal a greater initial stiffness, followed by well-defined yield, and plastic deformation. The rod-hole void was more completely filled in this specimen than in any other of this group. No slip was observed in this test.

4.4.2 3/16-Inch Clearance. Results from tests 3CE, 3TE, and 3CEH are shown in Figs. 4.8, 4.9, and 4.10 respectively. Average deformation at ultimate strength increased to an average of 0.31 in., while average ultimate strength reached 42.0 kips.

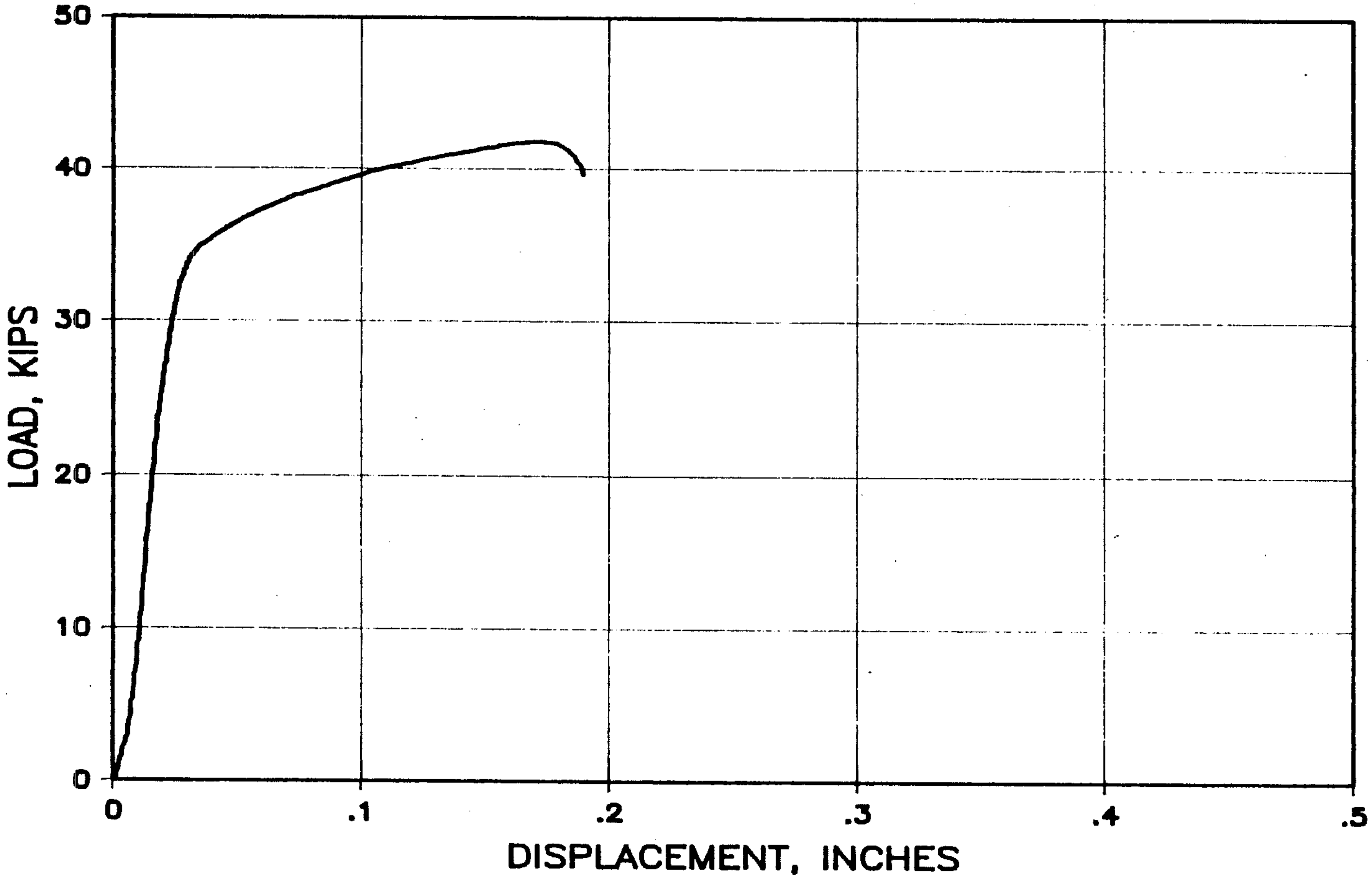


Fig. 4.7 Load-displacement plot, Test 1CE

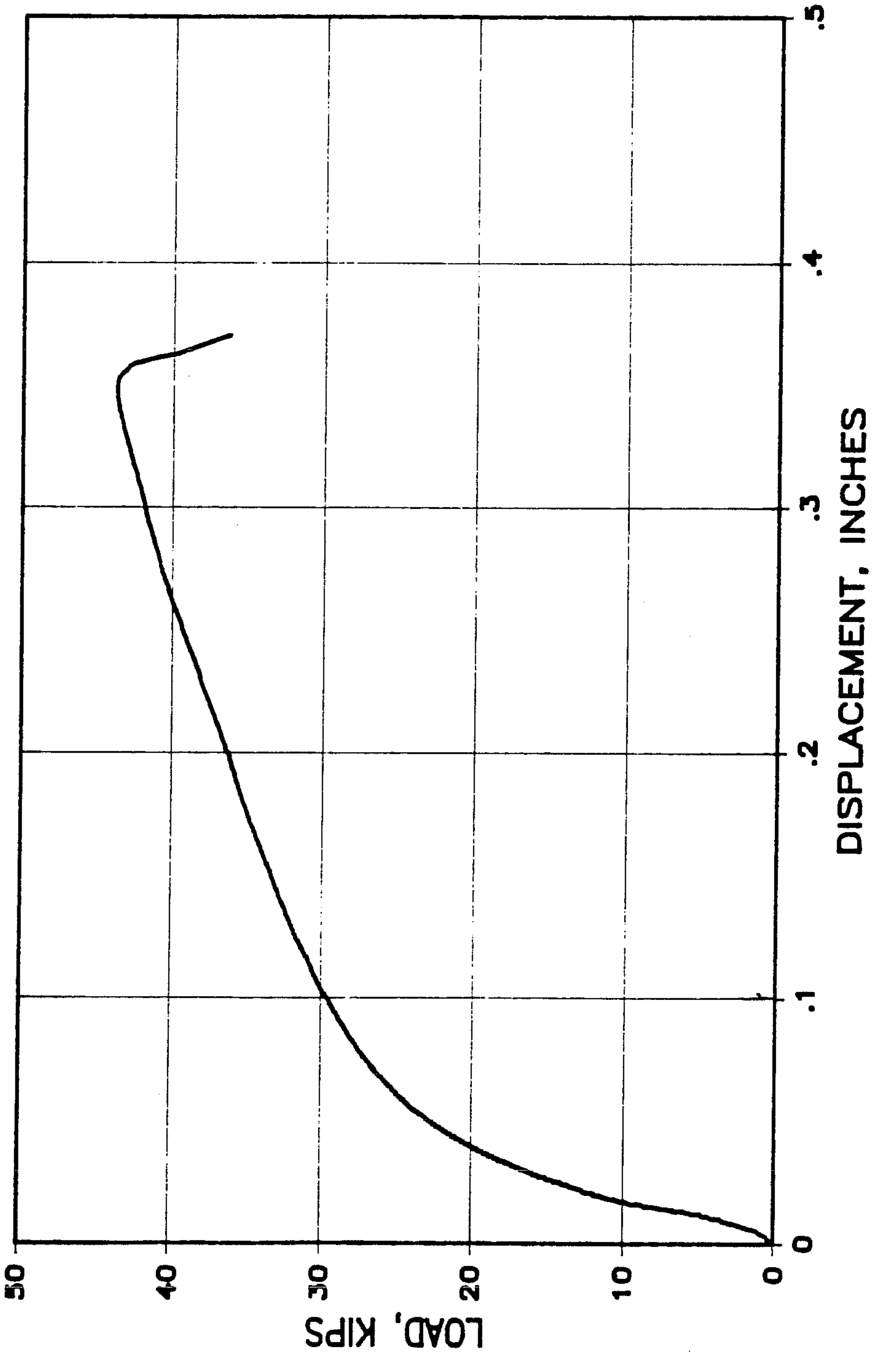


Fig. 4.8 Load-displacement plot, Test 3CE

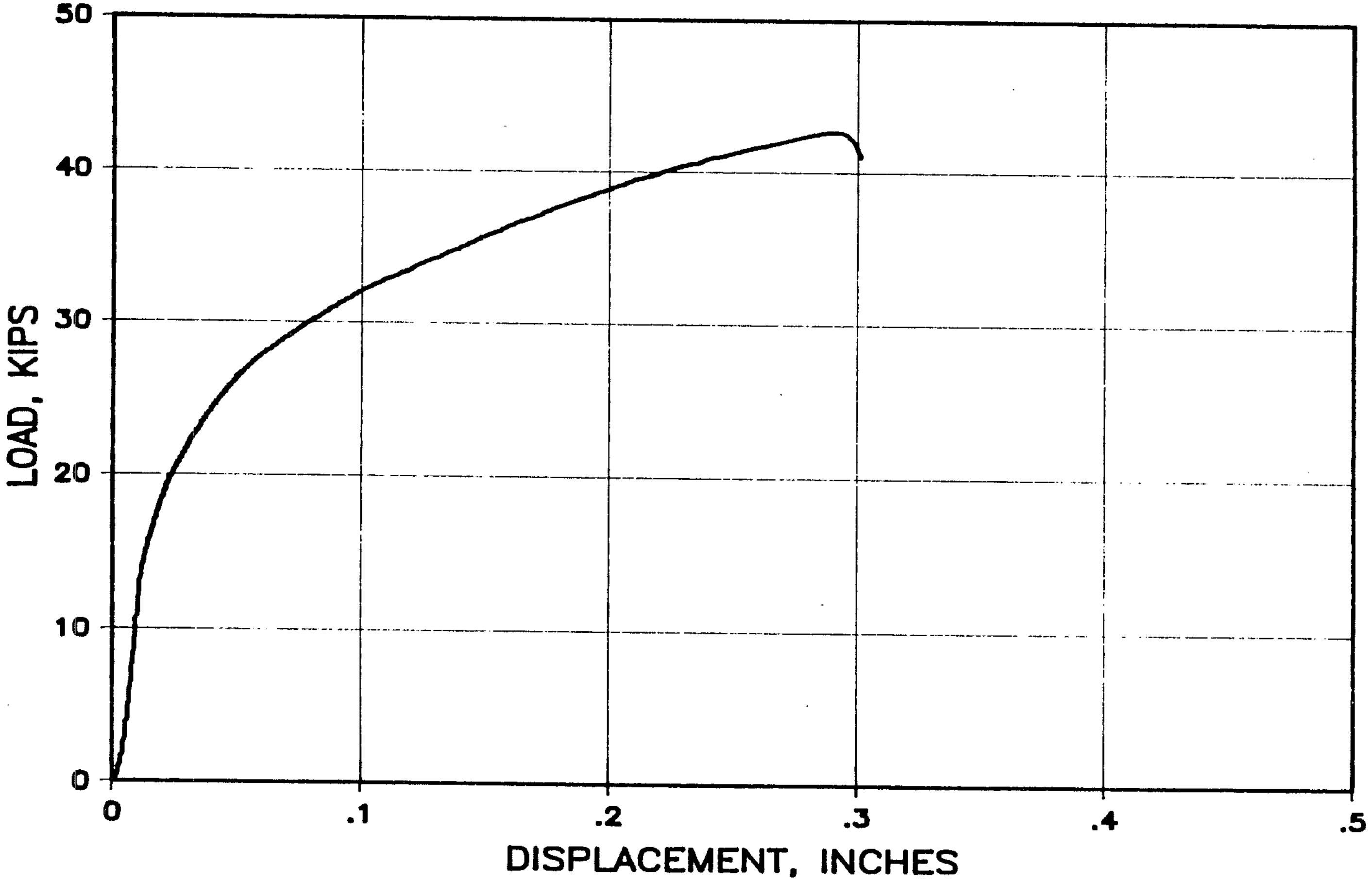


Fig. 4.9 Load-displacement plot, Test 3TE

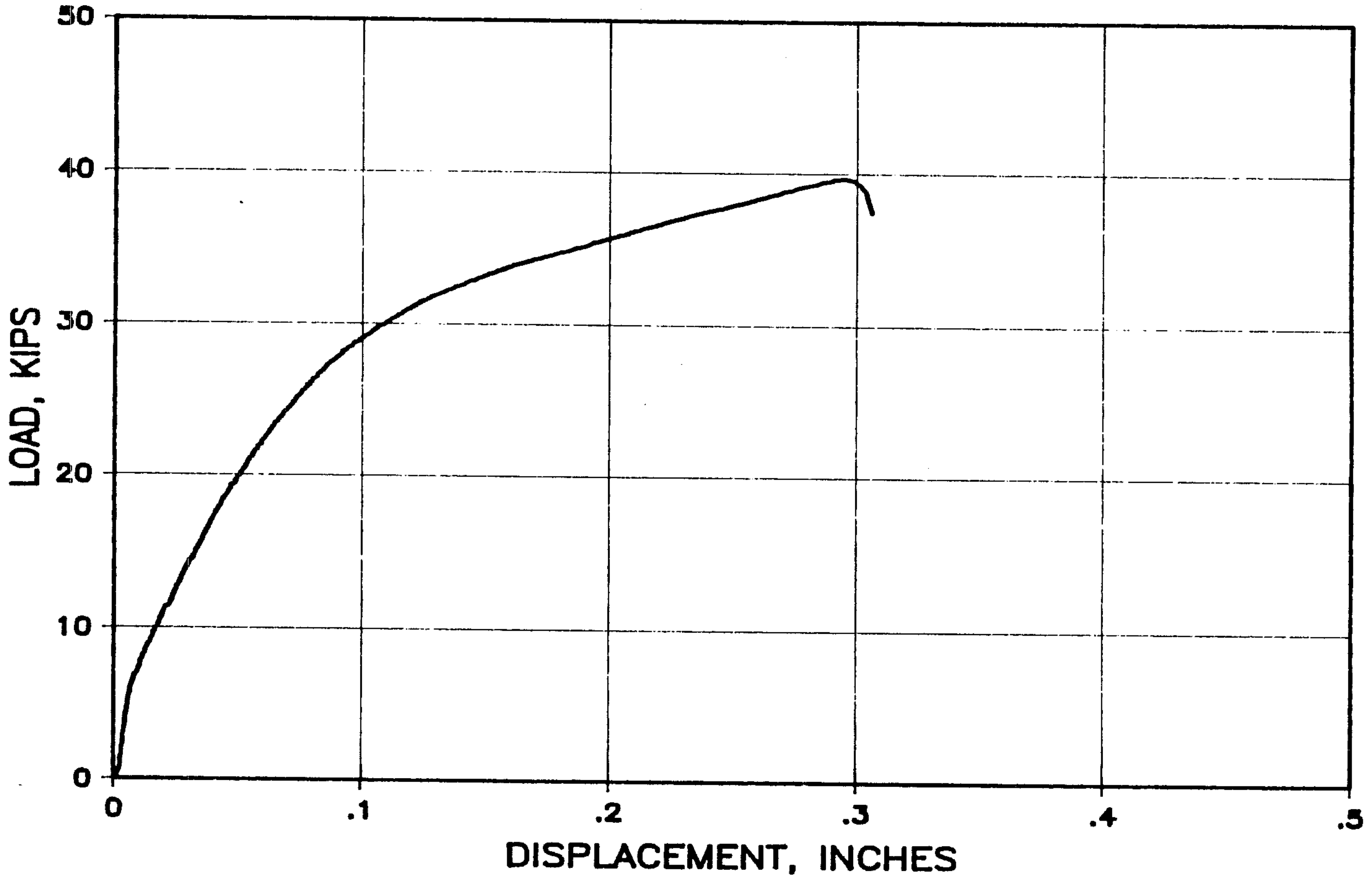


Fig. 4.10 Load-displacement plot, Test 3CEH

No slip was observed in these tests. Upon dismantling the specimens, it was found that on the outer side of the connected plate, the bolt was still held rigidly in its original position by the adhesive filler. All measured deformation was therefore due to yielding of the bolt in shear and bending, rather than to slip. Position of the rod in the hole did not appear to affect the results of these tests.

4.4.3 5/16-Inch Clearance. Results from Tests 5CE, 5TE, and 5CEH are presented graphically in Figs. 4.11 through 4.13. Specimen 5TE unexpectedly continued to resist past the pre-specified 3 minutes. Data acquisition terminated at 48.2 kips and 0.57 in. Using these values, average load increased to 46.3 kips, and deformation to 0.47 in.

As for specimens with 3/16-in. clearance, deformation was achieved gradually rather than by abrupt slip. Thread marks could be seen in the adhesive filler near the steel-concrete interface, indicating yielding of the adhesive as the deformation of the rod increased. At the face of the plate, the rod and nut maintained their original position and the rods ultimately failed next to the concrete interface. Rod position in the hole did not significantly affect results of these tests.

4.5 Tests Involving a Completely Filled Void

For this series of tests the adhesive was applied to the base of the rod and surrounding concrete before assembly with the plate, assuring that the void between rod and hole was completely filled. Some effects of adhesion between steel and concrete were anticipated.

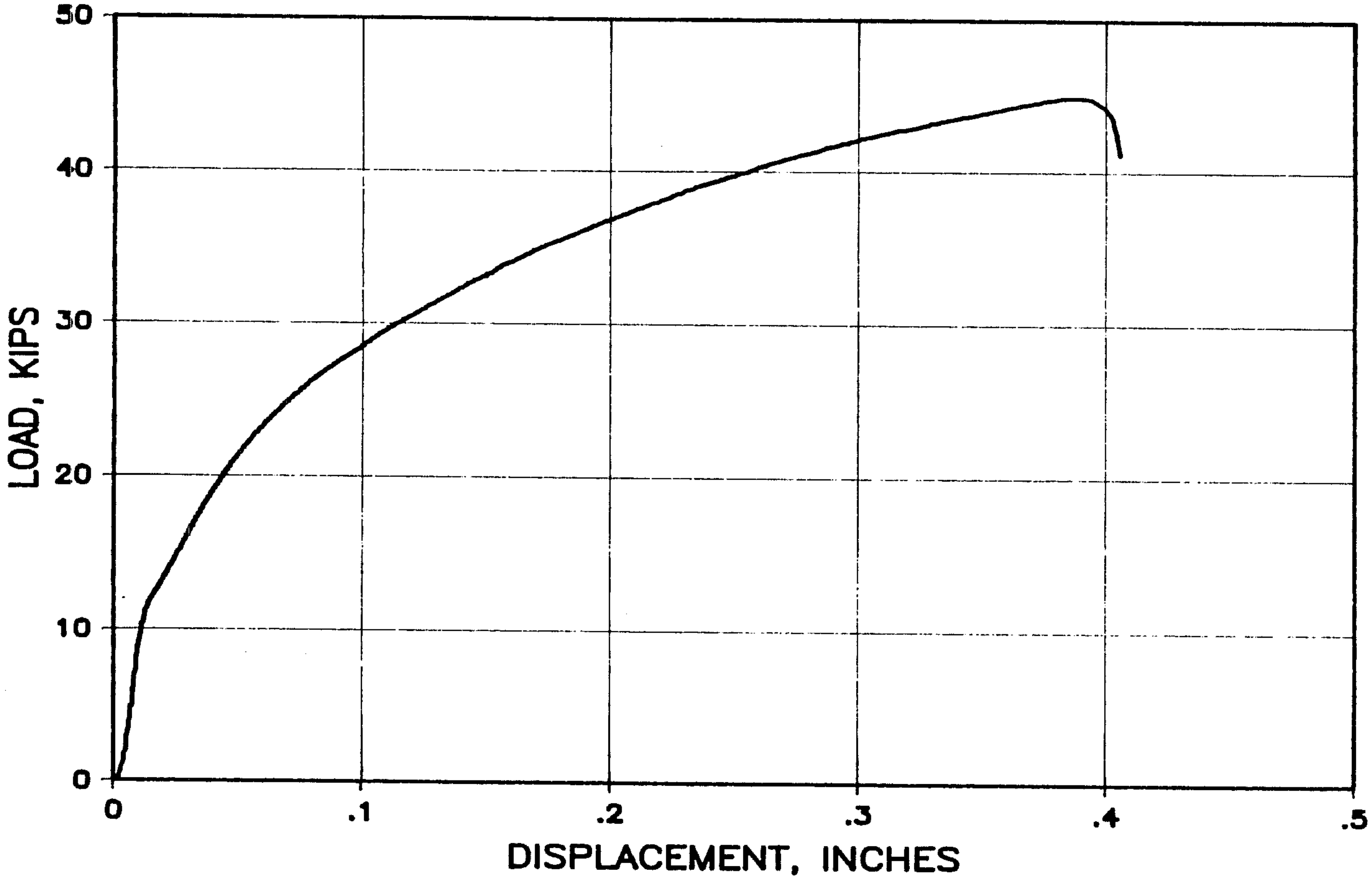


Fig. 4.11 Load-displacement plot, Test 5CE

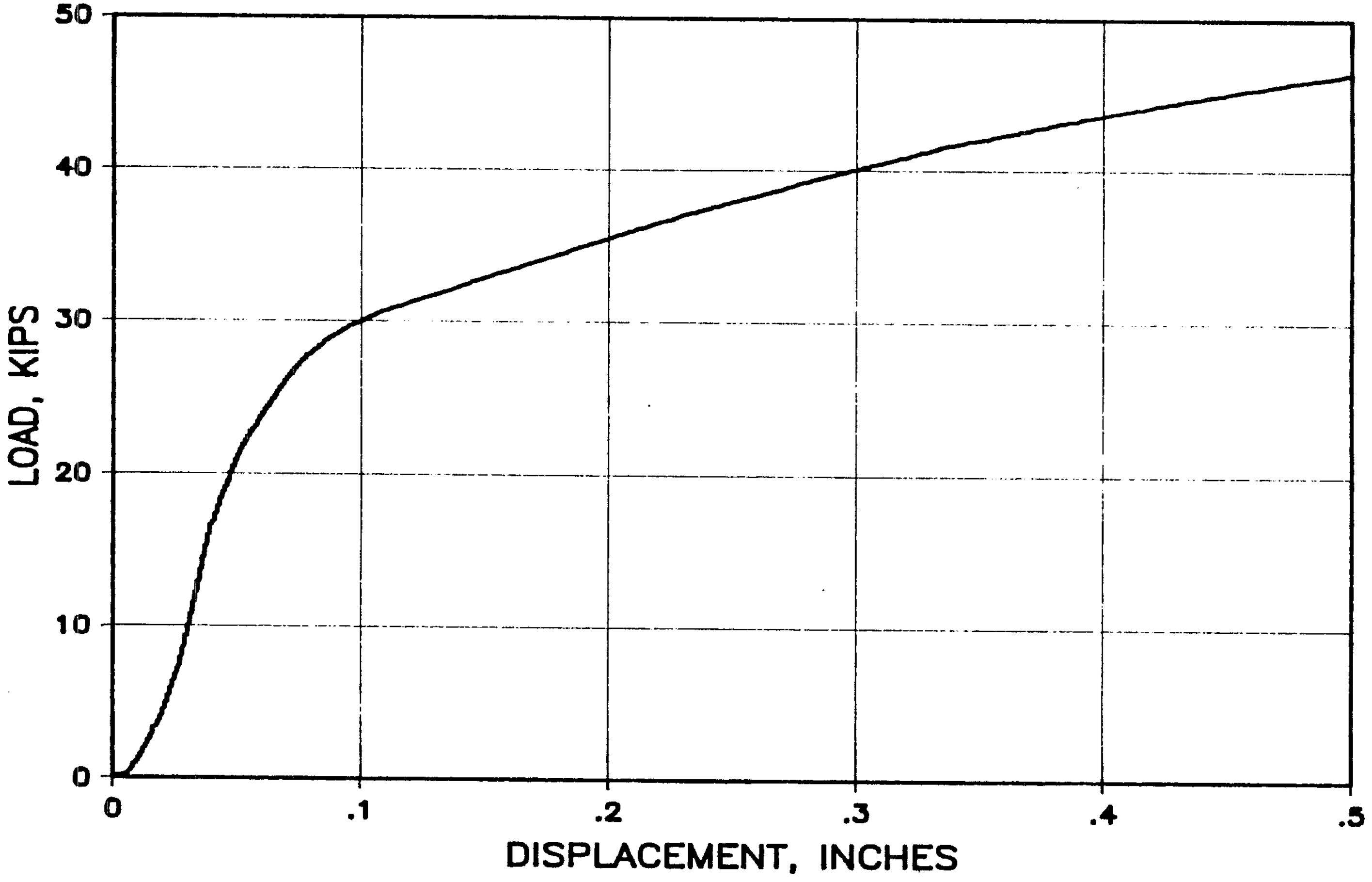


Fig. 4.12 Load-displacement plot, Test 5TE

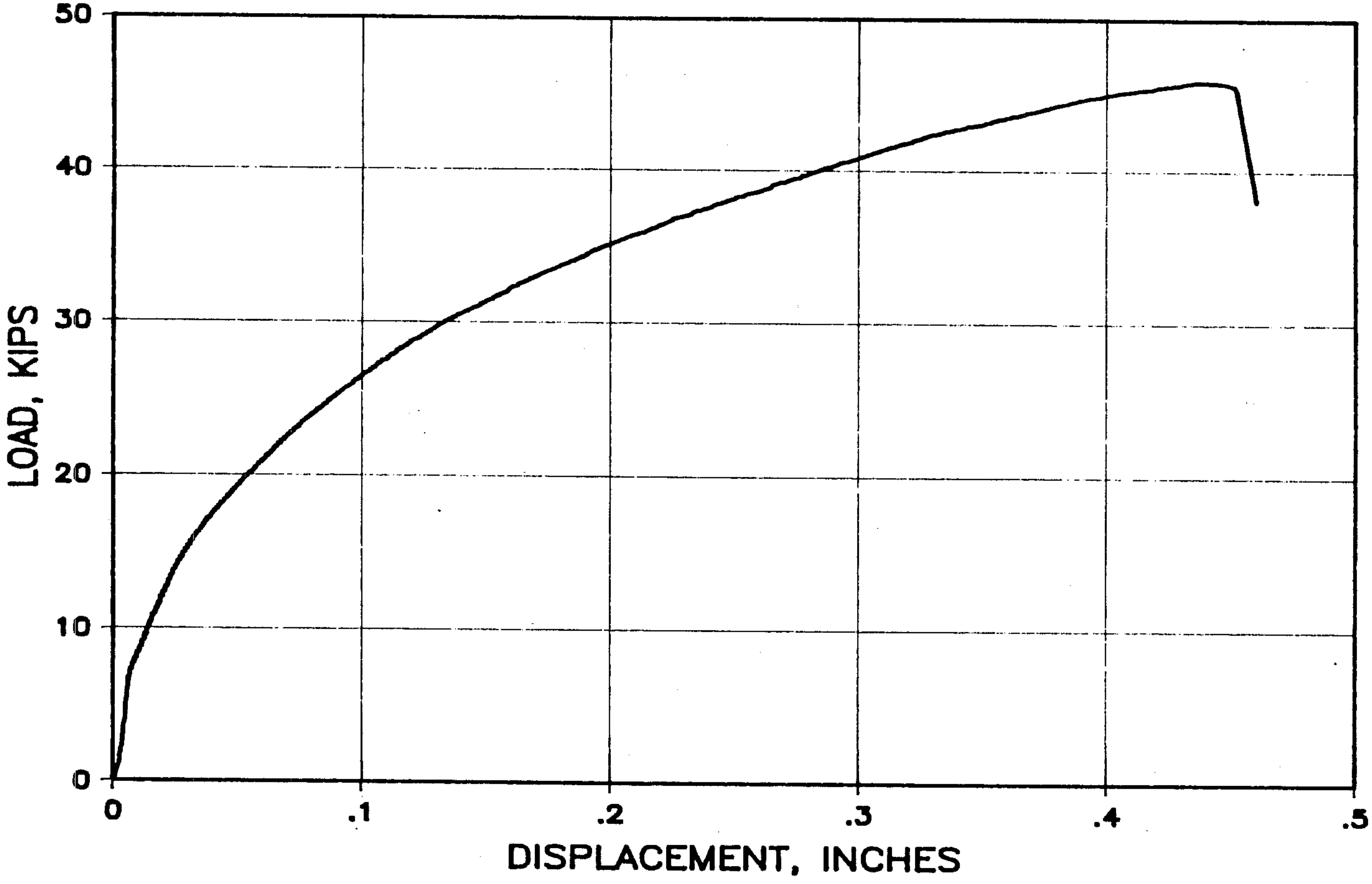


Fig. 4.13 Load-displacement plot, Test 5CEH

4.5.1 3/16-Inch Clearance. Results of Tests 3CE-I and 3TE-I are presented in Figs. 4.14 and 4.15. Debonding of the adhesive at the interface can be noted at around 37 kips. This effect is negligible in Test 3CE-I, but more noticeable in Test 3TE-I. After dismantling the specimens, it was found that the bonded interface on Specimen 3TE-I was significantly larger than on any other specimens. Most specimens had a bonded surface area that was roughly circular and 3 to 4 inches in diameter. Specimen 3TE-I had a circular interface about 9 inches in diameter. This was probably due to the application of more adhesive, and possibly also to better mating of the surfaces. Extending the load-deformation curve from the post slip value back to the origin still indicates an adequate initial stiffness. Average deformation at ultimate was 0.25 in., and the average peak load was 43.0 kips.

4.5.2 5/16-Inch Clearance. The curve from Test 5TE-I was nearly identical to that of 3CE-I, the only difference being the increase in deformation to 0.32 in. and in ultimate load to 45.4 kips. These results and those of Test 5TEH-I are shown in Figs. 4.16 and 4.17. The slip caused by debonding in either case was again insignificant. Average ultimate load was 45.4 kips, coupled with an average deformation of 0.35 in. Rod position in the hole did not affect the results of these tests.

4.6 Comparison of Results

Bolted shear connections are usually designed with a minimum factor of safety of 2.0 against bolt shear failure. For 5/8-in.

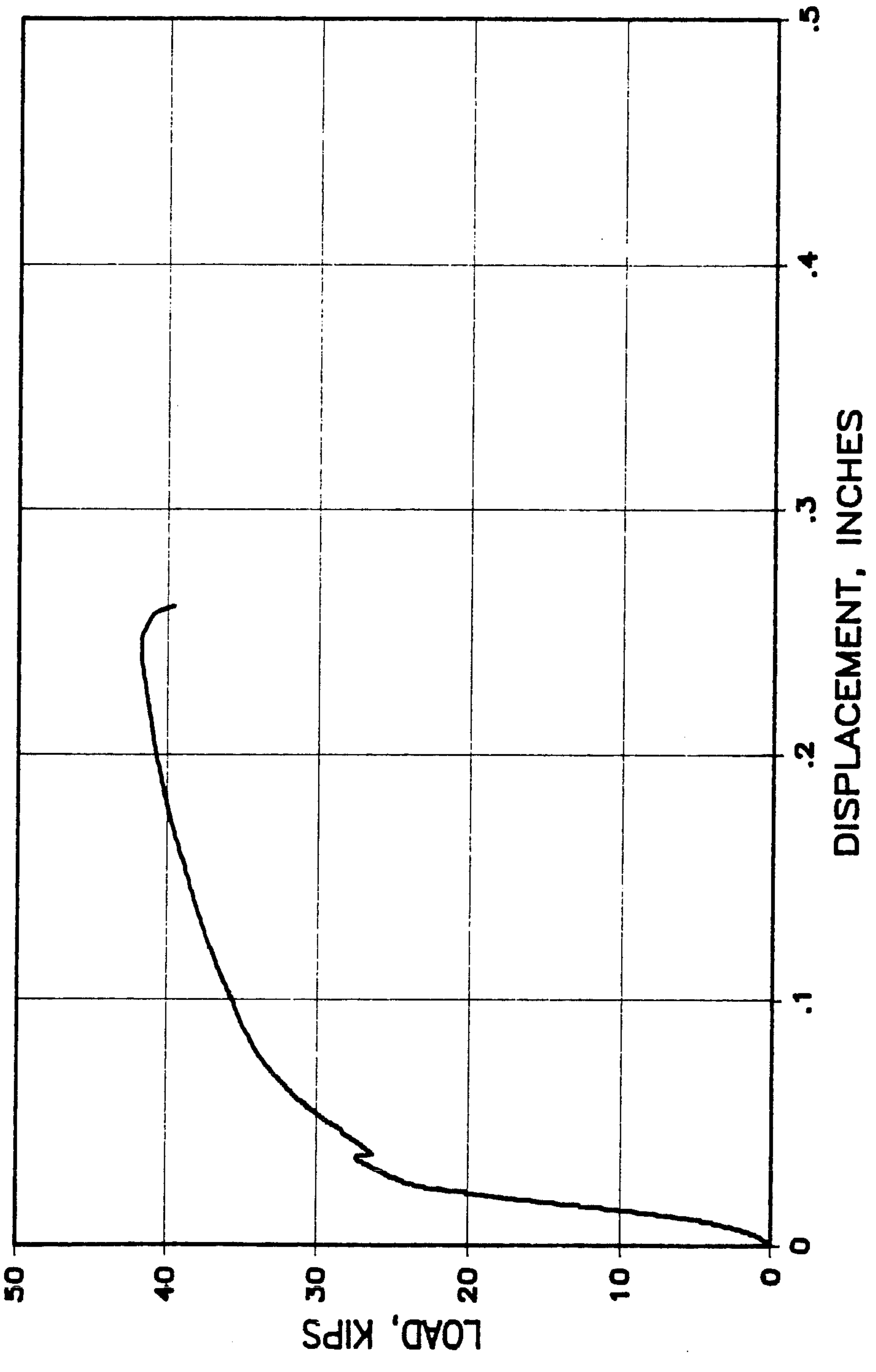


Fig. 4.14 Load-displacement plot, Test 3CE-I

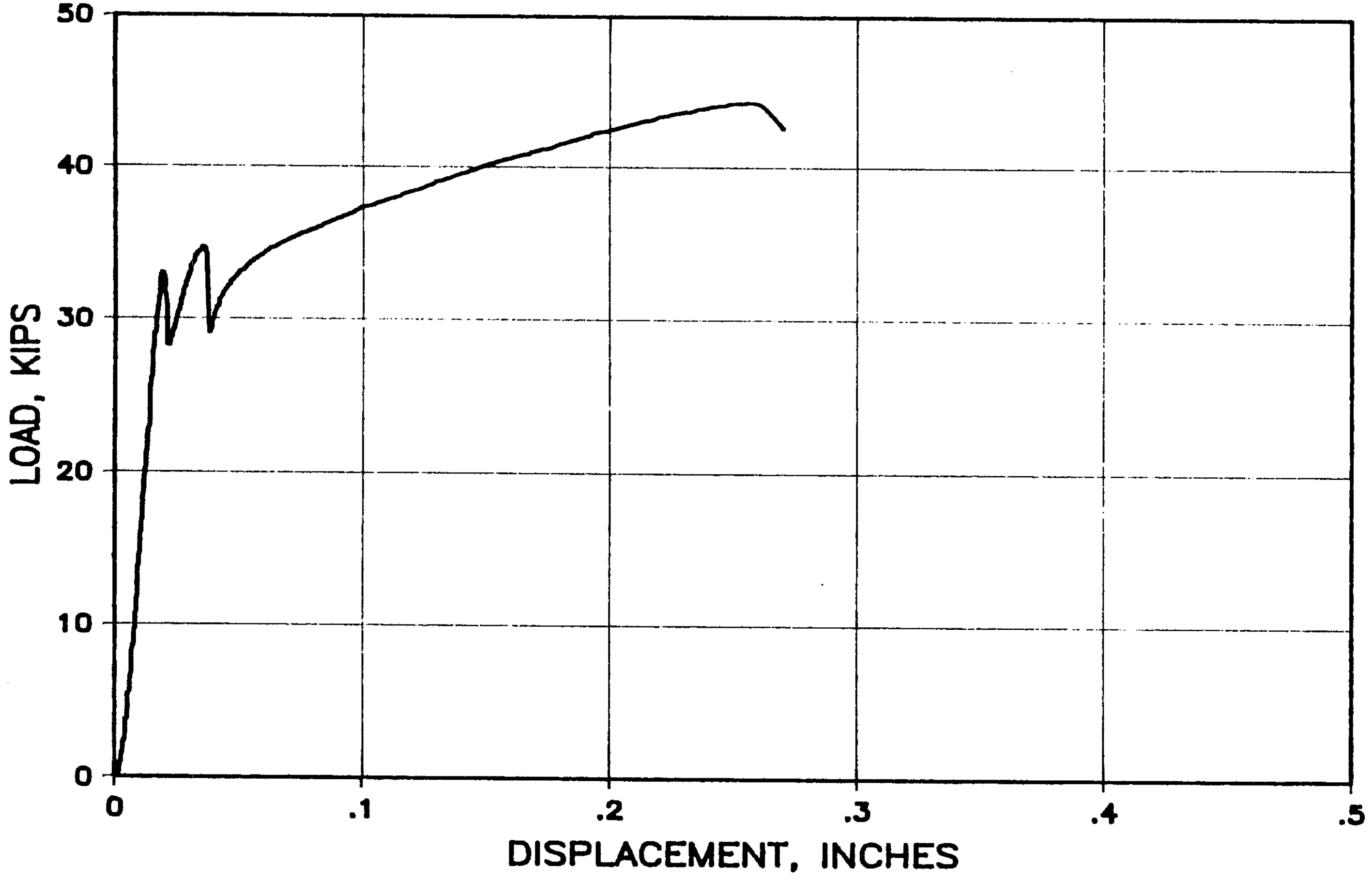


Fig. 4.15 Load-displacement plot, Test 3TE-I

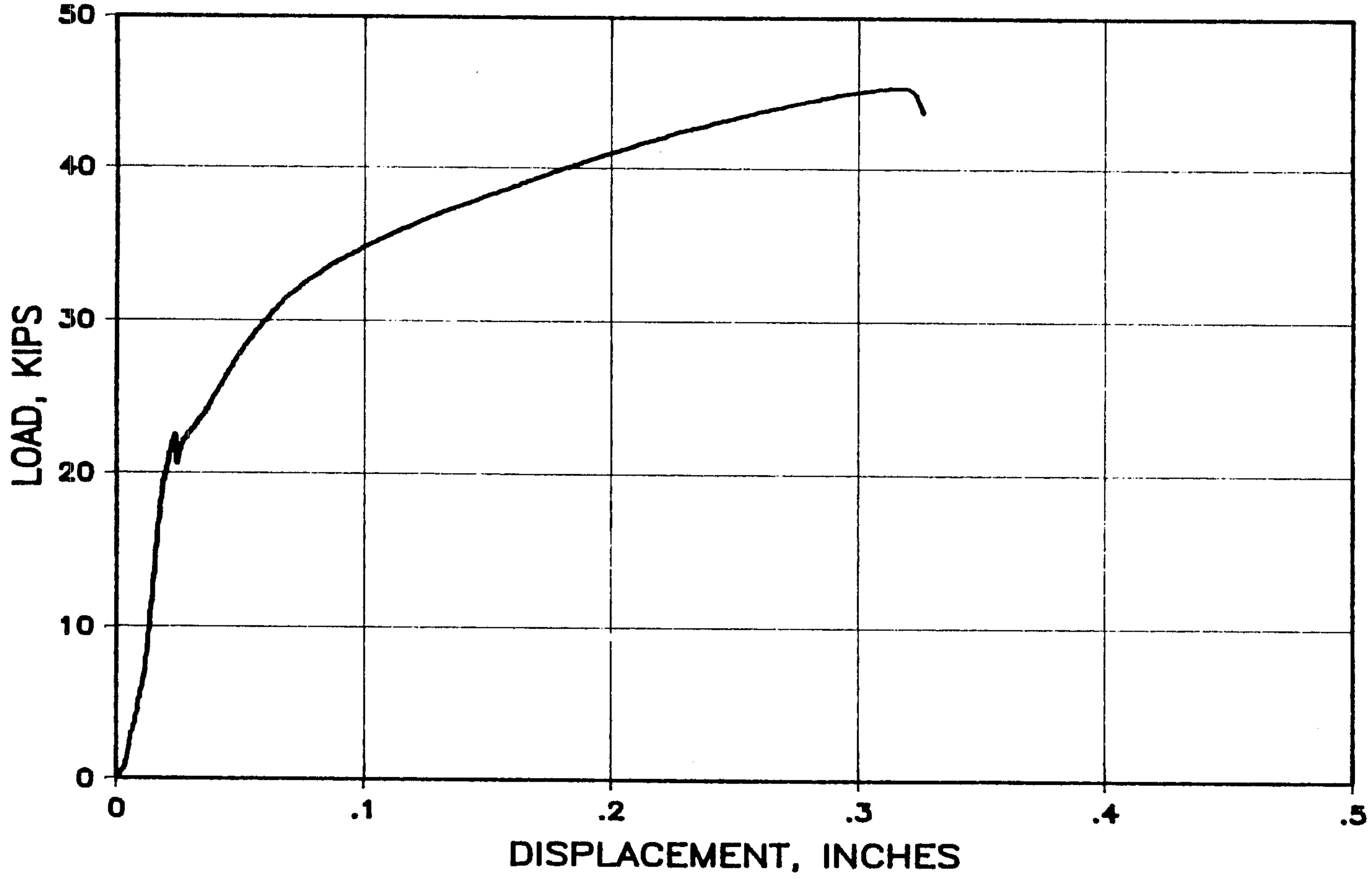


Fig. 4.16 Load-displacement plot, Test 5TE-I

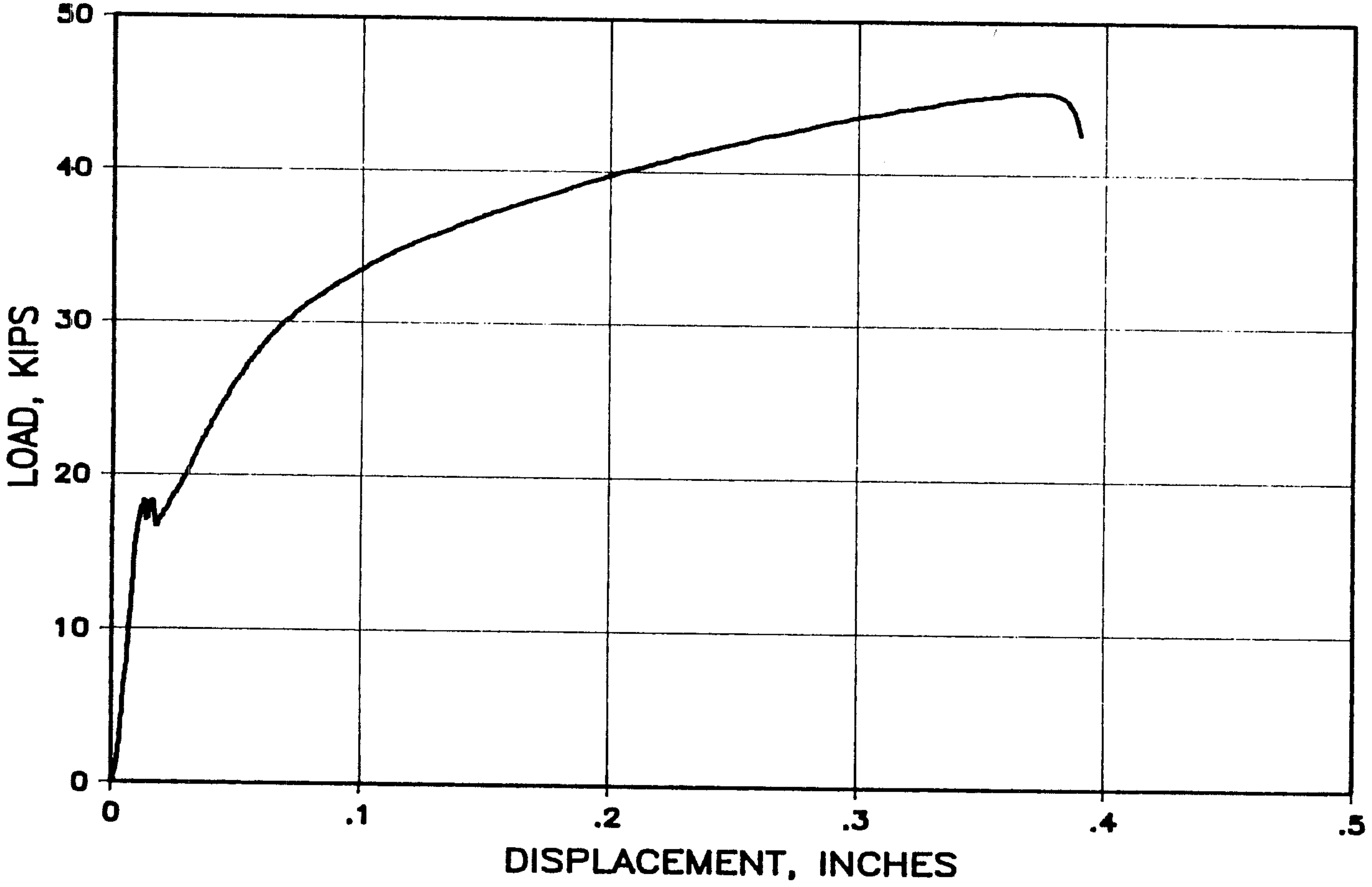


Fig. 4.17 Load-displacement plot, Test 5TEH-I

A325 bolts in double shear with threads included in the shear plane, the AISC Load and Resistance Factor Design Specification [4] gives a design load of 21.5 kips for bearing connections, and 10.4 kips for slip-critical (friction) connections.

To more effectively compare results at design loads as well as at ultimate, average values of deformation at 5-kip intervals and at ultimate were plotted for specimens with oversize holes with adhesive along with the corresponding values from the standard connections. The average data from standard connections did not include values from hand-tightened connections for applied loads less than 25 kips. In tests involving adhesive, values from specimens with hand-tightened nuts were included at all points.

Individual test results for standard holes without adhesive (for example Fig. 4.6) clearly show the plateau indicating major slip. However, the curve generated by using average values of deformation at 5-kip intervals for these tests (such as used in Figs. 4.18 to 4.20) does not show such a plateau. Because the major slip occurred at a different load for each test, the slip appears in the averaged curve as a range of reduced stiffness. The average curves are still believed to give a good picture of overall behavior.

In Fig. 4.18, average results from standard connections are compared with those from tests involving oversize holes with partially filled voids. The effect of slip around 20 kips in the standard connection is not present in the 13/16 or 15/16-in. holes with adhesive.

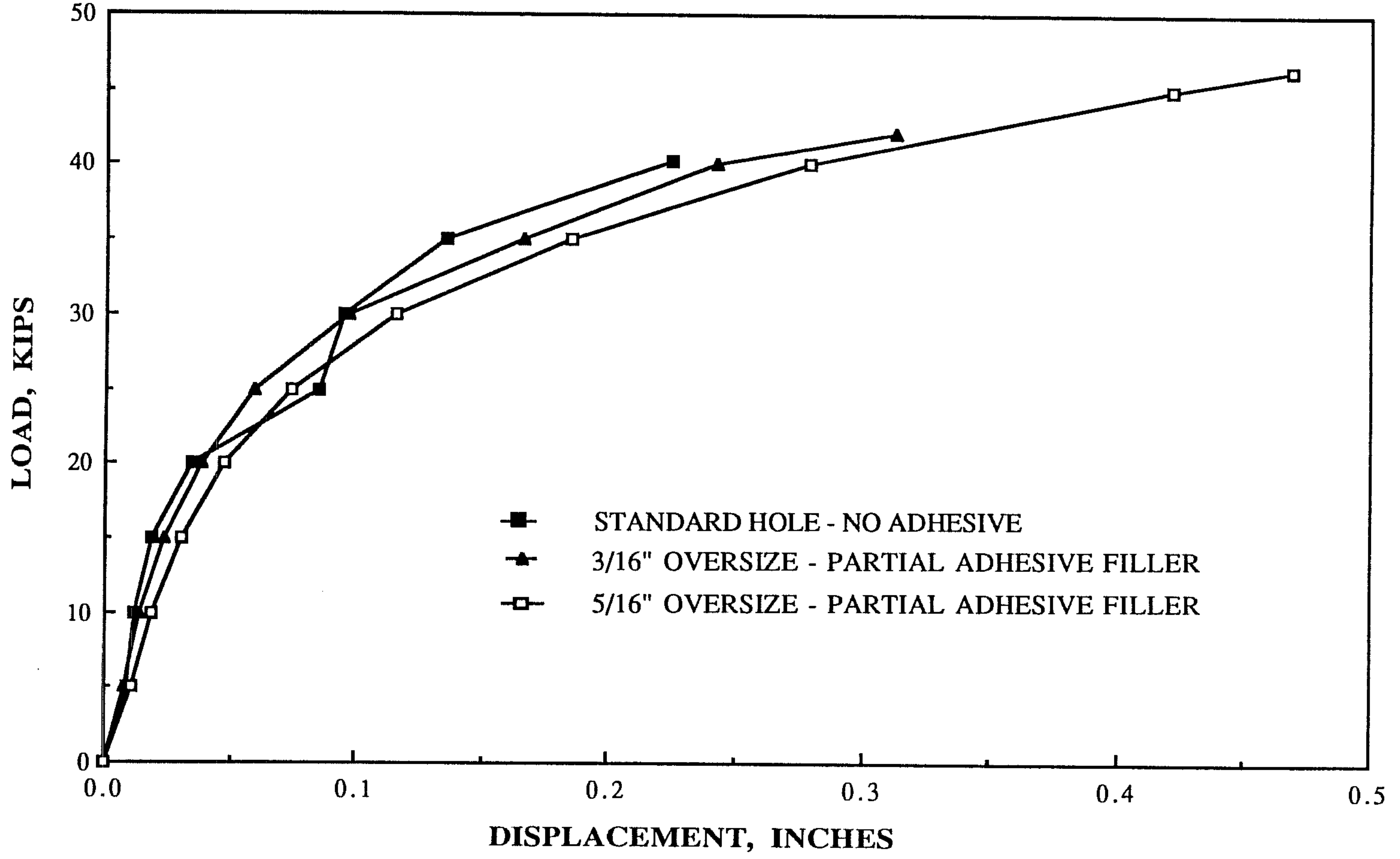


Fig. 4.18 Average load-deformation plots; standard connections vs. oversize holes with partial adhesive filler

In Fig. 4.19 average results from standard connections are compared with those involving oversize holes with the void completely filled with adhesive. Specimens with adhesive exhibited greater stiffness in all phases of testing, and a significant increase in ultimate deformation.

In Fig. 4.20, results from individual tests involving adhesive and hand-tightened nuts are compared with the average curve from standard connections. The specimen with the complete adhesive filler again performed better in all stages of loading. Specimens with a partially filled void exhibited reduced stiffness at service load levels, but still had a greater ultimate capacity.

Since the area under the load-displacement curve equals the energy absorption capacity of the connections, Figs. 4.18 through 4.20 also indicate that connections with oversize holes and adhesive fillers can absorb significantly more energy than standard connections without adhesive.

4.7 Discussion and Analysis

4.7.1 General. Tests involving oversize holes with adhesive showed increased deformation capacity and ultimate strength when compared to tests with no adhesive and standard size holes. Specimens in which the adhesive partially filled the rod-hole void showed the highest ultimate capacity, while their behavior at design loads was comparable to that of standard connections. Specimens with a complete adhesive filler

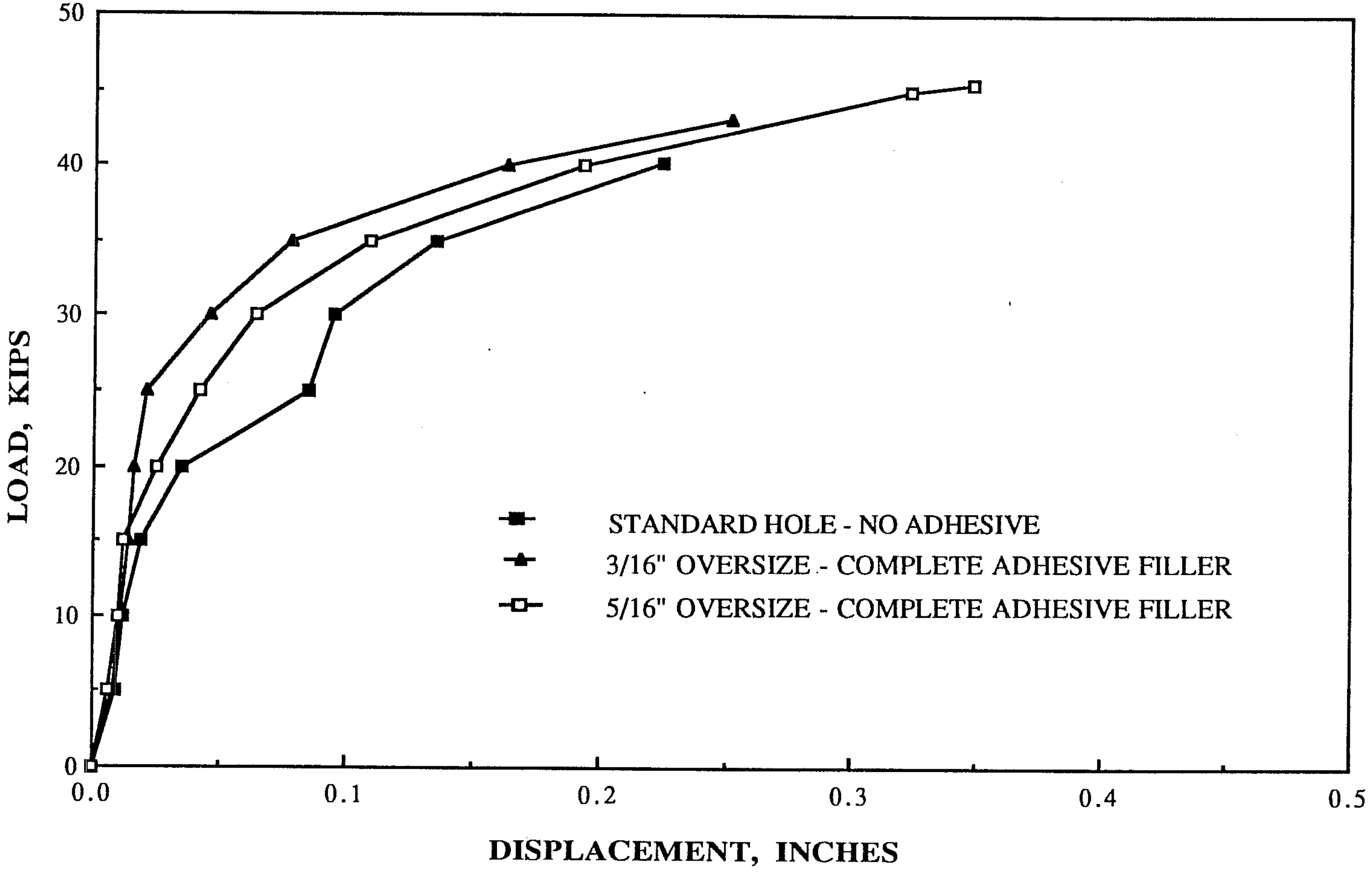


Fig. 4.19 Average load-deformation plots; standard connections vs. oversize holes with complete adhesive filler

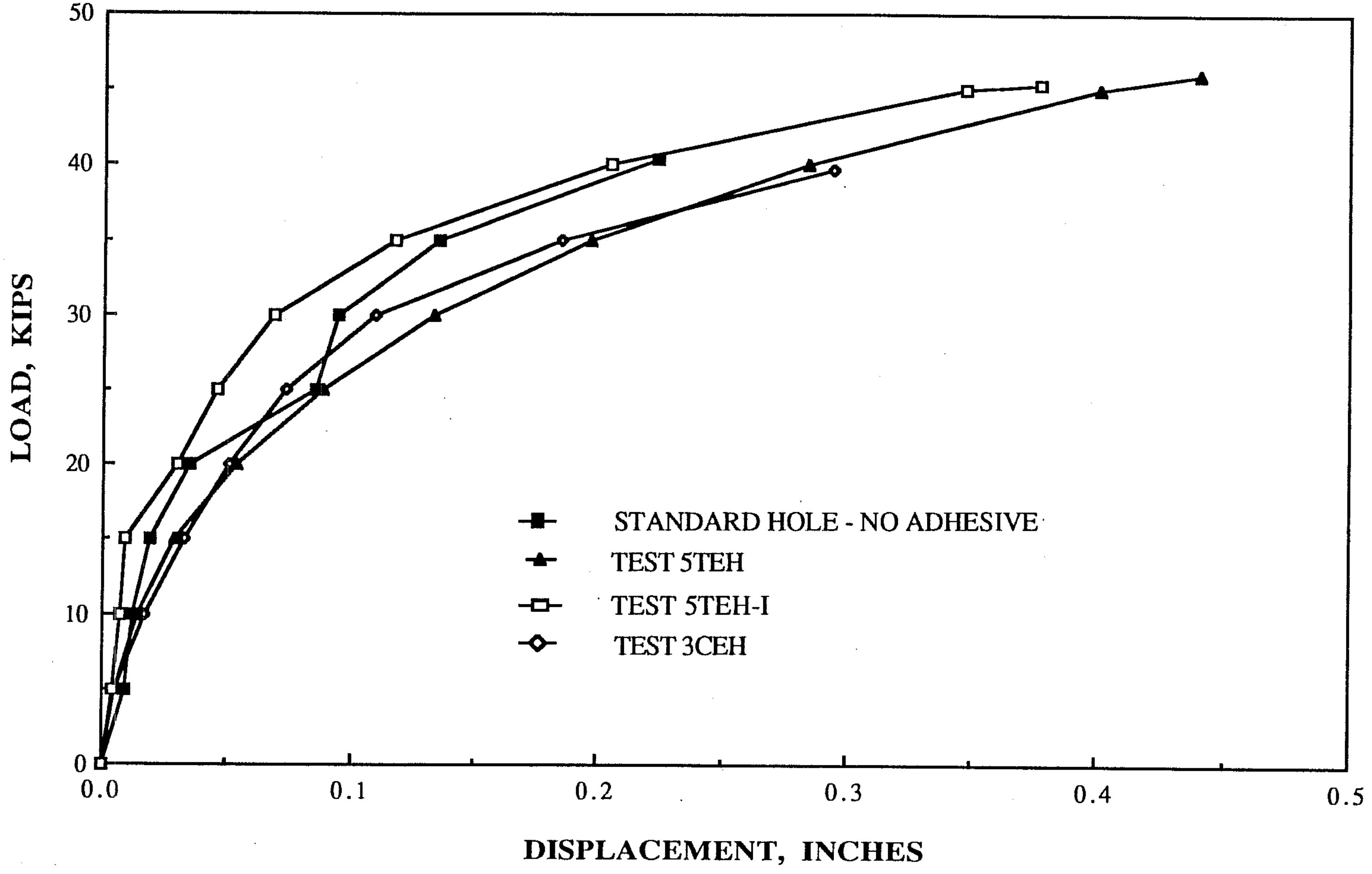


Fig. 4.20 Average load-deformation plot from standard connections vs. actual values from tests with hand tightened nuts

showed less of an increase in ultimate strength and deformation, but were stiffer at design loads than either specimens with a partial adhesive filler, or the standard connections.

Since ultimate strength is not affected by hole size or bolt preload [2], it can be concluded that the use of adhesive fillers in specimens with oversize holes has caused this improvement in behavior. The increase in ultimate deformation is probably due to the following. The adhesive filler holds the rod in its original position at the outside face of the plate, but permits additional deformation of the rod between the steel-concrete interface and the outside of the plate. Deformation then occurs through a combination of shear, bending and tension in the rod, not just through shear alone. The increase in ultimate strength is probably a result of the more uniform load distribution on the rod itself due to the fitted hole created by the adhesive. In contrast to this, connections without adhesive fillers impose a severe stress concentration on the rod. The situations with and without adhesives are contrasted schematically in Figs. 4.21 and 4.22.

4.7.2 Tests Involving a Partially Filled Void. In the specimens with 5/16-in. clearance, ultimate deformation was increased by a factor of 2.1 compared to specimens with no adhesive. Ultimate strength was increased by 15 percent and initial stiffness was comparable. The increase in ultimate deformation may be attributed in part to the unfilled portion of the rod-hole void. Thread marks could be seen on the inside surface of the adhesive, indicating yielding of the

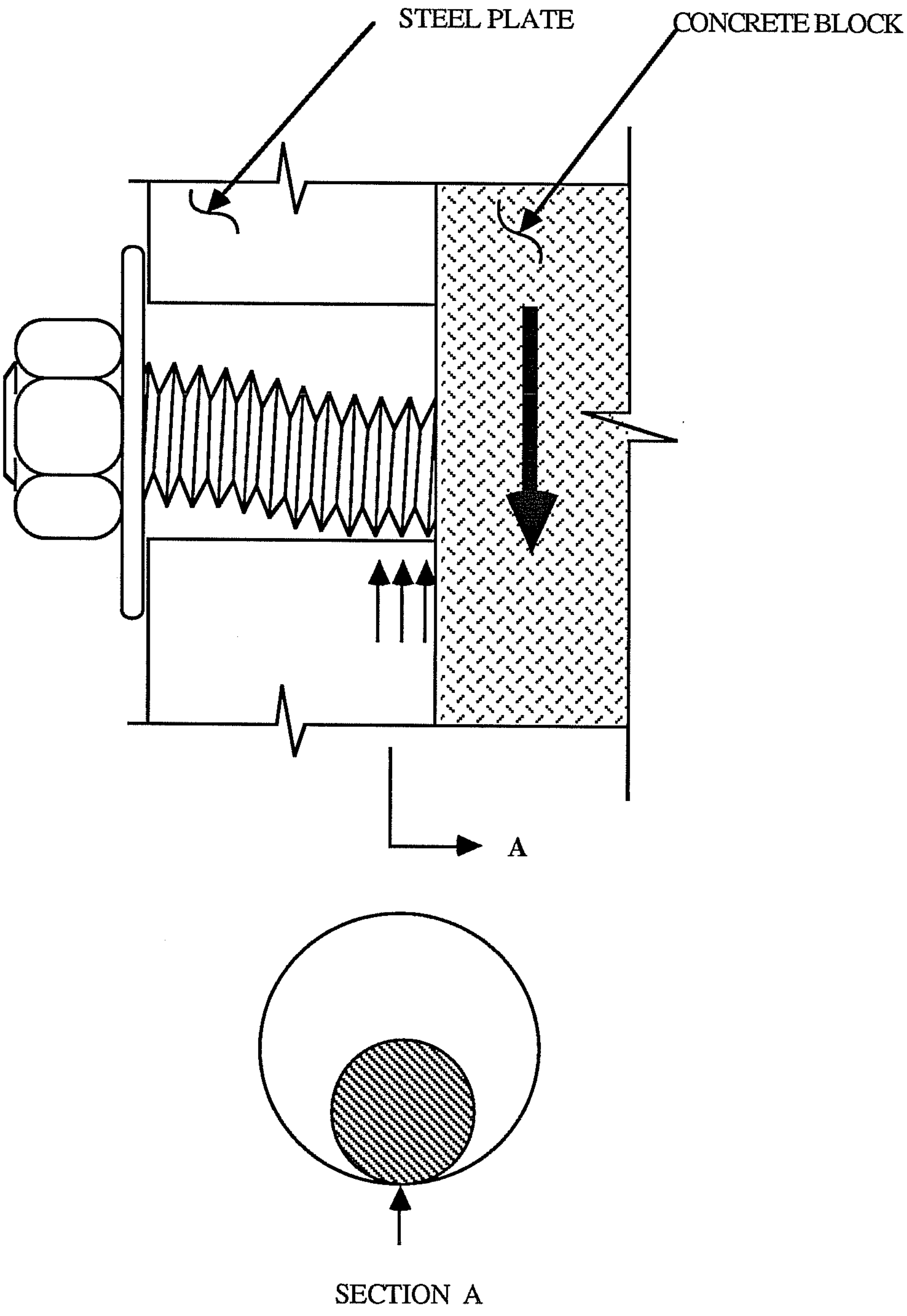


Fig. 4.21 Load distrubution on rod with no adhesive filler (schematic)

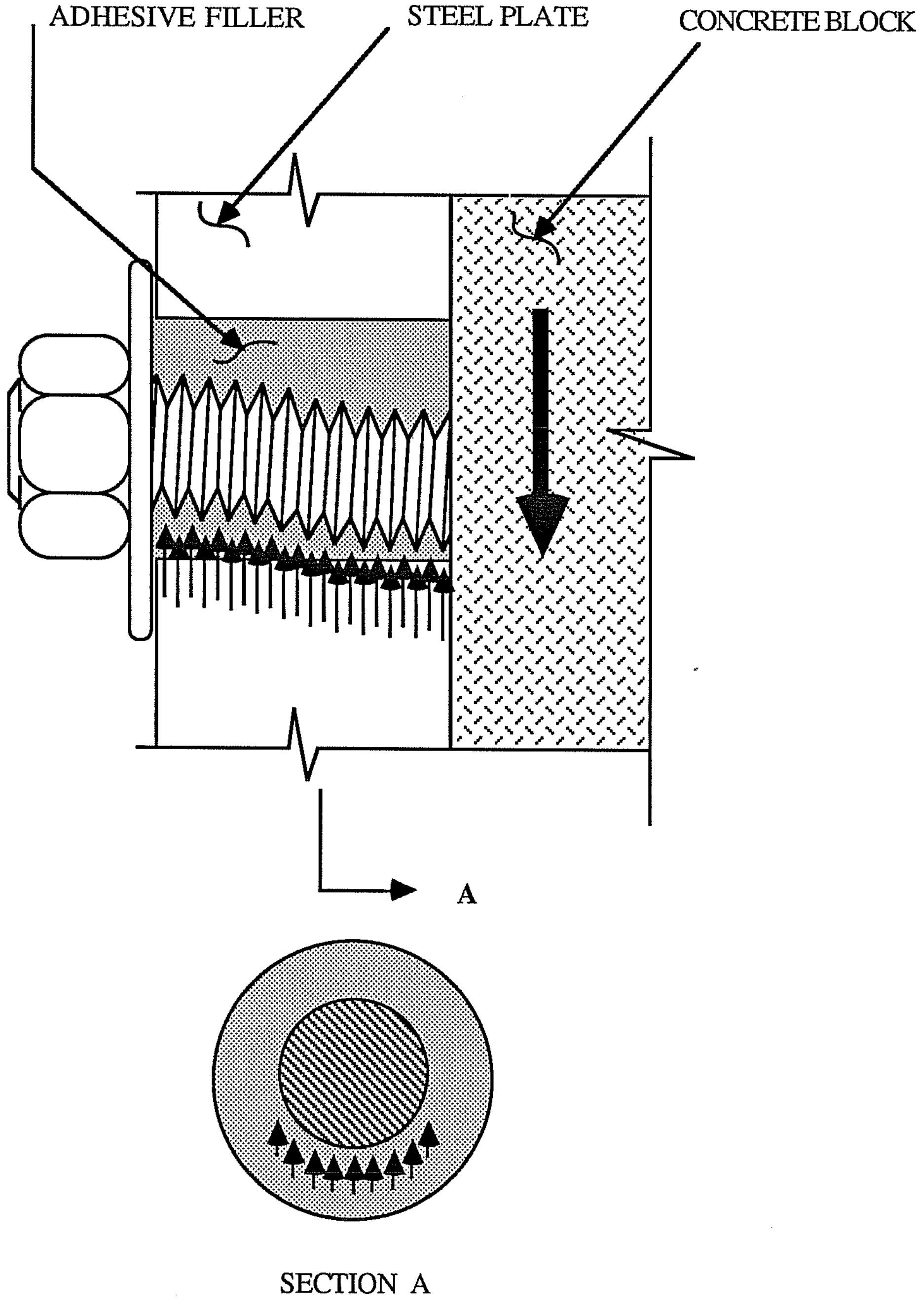


Fig. 4.22 Load distrubution on rod with adhesive filler (schematic)

adhesive as the deformation of the rod increased. At the shear plane, the rod was no longer loaded by the cutting edge of the steel plate, but rather by the adhesive filler. This allowed for additional bending of the rod. The rods ultimately failed in shear at the interface without ever touching the plates. Fig. 4.23 shows a the additional deformation of the rod failed in Test 5TE, beside the rod from Test 1B.

4.7.3 Tests involving a Completely Filled Void. Compared to tests involving a partial adhesive filler, these tests show a decreased deformation capacity at a similar ultimate load. This is due to the fact that when the filler extends completely to the concrete, bending deformation of the bolt is restricted. Compared to tests with no adhesive, these results indicate a stiffer and more ductile connection in every case. The tests with 5/16-in. hole clearance showed 1.6 times the ultimate deformation capacity of tests with standard connections, and an increase of 13 percent in ultimate load.

The yielding of the adhesive filler noted in partial filler tests was not present in these specimens. This is probably due to the additional confinement of the adhesive in these tests. As the Poisson's ratio of a confined material increases, stress resulting from compression approaches a spherical state. A confined material with the maximum Poisson's ratio of 0.5 will exhibit no deformation regardless of load [27]. While information was not available regarding the Poisson's ratio of the Sikadur Hi-Mod Gel, it clearly must be less than 0.5. In these conditions, confinement of the adhesive would still result in an increase in its

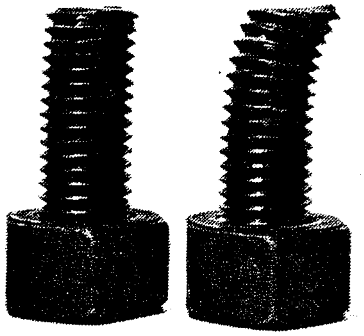


Fig. 4.23 Failed rods from Test 1B (left) and Test 5TE

compressive stiffness. It would also be expected to increase its compressive strength, hence the lack of yielding of the confined adhesive at the interface.

4.7.4 Effect of Rod Position in the Hole. Unsurprisingly, rod position in the hole had a pronounced effect on the slip behavior of connections without adhesive, as evidenced by comparison of results from Tests 1B and Test2 1T.

The results of tests involving adhesive fillers did not show consistent variation with rod position in the hole. When comparing results from Test 3CE and Test 3TE, the specimen with the rod positioned at the top of the hole shows greater stiffness than with the rod positioned at the center of the hole. The fitted hole created by the adhesive filler could account for this, since the rods were failed against the adhesive filler before slipping into bearing with the steel plate. In Fig. 4.24, the adhesive filler from Test 5TE-I is shown to be intact in the hole after removal of the failed rod. In Fig. 4.25, the adhesive filler on the unfailed end of the rod is shown after removal of the plate. The fitted hole effectively reduced the hole diameter preventing slip. Displacement occurred gradually by shear and bending deformations in the rod.

4.7.5 Effect of Hand Tightening the Nuts. The specimens with hand-tightened nuts showed increased ultimate load and deformation, but were not as stiff in the early loading stages as the other specimens with adhesives. The hand-tightened tests with a complete filler were still stiffer at design loads than were standard connections.

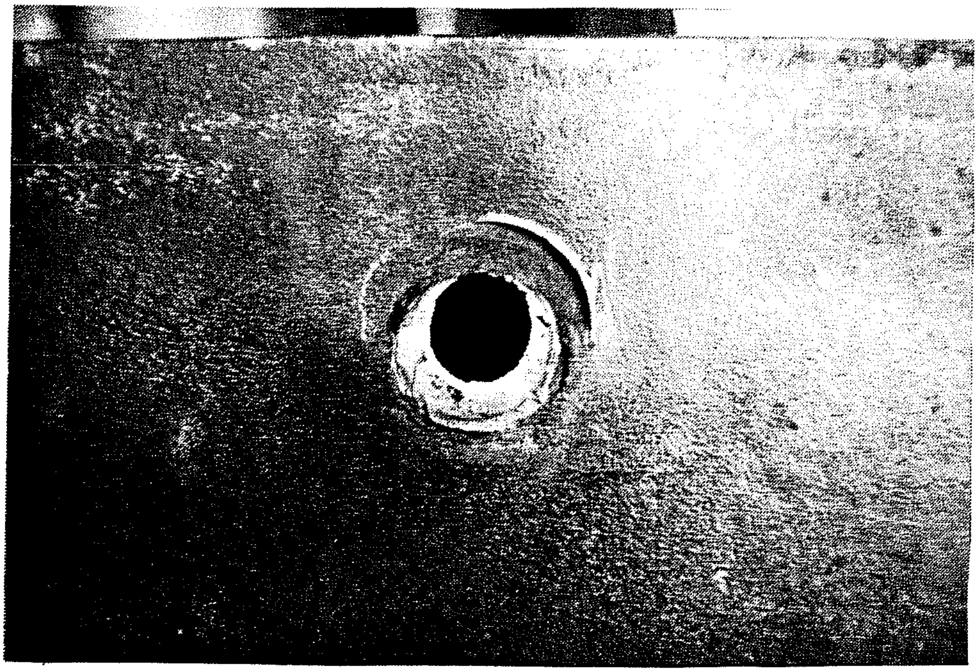


Fig. 4.24 Fitted hole created by adhesive filler; Test 5TE

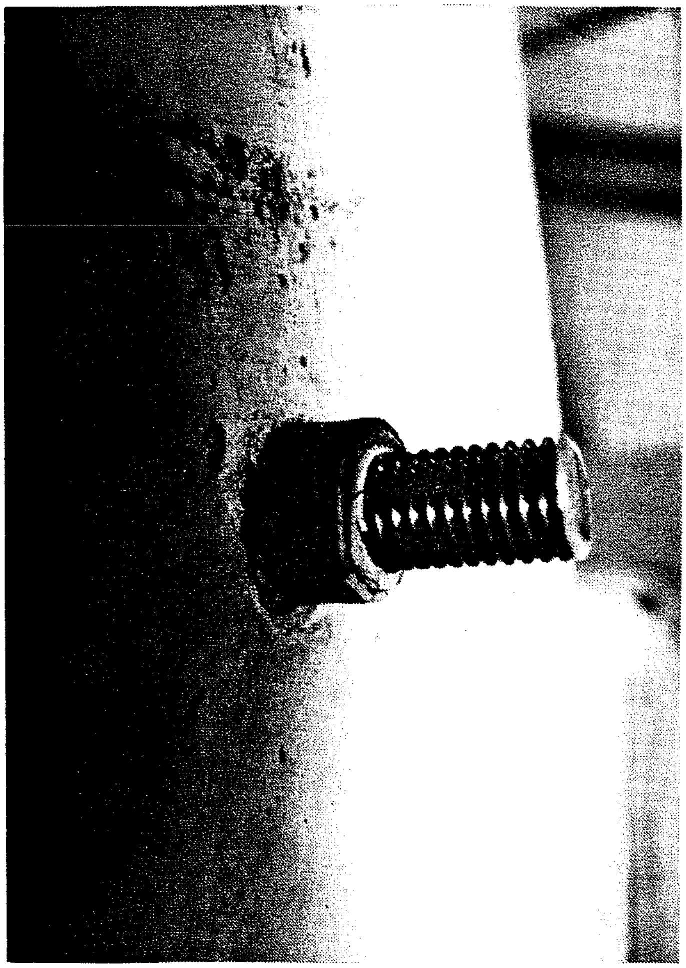


Fig. 4.25 Adhesive filler intact on the unfailed end of the rod

Eliminating the need for high bolt preload would prevent dishing problems associated with oversize holes, since the washer in these connections would serve primarily to confine the adhesive filler. Uniformity of preloads and clamping force would not be critical since loads are borne in bearing from the start. Since some of the adhesive would inadvertently (or purposely) be applied to the rod threads, the nut would become bonded to the rod and prevent loosening problems.

4.8 Applications to Repair and Strengthening

As noted in chapter 2, performance of steel retrofitting systems depends largely on the performance of the connections. In a seismic situation, loadings encountered by connections of this type are commonly impact and cyclic in nature. Adhesives perform exceptionally well under these types of loadings, and also provide a damping effect [24]. Since the area under the load-slip curve represents the energy absorption capacity of the connections, it can be seen that connections with adhesive fillers are able to absorb significantly more energy than those without. Connections with adhesive fillers do not experience the problems associated with major slip as in conventional connections, since displacement occurs in the form of gradual shear and bending deformation in the rod with no significant slip. Combined with the early stiffness of these connections, this makes oversize holes with adhesive fillers well suited for repair and strengthening.

Problems associated with structural adhesives usually involve debonding or susceptibility to creep. When adhesives are used as hole fillers, loads are not intended to be carried by adhesion between concrete and steel, therefore bonding effects need not be considered in calculating capacity, and no additional surface preparation would be required. Any adhesion effects would only increase connection stiffness in the early loading stages. Steel members used in a retrofitting scheme are not usually subjected to long-term static loads, so creep would not be a problem. Since the compressive strength and stiffness of the adhesives used as fillers has been enhanced by the effects of confinement discussed in sub-section 4.7.3, problems usually associated with adhesive creep would be significantly reduced.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of Investigation

Seventeen specimens were tested to investigate the load-deformation behavior of steel-to-concrete connections with oversize holes incorporating structural adhesive fillers. A typical specimen consisted of a one cubic foot concrete block through which a single 5/8-in. threaded rod was cast in place. Steel plates attached to the threaded rods on opposite faces of the block were loaded to fail the rods in shear.

Three hole clearances were tested: standard 1/16-in. clearance (11/16-in. diameter hole); 3/16-in. clearance (13/16-in. diameter hole); and 5/16-in. clearance (15/16-in. diameter hole). Rods were positioned at the top, center and bottom of the holes. The standard-clearance holes were first tested without any adhesive. In specimens with oversize holes, an epoxy gel adhesive was used to fill the void between the rod and hole. Two adhesive application procedures were tested: one resulted in a partially filled rod-hole void, while the other completely filled the void. The effect of hand tightening the nuts was also investigated.

5.2 Summary of Test Results

5.2.1 Tests with No Adhesive. Specimens with no adhesive and standard-size holes (1/16-in. clearance) experienced a major slip of more than 0.05 in. at about 20 kips.

5.2.2 Tests Involving a Partially Filled Void. When compared to specimens with no adhesive, specimens with oversize holes and a partially filled void showed a similar stiffness up to about 20 kips, but did not experience major sudden slip. Both ultimate strength and deformation capacity were significantly increased. The rod position at the outside face of the plate was maintained by the filler as the rod gradually deformed in bending and shear near the steel-concrete interface. When clearance was increased from 3/16 to 5/16 in., connection stiffness decreased, but ultimate strength and deformation capacity increased.

5.2.3 Tests Involving a Completely Filled Void. Specimens with the rod-hole void completely filled with adhesive were stiffer at all stages of loading than either specimens involving standard holes without adhesive, or oversize holes with partially filled voids. Ultimate strength and deformation capacity were greater than those of specimens with no adhesive, but less than the specimens with only partially filled voids. The effect of debonding at the steel-concrete interface could be seen in most of these tests, but was insignificant in all but one. It was later discovered that the bonded interface in this specimen was nearly three times as large as in the other specimens of the group. As in tests involving partially filled voids, the specimens with 5/16-in. clearance showed less stiffness than did those with 3/16-in. clearance, but also an increased ultimate load and deformation capacity.

5.2.4 Rod Position in the Hole. Position of the rod in the hole had a pronounced effect on the slip behavior of specimens with no adhesive, but had no effect on the behavior of specimens with oversize holes and adhesives.

5.2.5 Effect of Hand Tightening the Nuts. Specimens with adhesive and hand-tightened nuts showed a slight reduction in stiffness compared to otherwise identical specimens prepared with standard tightening procedures, but maintained the same increased ultimate load and deformation capacity. The specimen with hand-tightened nuts, 5/16-in. clearance, and a completely filled void was still stiffer at all stages of loading than the standard specimens with no adhesive .

5.3 Conclusions and Recommendations

When bolted shear connections between concrete and steel are made using oversize holes filled with structural adhesive, the connection is stiffer, stronger, and more ductile than a standard connection without adhesive filler. Since previous research has shown that the ultimate shear strength of bolted connections is not affected by hole clearance or bolt preload, it can be concluded that this improvement in performance is due to the use of adhesive. Results of this testing program have also led to the following specific conclusions and recommendations:

1) The use of adhesive fillers prevented the occurrence of major slip in the connections.
2) Specimens with completely filled rod-hole void were stiffer at all stages of loading than either specimens with partially filled voids or with no adhesive and standard-size holes. Specimens with a partially filled voids were approximately as stiff as specimens with standard hole clearance and no adhesive.
3) Connections with adhesive fillers showed an increase in ultimate strength compared to standard connections. In tests involving a 5/16-in. hole clearance:
    a. specimens with a partially filled void were 15 percent stronger
    b. specimens with a completely filled void were 13 percent stronger.
4) Connections with adhesive filler had more deformation capacity than standard connections. In tests involving a 5/16-in. hole clearance:
    a. specimens with a partially filled void exhibited 2.3 times the deformation at failure
    b. specimens with a completely filled void exhibited 1.6 times the deformation at failure.

5) When using adhesive fillers, as hole clearance increases, ultimate strength and deformation capacity increase, but connection stiffness decreases.

6) Uniformity of bolt preload is not critical when adhesive fillers are included. Adhesive applied to connector threads would prevent unintentional loosening of the nut.

7) Adhesive bonding of the concrete-steel interface is not necessary to ensure connection capacity. Therefore no special surface preparation of either material is necessary.

8) The increased deformation capacity of connections with adhesive fillers would result a more uniform load distribution among all connectors in a multi-fastener connection. The "unbuttoning effect" seen in longer joints could be reduced.

Although specimens with partially filled voids had higher ultimate strength and deformation capacity than did those with completely filled voids, the degree to which the void is filled would be difficult to determine or control. Combined with the additional stiffness associated with the complete fillers, these factors lead to the recommendation that the void be completely filled with adhesive. Generous application of the adhesive to the base of the rod prior to assembly with the connected part is sufficient to achieve this. Voids which are unintentionally left only partially filled would not significantly undermine the effectiveness of the connection.

The use of structural adhesive to fill oversize holes is particularly well suited for repair and strengthening applications for the following reasons:

1) As indicated by the areas under the load-deformation curves, the energy absorption capacity of connections with adhesive fillers significantly exceeds that of standard connections.
2) Adhesives are particularly resistant to cyclic and impact loads, and provide a damping effect in the presence of these loads.
3) Retrofitting systems are not commonly subjected to sustained static loads which might result in creep of the adhesives.
4) Steel retrofitting schemes are typically constructed on the exterior of a structure, and adhesives can help seal connections against environmental attack.
5) Holes drilled into existing concrete for grouting connecting rods are customarily rod diameter plus 1/4-in. A 5/16-in. oversize hole in the prefabricated steel section would allow the section to be used as a template for drilling anchor holes into the concrete. Using an adhesive such as epoxy, rods could be grouted while

simultaneously filling the void between the rod and rod hole in the steel section.

5.4 Further Research Needs.

Based on the findings of this investigation, continuing research is suggested in the following areas:

1. the effect of oversize holes with adhesive filler on long, multiple-bolt connections
2. the effects of creep in the adhesive fillers.

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