Report No. FRA-OR&D-75-91

SHOTCRETE
STRUCTURAL TESTING OF THIN LINERS

AUGUST,1975

S.C.R.T.D. LIBRARY

FINAL REPORT

RECEIVED
MAY 11 1976
S C R T D
OFFICE OF
MGR. RAPID TRANSIT DEPT.

Prepared for

Department of Transportation
FEDERAL RAILROAD ADMINISTRATION
Washington, D.C. 20590

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof.

Technical Report Documentation Page

1. Report No. FRA OR&D 75-91	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle
Shotcrete: Structural Testing of Thin Liners

5. Report Date
August 1975

6. Performing Organization Code

7. Author(s)
G. Fernandez-Delgado, J. Mahar, E. Cording

8. Performing Organization Report No.
UILU-ENG-75-2015

9. Performing Organization Name and Address
Department of Civil Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
DOT FR 30022

12. Sponsoring Agency Name and Address
Federal Railroad Administration
Department of Transportation
Washington, D. C. 20590

13. Type of Report and Period Covered
August 1974 - August 1975
Final Report

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report presents the results of engineering studies related to the development of new and improved tunnel support systems. Thin shotcrete layers were studied to assess their capacity and behavior as temporary tunnel supports.

The design, construction, and operation of a large-scale test facility simulating a planar tunnel roof with a punching block 2 ft x 2 ft (60.8 cm x 60.8 cm) are described. Preliminary tests were conducted using thin mortar layers to assess the performance of the test device and the principal variables controlling the capacity of the thin liner. Results obtained from these tests were used in the planning and evaluating of the shotcrete test program.

This report describes the development of the test-device, the equipment, and its arrangement and the shotcrete used in the model. The capacity of shotcrete layers for different thickness and strength of shotcrete and shotcrete-rock bond was determined.

Two principal modes of failure, diagonal tension in the shotcrete and progressive separation of the layer from the wall (adhesion), were obtained. When progressive separation occurred and boundaries were present in the model, the layer retained a residual capacity and a bending failure developed for large displacements of the punching block. Steel fiber reinforced shotcrete showed greater ductility but had approximately the same load-carrying capacity as conventional shotcrete.

17. Key Words Shotcrete; Tunnel Supports; Tunnel Liners; Thin Shotcrete Liners	18. Distribution Statement Document is available to the public through the National Technical Information Service, Springfield, VA 22151

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 219	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

01101

PREFACE

This study was performed by the Department of Civil Engineering of the University of Illinois at Urbana-Champaign, Urbana, Illinois from August 1974 to August 1975. The project was sponsored by the Federal Railroad Administration, Department of Transportation, through contract No. DOT FR 30022, under the technical direction of Mr. William N. Lucke. Supervision and coordination of the entire project was performed by Dr. Stanley Paul. Dr. Paul also contributed many ideas and participated in the lively discussions which stemmed from this work.

Mr. Harvey Parker contributed many original ideas and did much to assist in the performance and analysis of these tests.

Construction of the test facility, shooting of the specimens and experimental and field testing was assisted by R. Castelli, L. Lorig, and W. Wuellner.

Special assistance in organizing and developing the shotcrete operation and providing good quality shotcrete was given by Mr. Warren Alvarez and Mr. Jan Blanck.

Many valuable suggestions on the geotechnical significance of the study and on the validity of the tests were provided by Dr. R. B. Peck and Dr. D. U. Deere who serve as consultants to the project.

The authors also wish to thank Mr. Paul Diemert and Mr. E. R. Rogers of Contractors Warehouse Inc. for providing us with a Reed Shotcrete machine at a greatly reduced price.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

A device was constructed to study and test the structural behavior of thin shotcrete linings under load in a configuration that simulates loosening behavior in a jointed rock tunnel. In the first series of tests the thin shotcrete lining was replaced by a sand-cement mortar layer which was troweled onto the surface of the testing device. These tests were used to evaluate the performance of the testing apparatus and the modes of failure and performance of a material having properties similar to shotcrete. A second series of tests were conducted on shotcrete which was applied to the surface of the model in the same manner used for placing shotcrete underground. In these tests the major variables that influence the support capacity of a thin shotcrete lining in a plane configuration were investigated; the results of these tests, application of the shotcrete, and performance of the test device will be described herein.

The ultimate objective of this testing program is to develop a more rational procedure for the design of the thin shotcrete linings used as support in tunnels driven through jointed rock. One means of developing such procedures is to study the structural behavior of thin linings using physical models which represent actual conditions encountered in tunnels. The approach employed in this project was to perform a series of structural load tests in which parameters of shotcrete and pertinent geology were methodically varied while keeping the configuration of the tunnel surface constant. As it was impractical to perform enough tests to cover the full range of variables, procedures to predict the structural behavior of a lining subject to untested conditions were developed, based on the results obtained from the tests. These procedures, involving simple hand calculations as well as computer analyses using finite element methods, will make possible the construction of design charts to be used for estimating the maximum load that a given lining could support in a given set of field conditions.

Two types of variables were studied in the determination of the load-deformation characteristics of the thin shotcrete linings. Geological variables included (1) the nature of rock surface as it affects adhesion between the shotcrete and the rock and (2) the boundary conditions of the shotcrete layer. Other geological variables such as filling of joints and filling of shotcrete between their surfaces were not studied. The second type of variable involved the strength and deformability of the shotcrete; they were varied by changing the thickness, time of curing, and type of reinforcement. The proportions of the materials used in the shotcrete mix were kept constant for all the tests.

Typical geometric configuration that has been observed in tunnels driven through flat-lying sedimentary rocks, rocks containing horizontal stress relief joints and flat-roofed openings in jointed rock are shown schematically in Fig. 1.1. Sketches of actual tunnels having a similar geometry are shown in Fig. 1.2. In actual tunnels, there are a very large number of possible rock block geometries as well as variations in the relative sizes of the blocks. This last variable however could be standardized using a suitable scaling factor.

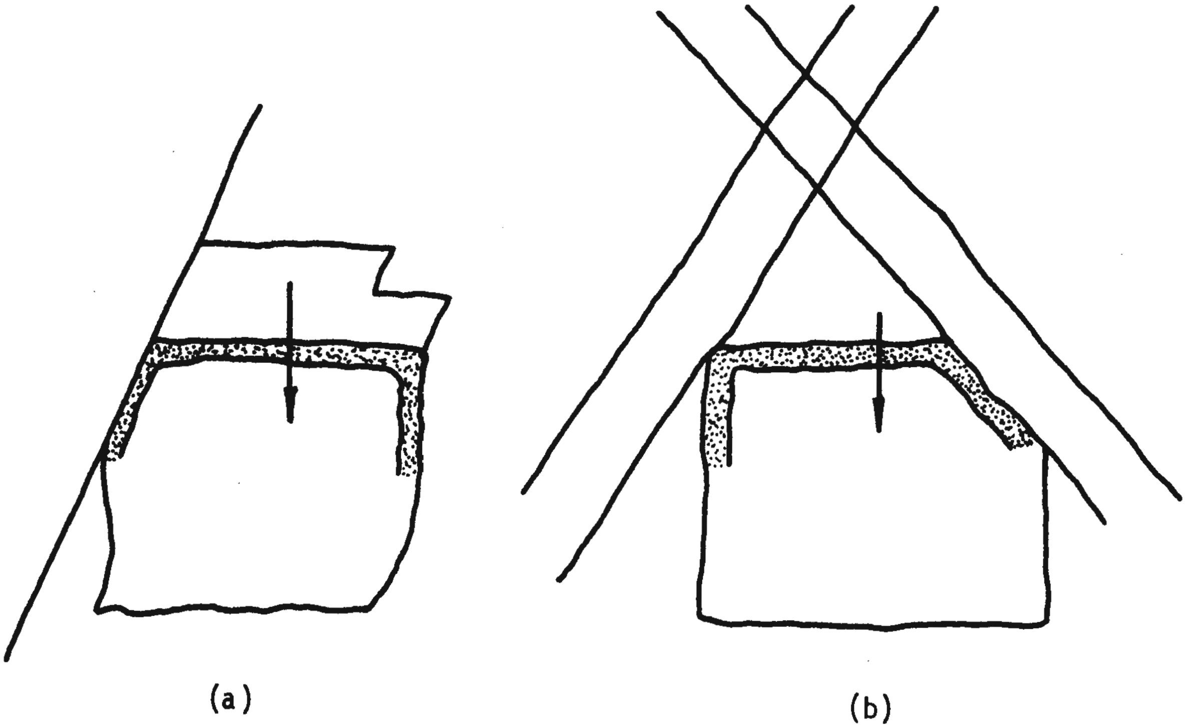


FIGURE 1.1 TYPICAL GEOMETRIC CONFIGURATIONS AND LOADING CONDITIONS IN TUNNELS INTERSECTED BY FLAT-LYING DISCONTINUITIES OR IN FLAT-ROOFED OPENINGS IN JOINTED ROCK

FIGURE 1.2 FIELD EXAMPLES OF TUNNELING IN "BLOCKY" RCCK MASSES

(Craig, C. L. and Brockman, L. R., 1971)

A testing device was designed to simulate the flat-roof condition yet have the versatility to model other geometric configurations (Fig. 1.3). The model was set up so that a continuous record of the lining loads and deformations was obtained throughout the tests. The force on the shotcrete lining was applied using hydraulic rams so that loads could be controlled and measured accurately. The rams selected for use on this project are controlled electronically to provide either load or deformation rate control. When combined with incremental loading, this system allows observation of lining behavior at various load levels.

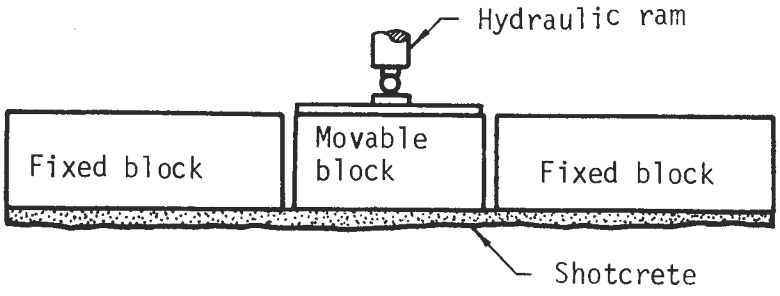


FIGURE 1.3 PLANAR GEOMETRY OF TEST DEVICE FOR STRUCTURAL TESTS ON SHOTCRETE LAYERS

A system of reinforced concrete blocks was devised to simulate the basic tunnel geometry (Fig. 1.3). A movable block was attached to a hydraulic ram to represent a rock block as it applies load to a thin shotcrete lining. Adjacent fixed blocks simulated the stationary rock mass within the tunnel. The fixed blocks were attached to the laboratory test floor with prestressed rods. The model was set up so that the movable block was pushed horizontally rather than falling downward as would take place in a tunnel. This adjustment avoided some problems associated with the dead weight of the block, allowed the test device to be secured to the laboratory floor more easily, and provided a more convenient test surface for placing the shotcrete. In addition, it reduced danger from spalling of shotcrete during testing while measurements were being made. In the original design of the loading system only one movable block was provided, but it became apparent that preparation for placing the shotcrete for each test would be so extensive that it would be desirable to have at least two structural tests for each shooting. Therefore, a second movable block was added below the first. This arrangement also provided a means for checking possible variations in shotcrete properties and behavior associated with shotcrete application by performing two identical tests on shotcrete applied at the same time.

In order to study the effects of surface adhesion, and to provide various surfaces that are typical of the tunnel environment, provisions were made for changing the surface of the fixed and movable blocks. This was accomplished by bolting 3 in. (7.62 cm) thick mesh-reinforced concrete slabs to the fixed and movable blocks. The surface roughness of these slabs was varied to simulate different joint surfaces. The shotcrete was applied directly to these slabs.

In the next chapter the test device is described in greater detail. Chapter 3 outlines the test program and the results obtained from the preliminary mortar tests. The characteristics and results obtained from the structural tests on thin shotcrete linings in a planar configuration are described in Chapter 4. Finally, in Chapter 5, the conclusions and recommendations drawn from the testing program are presented.

Geometric configurations other than a planar surface will be studied and tested in future work (Fig. 1.4). These configurations will be obtained by replacing the existing blocks or adding new sections with different shapes. The movable blocks, load arrangement and test procedures will remain essentially the same. These tests will be used to develop design criteria for thin shotcrete linings and a large range of geologic conditions.

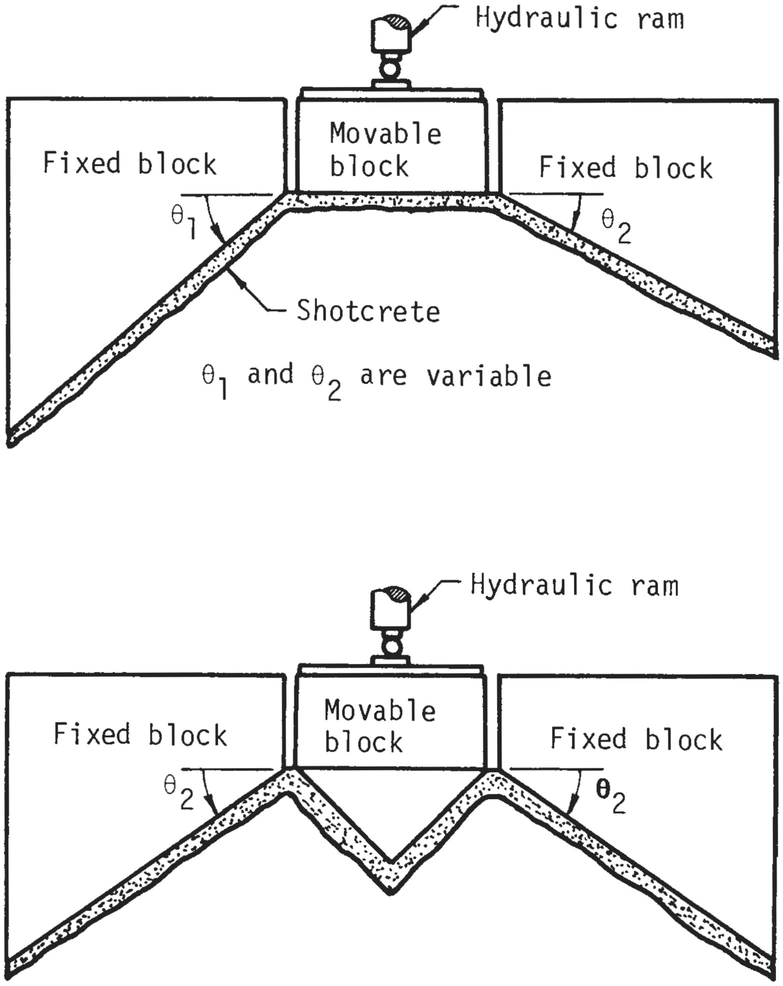


FIGURE 1.4 FUTURE SHOTCRETE TESTS INVOLVING OTHER ROCK GEOMETRIES

CHAPTER 2

DESCRIPTION OF TEST DEVICE

A testing scheme, versatile enough to be adapted to the variation of the chosen parameters, was designed. This scheme is shown in the photograph of Fig. 2.1 and consists of (1) the reaction abutment on the left, which remains unaltered from test to test; (2) the test wall on the right with fixed and movable portions, the front surfaces of which are covered with the thin shotcrete layer; and (3) the two hydraulic rams, which thrust against the reaction abutment to apply load to the movable portion of the wall. The test device and instrumentation are further described in the following sections.

2.1 REACTION ABUTMENT

The reaction abutment shown in Fig. 2.2 acted as a reaction to the force applied through the rams to the thin shotcrete layers. It was attached to the floor of the test area by three steel bolts that were prestressed to 50 kips (220 kilonewtons). The abutment was similar to those employed as reactions for the forces applied during the testing of cylindrical liners previously performed in the University of Illinois laboratory (Parker, et al., 1973). Successful performance of the abutment during the previous tests, which required loads equal or greater than those applied in this test program indicated that the abutment would perform adequately.

FIGURE 2.1 OVERALL VIEW OF THE TESTING DEVICE

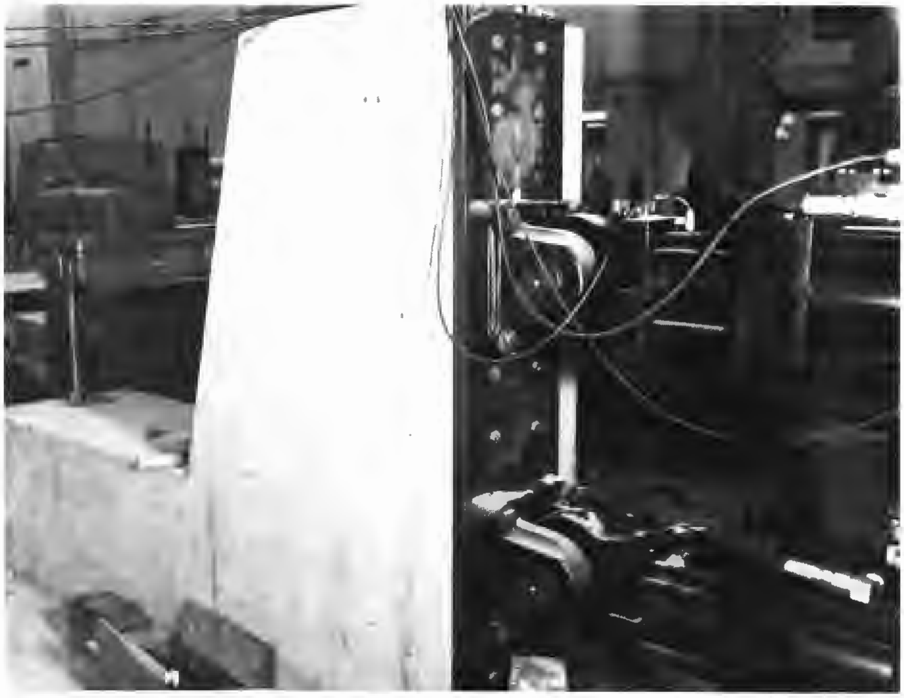


FIGURE 2.2 DETAIL OF RAMS-ABUTMENT CONNECTION

2.2 HYDRAULIC RAMS

Two MTS hydraulic rams, shown in Fig. 2.3, each 85 in. (216 cm) long with a 5-in. (12.7-cm) stroke and able to apply a maximum load of 100 kips (440 kilonewtons) in either tension or compression were used in these tests. Each loading unit consisted of the ram and its valve system, a load cell, and a ball and socket seating arrangement at the connection between the movable block and the loading unit. Details of the basic structure of the ram and its characteristics are given in Appendix A. The rams were located 21 in. (53.3 cm) and 48 in. (122 cm) above the floor, and were leveled and aligned so that the axial thrust would be perpendicular to the wall. They were bolted to a steel plate embedded in the concrete abutment. A steel frame providing intermediate support for the rams was located 36 in. (91.4 cm) from the reaction abutment as shown in Fig. 2.3. These supports were used to set and maintain the vertical and horizontal alignment of the loading unit. The load in the rams was transmitted to the movable blocks through a 1 in. (2.54 cm) spherical steel seat at the end of the rams and the movable blocks (Fig. 2.4). The sphere was used to transfer the loads so that moments would not be induced in the movable blocks.

The rams were controlled electronically to provide a predetermined rate of loading or rate of displacement of the movable block. This control allowed the simulation of different types of loading on the shotcrete specimen. It was also possible to stop the displacement or load application at any desired load level and maintain that level for any time span. Thus, the test can be performed continuously, or in increments,

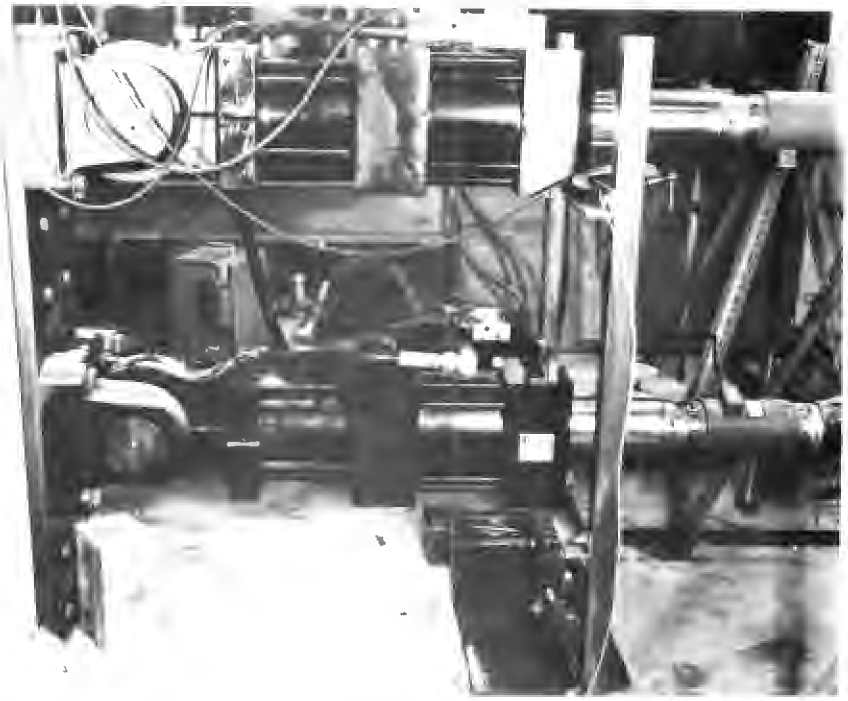


FIGURE 2.3 STEEL FRAME ASSURING VERTICAL AND HORIZONTAL ALIGNMENT OF THE RAMS

FIGURE 2.4 DETAIL VIEW OF RAM-MOVABLE BLOCK CONNECTION

allowing the behavior of the shotcrete to be investigated at any stage during the test. The rate of loading, or displacement, was controlled by electronic regulation of the hydraulic flow into the rams. The load-deformation output of the rams was monitored with an x-y recorder.

2.3 FIXED WALL AND MOVABLE BLOCKS

The wall on which the shotcrete layer was applied is 10 ft (305 cm) long and 6 ft 6 in. (198 cm) high. Two 2 x 2 ft (61.0 x 61.0 cm) movable blocks, one above the other, were located in the middle of the wall. The back of this wall is shown in the photograph of Fig. 2.1. A front view of the wall illustrating the relative position of the concrete blocks comprising the test model is shown in Fig. 2.5. A photograph of this same frontal view is presented in Fig. 2.6. The fixed blocks were held to the test floor with four vertical bolts extending through the entire wall. These bolts were prestressed to 25 kips (110 kilonewtons) thereby producing a rigid structure on which the shotcrete was placed. During some early tests the blocks of concrete were not grouted to the floor. Early tests were also conducted using only one movable block. To increase the stiffness of the model and the number of tests that could be conducted from a single shotcrete application, an extra movable block was added and the concrete blocks were grouted to the floor. In order to provide the desired bonding conditions without replacing the fixed or movable blocks, precast facing slabs were placed on the front or the wall. These slabs were 3 in. (7.62 cm) thick and were bolted and grouted to both the fixed and movable blocks.

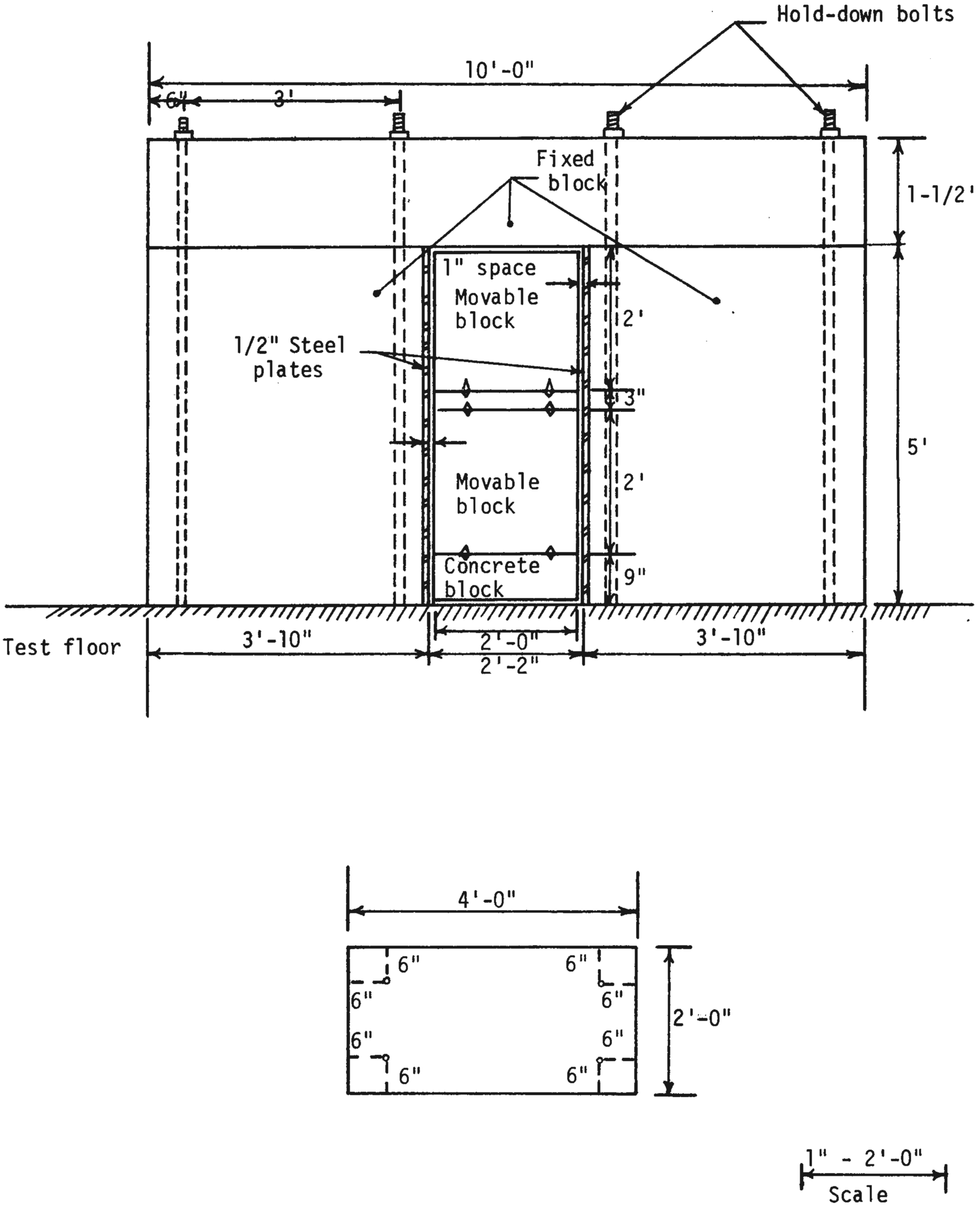


FIGURE 2.5 DIMENSIONS OF SURFACE SLAB AND HOLE PATTERNS FOR ATTACHING THEM

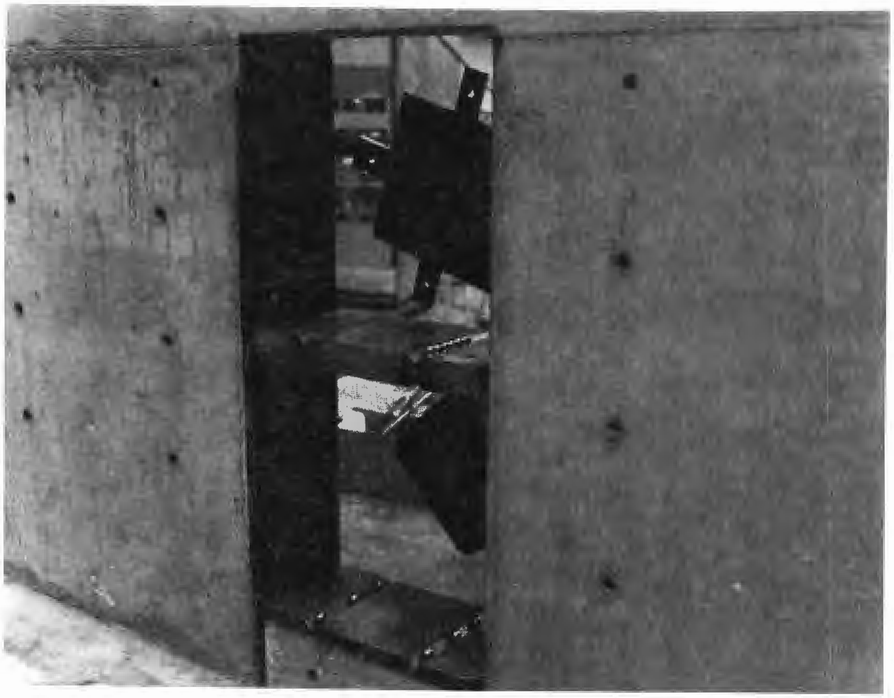


FIGURE 2.6 FRONT FACE OF THE FIXED WALL

The fixed walls were used in this model to simulate a stable rock mass in a tunnel roof or wall. They were constructed of reinforced concrete and were provided with horizontal holes for attachment of the surface slabs. Concrete with a nominal 5000 psi (350 kg/cm^2) compressive strength and obtained from a local ready mix plant was used. The forms and reinforcement for the fixed blocks are shown in Fig. 2.7. A similar form was used for the long concrete block placed across the top of the model (Fig. 2.5). The reinforcing bar cage shown in Fig. 2.7 consisted of No. 3 and No. 6 deformed bars; the larger diameter vertical bars being placed 1 in. (2.54 cm)

FIGURE 2.7 FORMS AND REINFORCEMENT FOR THE FIXED SIDE BLOCKS

from the front face of the blocks where the compression stresses due to forward bending of the walls would be high. The prestressing bolts used to attach the fixed blocks and transverse beam to the test floor were placed through two, 2.5 in. (6.35 cm) diameter pipes in each block. Eight steel pipes, 1 in. (2.54 cm) O.D., were placed 1 ft (30.5 cm) apart in two rows for attachment of the surface slabs. A steel plate 5 ft (150 cm) by 1 ft (30.5 cm) by 1/2 in. (1.27 cm) thick was cast into the fixed walls adjacent to the movable blocks. A front view of this plate is show in Fig. 2.5.

The lower movable block and its connection with the rams was supported on a concrete base block (Fig. 2.5). The base support block was 9 in. (22.9 cm) tall, with dimensions of 2 ft (61.0 cm) by 1 ft (30.5 cm) and was lightly reinforced. This block was grouted to the floor and its surfaceleveled. Both movable concrete blocks rested on a ball and groove arrangement like those shown in Fig. 2.6. This device served to guide the movable blocks and minimize the friction between them and their support. The upper one rested on a steel support bolted to the plates located on sides of the fixed walls (Fig. 2.5). A ball and groove guide was also employed at the top of each movable block. This served to prevent the blocks from tilting forward or backward. The movable blocks 2 ft x 2 ft x 1 ft (61.0 cm x 61.0 cm x 30.5 cm) were cast in the form shown in Fig. 2.8. In this figure the reinforcing cage, which consisted of No. 6 deformed bars, can also be seen.

The surface slabs were attached to each block by four, 1/4 in. (0.635 cm) diameter steel rods which were threaded into nuts cast in the slabs and were bolted on the back side of the blocks. The forms for the surface slabs were made of steel so that deflections from the wet concrete would be minimized and maximum reusability would be assured. One of these forms including the mesh reinforcement and threaded inserts for the attaching bars is shown in Fig. 2.9.

2.4 INSTRUMENTATION

Two basic types of deformation measurements were made in the mortar tests; the displacement of the mortar layer with respect to the

FIGURE 2.8 FORM AND REINFORCEMENT FOR THE MOVABLE BLOCKS

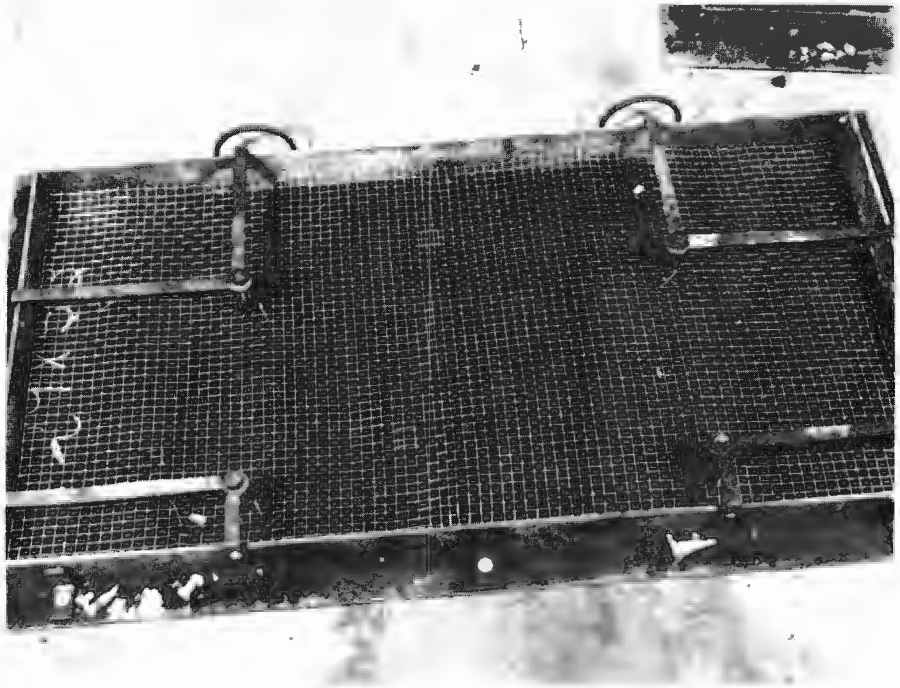


FIGURE 2.9 FORMS, MESH REINFORCEMENT AND THREADED INSERTS FOR SURFACE SLABS

fixed walls and the floor, and the strains occurring in the mortar layer. The last set of measurements was discontinued in the shotcrete tests.

Displacement measurements were made with dial gages having sensitivities of 0.001 and 0.0001 in. (2.54×10^{-3} cm) and (2.54×10^{-4} cm). These gages were attached to a steel frame which was bolted to the floor (Fig. 2.10). These dial gages, located 10 in. (25.4 cm) apart on a horizontal line at the midheight of the mortar or shotcrete layer, were used to measure the relative displacement of the layer with respect to the floor. Because of irregularities in the layer surface, and to avoid damage of the dial gages after failure of the shotcrete, the gages were not in direct contact with the layer; the contact was made through steel plates previously grouted to the surface, as shown in Fig. 2.11. Three dial gages were mounted on the back of the movable block (Fig. 2.4) such that their plunger could bear directly against the back of the fixed block. These gages were used to monitor the relative horizontal displacement between the movable block and the fixed walls. The triangular arrangement of these gages also provided a means for detecting any tilting of the movable block caused by eccentric loading or non-uniform resistance of the mortar layer. Another set of dial gages recorded the displacements of the back of the fixed walls with respect to the laboratory floor. These gages, as shown in Fig. 2.11, were located at different distances from the movable blocks and at different elevations relative to the floor in order to detect any rotation of the walls that might occur during the loading process.

During the initial tests a Whittemore gage was used to measure the relative displacement of points located 10 in. (25.4 cm) apart on a

FIGURE 2.10 FRONTAL DIAL GAGES AND STEEL FRAME SUPPORTING THEM

FIGURE 2.11 MORTAR SURFACE-DIAL GAGE BRACKET CONNECTION

horizontal line at midheight on the outer surface of the mortar layers. Most of these Whittemore points were located on the same steel bearing plates that were used as surface reference points for the dial gages. The loading was performed incrementally, with dial gage and Whittemore readings taken at the end of each increment. After each load increment, up to the peak, the load was maintained constant while the readings were taken. After the resistance of the layer started to decrease, the testing procedure was changed. For some tests the constant rate of loading was continued until failure of the layer, without stopping for additional measurements. For most tests, however, the loading was changed to a constant strain rate, and controlled such that readings could be taken at predetermined deformation increments to determine the full load-deflection curve for the mortar or shotcrete layer.

CHAPTER 3

PRELIMINARY TESTING PROGRAM

A preliminary investigation using sand-cement mortar as a substitute for shotcrete was carried out to determine the performance of the test device, to assess the main variables influencing the mode of failure of thin linings, and finally, to check the repeatability of test results.

3.1 PREPARATION OF THE SPECIMENS

In all tests, the mortar of the thin layer consisted of the same mix design. Water, sand and cement were mixed in 260 lb (118 kgms) batches in a rotatory, pan-type mixer. Table 3.1 shows the amounts and relative percentages of the three mix components. The water/cement ratio of the mix was 0.54 and 0.52. In all of the tests approximately 1 in. (2.54 cm) of mortar was placed on the fixed and movable blocks. A thin layer about

TABLE 3.1

MORTAR COMPONENTS IN 260 LB (118 kgm) BATCH

Mix components	Weight lb (kgms)	Percentage of the total mix
Cement	65 (29.5)	25.0
Sand	160 (72.6)	61.5
Water, tests 1-4	35 (15.9)	13.5
tests 5-18	34 (15.5)	

1/2 in. (1.25 cm) was applied, first, with a trowel, and the remainder placed approximately 1/2 hr later using the same procedure. This two-stage application was used to avoid sloughing of the mortar layer which occurred when it was placed in one application. The mortar layer was cured by covering it with wetted burlap which hung down the front of the wall. The burlap was continuously wetted during the curing period until the specimen was ready to be tested. This procedure was intended to simulate the high humidity typically found in underground openings. Control specimens were cast to determine the approximate strength characteristics of the layer material and were cured in a fog room. In test Nos. 1 to 4, cracks were observed on the exposed surface of the mortar layer at the end of the curing period (Fig. 3.1). These cracks were believed to be the result of sloughing of the second layer of mortar rather than by shrinkage of the material. Pre-test cracks were not present in the remaining tests where the water content of the mortar was slightly reduced, and greater pressure was used in applying the mortar to the wall. Figure 3.2 shows the front faces of test Nos. 5 and 6 which were typical of the mortar layers having a reduced water/cement ratio. The apparent irregularities on the layer surface were traces left by the trowel during the placement of the mortar.

3.2 GEOMETRY AND BOUNDARY CONDITIONS OF TESTS

In all of the tests, the movable block slab surface was in the same vertical plane as the front face slabs of the fixed blocks before the mortar was placed. Therefore the resistance of the layer to the force

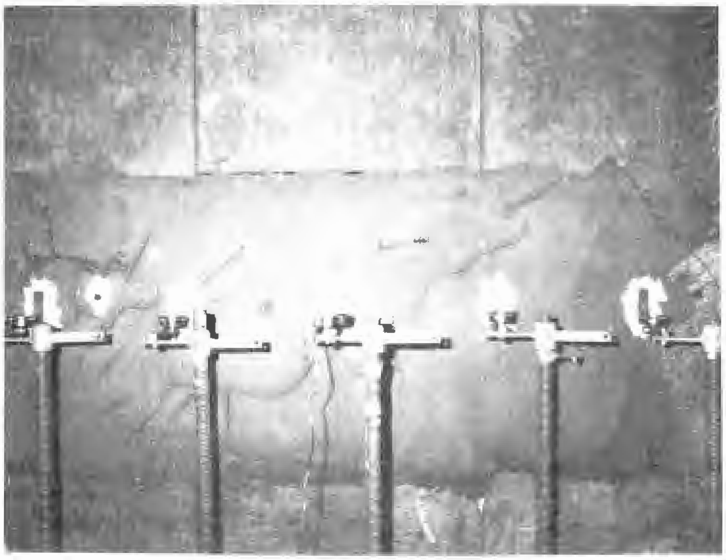


FIGURE 3.1 PRE-TEST SURFACE CRACKS IN TEST NO. 1

FIGURE 3.2 APPEARANCE OF SPECIMEN NOS. 5 and 6
IMMEDIATELY BEFORE TESTING

applied through the movable block could be developed only by the transmission of shear and/or adhesive stresses through the mortar layer. The top and bottom-edges of the mortar layer were aligned with the top and bottom edges of the movable block. This ensured a one-directional transmission of stresses and avoided stress concentrations around sharp geometrical transitions.

For the first 10 tests, no restrictions were imposed on the lateral boundaries of the layer, and the boundary was provided by the adhesion strength along the contact of the mortar layer and the concrete surface slabs of the fixed blocks. For test Nos. 11 to 18, steel plates were used to press the mortar layer against the fixed walls at specified distances from the movable block. Lateral boundary conditions were semi-fixed by the steel plates in these tests. These plates can be seen in Figs. 3.3 and 3.4.

For all tests, except the first two, wetted cotton was used to fill the 1/2 in. (1.27 cm) gap between the movable block surface slab and the surrounding surfaces. Filling of this separation presented possible intrusion of mortar which would result in frictional resistance between the movable block and fixed wall.

3.3 MAIN VARIABLES AFFECTING THE STRUCTURAL BEHAVIOR OF THE MORTAR LAYER

Once the geometrical condition of the tests was chosen, a set of layer and "rock-mass" characteristics, which would influence the structural behavior of the layer, were selected and are summarized in Table 3.2. For a series of tests, different values were given to the particular

FIGURE 3.3 USE OF 6 X 18 IN. (152 X 457 MM) PLATES IN TEST NOS. 13 AND 14 TO SIMULATE ROCK BOLTING

FIGURE 3.4 USE OF 16 X 24 IN. (406 X 609 MM) PLATES IN TEST NOS. 17 AND 18 TO SIMULATE ROCK BOLTING

TABLE 3.2

DIMENSIONS OF MORTAR LAYER

Test no.	Thickness, in.	(cm)	L*,in.	(cm)	Remarks
1	1.1	(2.79)	24	(60.96)	
2	.9	(2.29)	48	(121.92)	
3	1.0	(2.54)	48	(121.92)	
4	.7	(1.78)	7	(17.78)	
5	.7	(1.78)	48	(121.92)	
6	--	--	48	(121.92)	
7	1.1	(2.79)	14	(35.56)	
8	.9	(2.29)	18	(45.72)	
9	.7	(1.78)	48	(121.92)	
10	.8	(2.03)	48	(121.92)	
11	.6	(1.52)	6	(15.24)	Steel plates 6" x 18"
12	.6	1.52	6	(15.24)	Steel plates 6" x 18"
13	.7	(1.78)	6	(15.24)	Steel plates 6" x 18" (used tape on slabs)
14	.6	(1.52	6	(15.24)	Steel plates 6" x 18" (used tape on slabs)
15	1.1	(2.79)	6	(15.24)	Steel plates 6" x 18" (Mesh reinforcement)
16	1.0	(2.54)	6	(15.24)	Steel plates 6" x 18" (Mesh reinforcement)
17	.7	(1.79)	2	(5.04)	Steel plates 16" x 24"
18	.8	(2.03)	2	(5.04)	Steel plates 16" x 24"

* Distance between the edges of the movable block and the lateral boundaries of the layer.

characteristic under study while the values of the other parameters were kept constant. Differences in the mode of failure and maximum resistance loads obtained in these tests were used to assess the influence of that particular property on the overall behavior of the structure.

After a theoretical analysis complemented with a study of the available literature on shotcrete behavior (Cecil, 1972; Peck, et al., 1970; Cording, 1974; Cording and Mahar, 1974; Jones and Mahar, 1974; and Holmgren, 1975) was made, a hypothesis was developed to explain the possible failure mechanisms and the main variables as shown in Fig. 3.5. The maximum load resisted by the mortar layer depends on its mode of failure. There were two basic modes of failure predicted for this test series: (1) diagonal tension failure in the mortar layer; or (2) separation of the mortar layer from the surface slab. The actual mode of failure depends on the relative value of the forces F_0 and F_1, where F_0 is the maximum adhesive force holding the mortar layer against the fixed walls that could be developed along the contact area, and F_1 is the force required to induce a diagonal tension failure in the mortar layer. If F_0 is greater than F_1 the first mode of failure, diagonal tension, will occur or, conversely, if F_1 is greater than F_0, the second mode of failure, separation of the mortar layer, will occur. As seen in the diagram the value of F_0 depends on the size of the contact area along which adhesive stresses act together with the maximum value of adhesive strength between the layer and the slab, while the values of F_1 depend on the thickness of the layer together with the strength of the mortar. It was decided, therefore, to study the influence of these variables on the values of F_0 and F_1. The variables

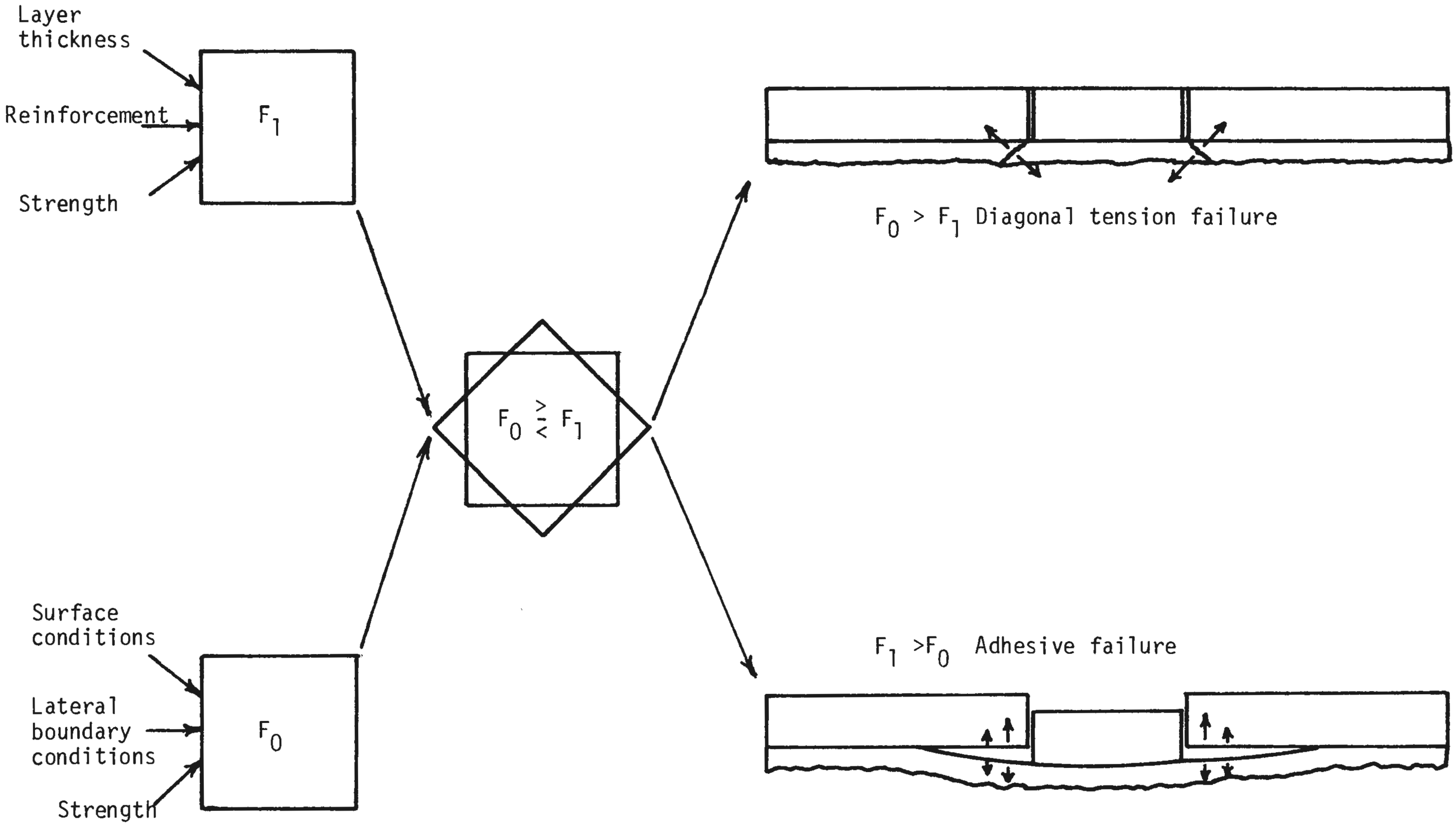


FIGURE 3.5 SCHEMATIC DIAGRAM SHOWING TWO TYPES OF FAILURE MODES

chosen in this study consisted of: (1) lateral boundary conditions of the layer; (2) the contact surface characteristics; (3) the mortar strength; (4) the type of reinforcement used in the layer; and (5) rate of load application to the mortar layer.

The mortar layer thickness was intended to be constant throughout the test series but could not be closely controlled due to the application method. For each test its value was measured and recorded along the two critical sections of the layer; between the fixed and movable blocks.

It was believed that the structural behavior of shotcrete layers is similarly influenced by the same variables aforementioned, so that the results of these mortar layer tests were useful in planning the testing program for the shotcrete layers. The nature of these variables and the different values assigned to them during the eighteen tests performed in this preliminary study are described in the following sections.

3.3.1 LATERAL BOUNDARY CONDITIONS OF THE LAYER

In the cases where no steel plates were used, the lateral boundary of the mortar layers was determined by its maximum distance away from the movable block. For the other cases, when a good contact between the steel plates and the mortar was obtained, the location of these plates determined the lateral boundaries of the layer. Column 3 in Table 3.2 shows the distance from the contact between the movable and fixed blocks at which the lateral boundaries of the layer were located. Column 5 of the same table indicates whether or not steel plates were used to establish these boundaries. As shown in the aforementioned table a considerable range of variation, 2 in.

(5.08 cm) to 48 in. (122 cm) was selected for the locations of the lateral boundaries of the layers. The location of these boundaries was expected to influence the structural behavior of the layers in as much as this location controlled the size of the area over which the adhesive strength between the mortar and the surface slab was developed. Even if the adhesive strength developed within just a few inches of the movable-fixed block contact, longer extensions of the mortar layer would have provided a larger "buffering" zone should shrinkage in the mortar layer have had adverse effects on the development of the adhesive strength. Shrinkage in the mortar (layer) tended to create shear-strains along its contact with the surface slab reducing and sometimes destroying any adhesive strength which could have developed. Longer extensions of the layer were also expected to provide better restraints to rotations induced in the layer after separation from the surface slabs was started.

3.3.2 CONTACT SURFACE CHARACTERISTICS

Slab surface conditions along the contact area determined to a major degree the maximum value of the adhesive strength that developed to hold the mortar layer to the fixed wall when load was transmitted to the layer through the movable block. As previously mentioned, the maximum value of the adhesive strength that could be developed along the contact area together with the effective size of this area determined the maximum value of the force F_0 and , therefore, the structural behavior of the layer.

In order to maintain a uniform surface condition for each test, and particularly for successive tests in which adhesion was not a variable, a standard surface treatment was established. After brushing the slab with an electrically powered wire brush, the roughness of the slab surface was measured at representative locations with a special device designed for this purpose. The device and results of the measurements are described in Appendix B. Mortar was placed after the roughness was measured.

The surface slabs were form-finished on one side and hand troweled on the other. For most of the tests, the mortar was placed against the finished side of the slab after it had been roughened. Variations of the maximum adhesive strength were provided by (1) the use of the rougher, hand troweled side of the surface slab as the contact surface in the first two tests or (2) by covering the inner edges of the fixed block with a filament tape in a strip 6 in. (15.2 cm) wide (see test Nos. 13 and 14).

3.3.3 MORTAR STRENGTH

Variations in the strength characteristics were obtained by allowing the mortar layer to cure under the same conditions for different lengths of time. Material properties of the mortar in each test are summarized in Table 3.3.

The strength of each mortar layer was estimated by performing a series of standard compressive and flexural strength tests on cast samples of mortar obtained from each mix and cured under similar conditions as the mortar on the wall. These strength tests were conducted at the same time as testing of the mortar layer in the model and were used to check differences in strengths between mortar layers cured for approximately the same length of time (strength control). Four cylinders 4 in. x 8 in. (10.2 cm x

TABLE 3.3

MATERIAL PROPERTIES OF TEST SPECIMENS

Test no.	Compressive strength, f'_c, psi	(KPa)	Flexural strength, f_r, psi	(KPa)	Splitting tensile strength, f_{sp}, psi	(KPa)	Young's modulus psix10^6	(KPa)	hours
1	6015	(41,400)	---	---	---	---	2.5	(1.72×10^7)	168
2	5540	(38,200)	640	(4,410)	---	---	---	---	168
3	1965	(13,550)	387	(2,670)	---	---	---	---	48
4	5925	(40,800)	510	(3,510)	450	(3,100)	---	---	168
5	5186	(35,800)	660	(4,550)	505	(3,480)	3.0	(1.72×10^7)	168
6	5186	(35,800)	660	(4,550)	505	(3,480)	3.0	(2.07×10^7)	168
7	4775	(32,900)	430	(2,960)	360	(2,480)	2.8	(1.93×10^7)	168
8	4775	(32,900)	430	(2,960)	360	(2,480)	2.8	(1.93×10^7)	168
9	385	(2,660)	---	---	60	(413)	0.3	(2.07×10^6)	7
10	385	(2,650)	---	---	60	(413)	0.3	(2.07×10^6)	7
11	5090	(35,100)	510	(3,520)	410	(2,830)	2.2	(1.52×10^7)	168
12	5090	(35,100)	510	(3,520)	410	(2,830)	2.2	(1.52×10^7)	168
13	5390	(37,200)	585	(4,030)	440	(3,040)	3.7	(2.55×10^7)	168
14	5390	(37,200)	585	(4,030)	440	(3,040)	3.7	(2.55×10^7)	168
15	5630	(38,800)	---	---	415	(2,860)	3.2	(2.21×10^7)	168
16	5630	(38,800)	---	---	415	(2,860)	3.2	(2.21×10^7)	168
17	5090	(35,100)	480	---	---	--	2.2	(1.52×10^7)	168
18	5090	(35,100)	480	---	---	--	2.2	(1.52×10^7)	168

20.3 cm), and two rectangular beams 6 in. x 6 in. x 22 in. (15.2 cm x 15.2 cm x 55.9 cm) were tested from each batch. Standard unconfined compression tests were performed on two or three of the cylinders and Brazil splitting tensile tests were conducted on the remaining cylinders. In the compression tests load deformations curves were obtained, and were used to calculate Young's Modulus; see column 5 of Table 3.3.

3.3.4 TYPE OF REINFORCEMENT

In order to investigate the influence of the mortar layer stiffness and ductility on its structural behavior, particularly after cracking in the layer occurred, two of the mortar layers tested were reinforced with mesh. The reinforcing mesh used in test Nos. 15 and 16 had a 1 in. (2.54 cm) square pattern, formed with a 0.063 in. (1.06 mm) diameter wire and was placed close to the outside surface of the layer. The mesh was pushed against a fresh mortar layer and covered immediately thereafter with the second layer. The reinforced mortar layer was held against the fixed walls with a set of steel plates similar to those shown in Fig. 3.3 but were located 3 ft (91.4 cm) rather than 1 ft (30.4 cm) away from the movable block.

3.3.5 RATE OF LOAD APPLICATION

It is reasonable to assume from a structural point of view that the rate at which the load is applied to the layer will have an influence on the numerical value of forces F_0 and F_1 in the aforementioned model. From the geological point of view, the rate of load application is a very important variable directly related to the "stand-up" time of the material surrounding the tunnel. Since the "stand-up" time of rock in blocky ground is highly variable, it was decided to run comparative tests at two extreme rates of loading.

For all the tests except 8 and 10, a "slow" rate of loading equal to 2 lbs/sec (8.9×10^{-3} kN/sec) was used. For test Nos. 8 and 10, the load was applied rapidly to simulate the instantaneous development of load on the layer imposed by a rock block whose gravity load was mobilized quickly and whose weight exceeded the support capacity of the layer.

3.3.6 THICKNESS OF THE MORTAR LAYER

For this series of preliminary tests the mortar layer was intended to have a uniform thickness of 1 in. (2.54 cm). However, due to the placement method, it was not possible to control this thickness accurately over the entire area of the layer. Column 2 in Table 3.2 indicates the average thickness of the mortar layers obtained from several measurements taken along the failure planes of the layer.

3.4 LOADING PROCEDURE

Results obtained from the first several tests indicated that it was pertinent to study the structural behavior of the mortar layer after the load reached a value equal to the maximum resistance of the layer. For the first tests, Nos. 1 through 11, the loading process was performed entirely under load control. The electrically controlled ram was set to apply a maximum load of 10,000 lbs (44.48 kN) over an interval of 5000 sec. The maximum displacement for the ram head (1/2 in.) was controlled by attaching an electrical contact switch to the dial gage monitoring the displacement of the center point of the mortar layer. Once the displacement reached 1/2 in. (1.27 cm) a contact was made cutting the load immediately to zero.

For the other series of tests, Nos. 12 through 18, the loading proceeded up to a maximum capacity of the layer under load control. Once this value was reached, however, the load in the ram was immediately cut off manually and the displacement of the ram head stopped. A small load, however, due to the back-up pressure in the hydraulic seals remained in the ram. Further displacements of the ram head were controlled in such a way that it applied whatever load necessary to advance at a pre-determined displacement rate of 0.0025 in./sec (displacement control). Use of this procedure permitted study of the behavior of the layer and measurement of the resulting loads and displacements once the maximum capacity of the mortar was reached.

3.5 TEST RESULTS

With the exceptions of test Nos. 5 and 6, no special difficulties were encountered in testing the mortar layers. Observations and measurements in each test were carried out as previously described and no major equipment or testing problems were encountered. Non-controllable, non-measured loads imposed in the mortar layer during ram head alignment for test Nos. 5 and 6 created a premature separation of the mortar layer from the surface slab. Results obtained from these tests were plotted but not used in comparisons with other test results.

3.5.1 MODES OF FAILURE

Of the two basic modes of failure proposed in the model of Chapter 3, only separation between the mortar layer and the concrete surface slab was observed in these preliminary tests. The continuous displacement of the movable block, induced by the load in the ram, produced adhesion stress in the contact area between the mortar layer and the surface slabs as well as tension and compression stresses in the mortar layer itself. It was observed, however, that in all cases the induced adhesion stresses exceeded the adhesion strength at the contact area before the level of stress in the layer reached the strength of the mortar. A separation of the mortar layer from the surface slab started at the movable block and progressed away from it toward the outer boundaries of the layer. Variations in the structural behavior of the mortar layer after separation from the surface slab were observed in different tests. In one case, test No. 4, the size of the contact area beyond the movable block was so small that the adhesion failure occurred almost simultaneously along its length and the layer moved as a rigid body uniformly outward with the movable block. Figure 3.6 shows a frontal view of the failed mortar layer; the fact that cracking did not occur in the mortar layer indicated that the magnitude of the stress induced in the layer never exceeded the flexural strength of the mortar.

In most of the cases, the mortar layer, after its initial separation from the surface slab, started acting like a simply supported beam having a uniformly loaded center section and end supports which continuously moved apart (see Fig. 3.7). When the separation between the mortar layer

FIGURE 3.6 FRONTAL VIEW OF FAILED MORTAR LAYER WITH NO CRACKS AT THE MOVABLE-FIXED BLOCK CONTACT

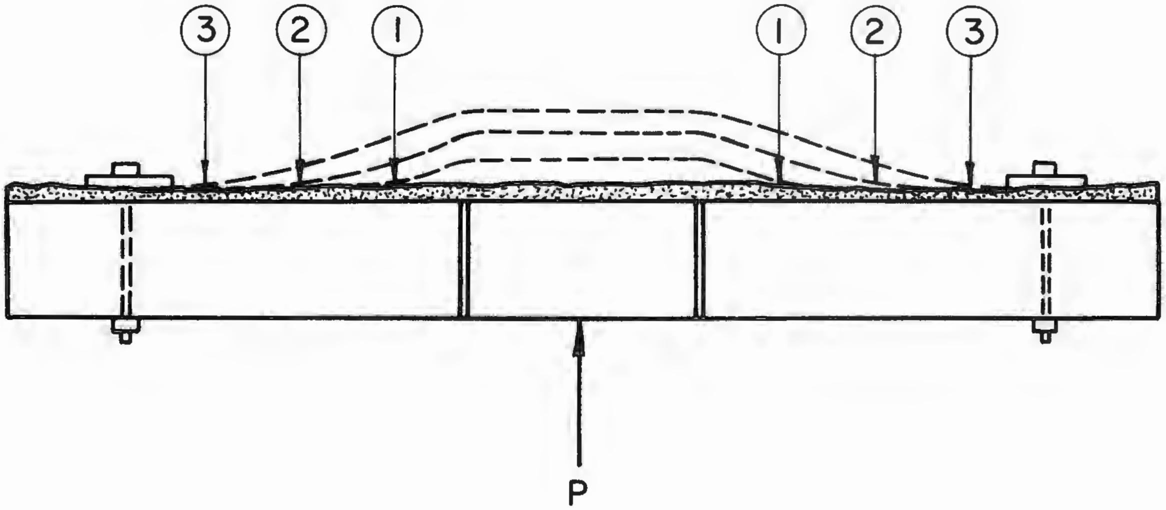


FIGURE 3.7 SCHEMATIC VIEW OF SHOTCRETE LAYER DEFLECTION AFTER SEPARATION STARTS

and the surface slab became long enough, the bending stresses in the layer exceeded its flexural capacity and two vertical cracks appeared in the mortar along the contact between the movable and fixed blocks. The progressive separation of the mortar layer occurred so fast that the cracks appeared almost simultaneously with the adhesion failure.

In some cases, when steel restraining plates were not placed at the boundaries of the layer, the separation of the mortar layer from the surface slab propagated all the way to the boundaries of the layer as shown at the right-hand side of the upper mortar layer in Fig. 3.8. In other cases, the separation of the layer from the slab propagated only to a point at which the negative moment, induced by the residual load of the ram, created bending stresses in the interior surface of the mortar layer which exceeded the mortar strength. At this point a vertical crack was formed at the interior surface of the mortar layer.

In the tests where no steel restraining plates were used, the necessary rigidity against rotation required at the boundaries was provided by the adhesion force F_0 developed in the remaining area of contact between the mortar and the surface slab. The left-hand side of the upper mortar layer and both sides of the lower layer shown in Fig. 3.8 are examples of this situation. Except in the tests in which the contact between the steel plates and the mortar layer was very irregular, the plates provided a limit to the length of separation between the mortar layer and the fixed wall (Figs. 3.9 and 3.10).

In tests carried out with reinforced layers (test Nos. 15 and 16), or for those in which the steel plates were closely spaced (test Nos. 17 and

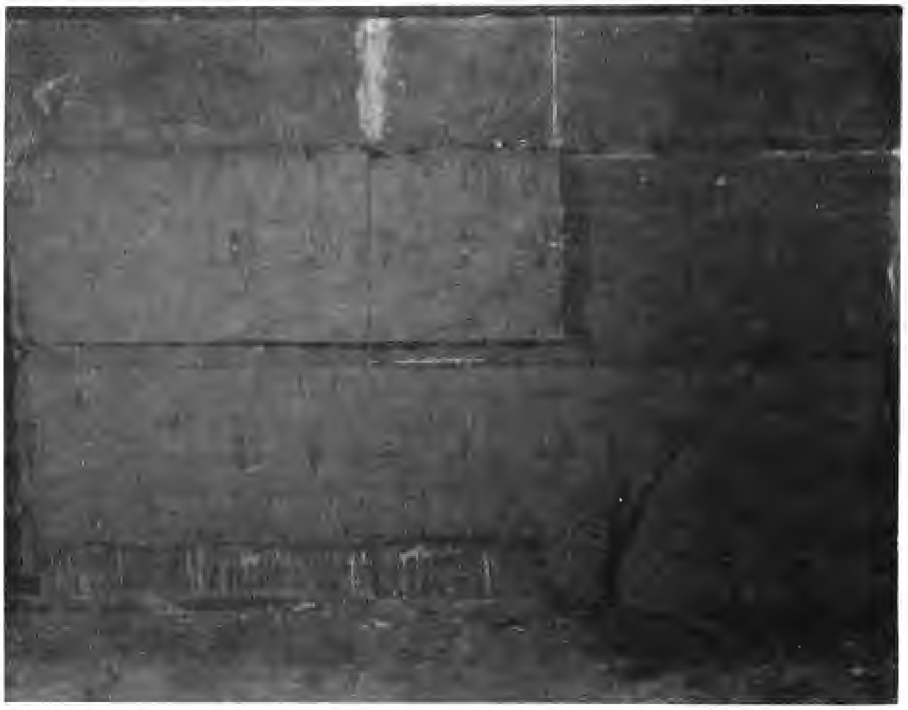


FIGURE 3.8 MORTAR LAYERS FAILED BY SEPARATION OF MORTAR LAYER FROM THE SURFACE SLAB

FIGURE 3.9 STEEL PLATES PROVIDING RESTRAINT TO ADHESION FAILURE PROPAGATION

FIGURE 3.10 TOP VIEW OF MORTAR CRACKING PATTERN IN TEST NO. 17

18), a significant residual resistant was present in the layer even after large displacements. This resistance was produced by an adhesion between the mortar layer and the concrete slab covering the movable block. Once this adhesion failure developed, another vertical crack occurred at the surface and along the center line of the mortar layer and the resistance of the layer suddenly approached zero. Figure 3.11 shows the three vertical cracks in the mortar layer, produced by bending stresses developed during the loading in test No. 16. The cracks at the contact of the movable block with the fixed walls, labeled Number 5, appeared immediately after

FIGURE 3.11 VERTICAL CRACKS IN THE MORTAR LAYER DUE TO BENDING STRESSES DEVELOPED BY LOADING PROCESS IN TEST NO. 16

separation of the mortar layer from the wall; the other crack, along the center line of the movable block and labeled Number 8, appeared later, after a considerable displacement of the movable block had taken place. Figure 3.10 shows a similar adhesion failure and the corresponding crack pattern, obtained in test No. 17 in which steel plates were used. The top view of the central zone of the mortar layer in Fig. 3.12 shows clearly the adhesion failure which developed between the mortar layer and the concrete slab.

In other cases, such as the case shown in Fig. 3.13 corresponding

FIGURE 3.12 TOP VIEW OF ADHESION FAILURE DEVELOPED BETWEEN THE MORTAR LAYER AND THE CONCRETE SLAB COVERING THE MOVABLE BLOCK IN TEST NO. 15

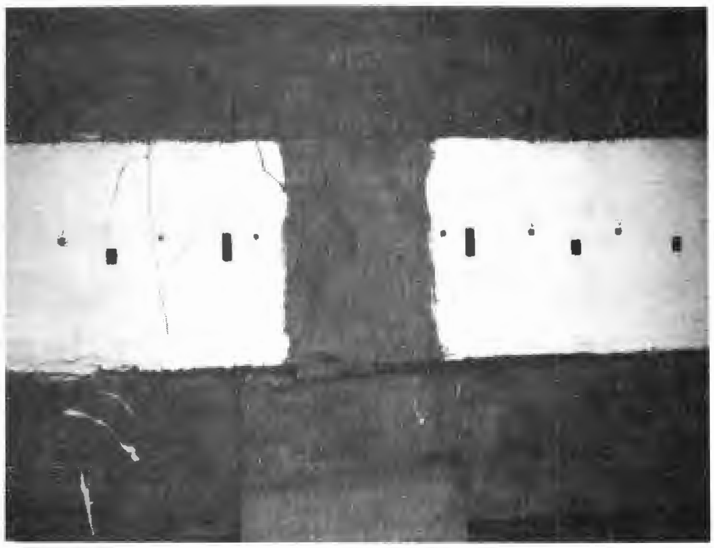


FIGURE 3.13 MORTAR SURFACE CRACKS DEVELOPED ALONG PRE-LOADING WEAKNESS ZONES

to test No. 2, the cracks in the mortar layer surface were not observed at locations where stresses in the layer were maximum. In these cases, failure occurred along existing cracks produced by shrinkage or relative displacement which occurred within the mortar layer shortly after its placement.

The load carrying capacity of the mortar layer after adhesion failure occurred, decreased rapidly to zero for all the cases in which steel plates were not used. This was observed independent of the length of separation between the mortar layer and the fixed walls.

3.5.2 LOAD VS. MOVABLE BLOCK DISPLACEMENT

The mortar layer resistance and the displacement of the movable block were monitored during the test using an x-y plotter connected to the ram control system. The unit load, i.e., the load divided by the 48 in. (122 cm) of contact between the mortar layer and the fixed walls, was calculated and used as a measure of the resistance of the layer. The portion of the monitored displacements due to deflection of the frame "fixed" wall were determined by comparing at equal load levels the magnitude of the plotted displacements with those measured by dial gages mounted on the back of the movable block. The magnitude of these loading system displacements was subtracted from those measured by the x-y recorder to obtain the net displacements of the movable block relative to the fixed wall.

For each of the tests performed, the unit load was plotted on the y axis while its correspondent displacement of the movable block relative to the fixed wall was plotted on the x axis. Figure 3.14 shows three types of curves, corresponding to three types of structural behavior observed in the preliminary tests.

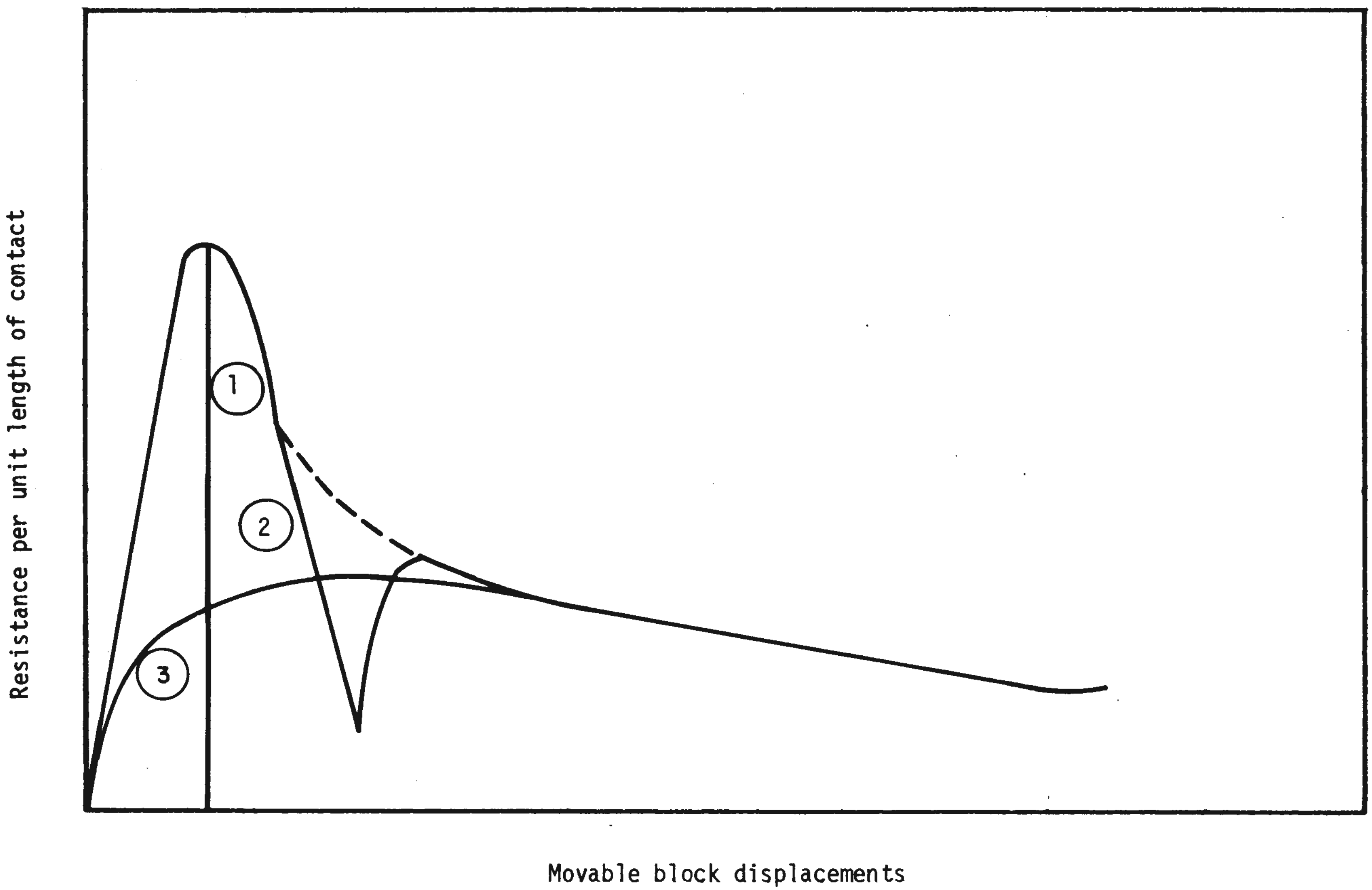


FIGURE 3.14 TYPICAL UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENT RELATIONSHIPS FOUND IN MORTAR LAYERS

For type No. 1 and No. 2 curves in Fig. 3.14 the maximum resistance of the layer was obtained as the layer separated from the surface slab. The initial portion of the load-displacement curve shows a linear-elastic behavior in which the maximum load is reached at a relatively small displacement. The type No. 1 curve shows that once separation occurred the resistance of the mortar layer dropped sharply to zero. This curve is representative of the structural behavior of the mortar layer in test Nos. 2 through 10, for which no steel plates or other types of boundary restrictions were used.

The type 2 solid line shows an instantaneous decline in the applied load immediately after the ultimate capacity of the layer was reached. The almost complete reduction of load, required to switch from load to displacement control, did not represent an actual reduction of the resistance of the mortar layer. Once the switch in the control was made, the load in the ram increased with further displacements of the movable block up to a level representing the actual residual resistance of the mortar layer at that displacement. For further displacements of the movable block the resistance of the mortar layer decreased at a rate determined by the stiffness of the layer and the extension of the adhesion failure beyond the movable block. The type 2 dotted line represents the relationship that would have been obtained if the load in the ram had not been reduced in order to switch from load to stroke control. The structural behavior of the mortar layer for test Nos. 11 to 17 for which steel plates were used to fix the boundaries of the layer, are represented by this curve.

The type 3 curve shows the case of test No. 8 in which the maximum resistance of the mortar layer was not reached at the beginning of the separation of the layer from the surface slab, but rather in bending with further displacements of the movable block. Curve 3 follows the same path as curves 1 and 2 up to a point that corresponds to the separation of the layer from the surface slab; from that point the curve represents the load deflection curve of a simply supported beam.

The structural behavior of the layers in test Nos. 1 and 2 correspond basically with the type 1 curve. The greater value of maximum load was the result of the presence of mortar in the gap between the surface slab covering the movable block and those covering the surrounding fixed walls.

The relationship between the unit-length resistance and movable block displacements for each of the tests are shown in Figs. 3.15 to 3.23. The values of the maximum resistance of the layer and the displacement at which it was obtained together with pertinent remarks for each of the tests are summarized in Table 3.4. From this table and the aforementioned relationship plotted in Figs. 3.15 to 3.23 the following conclusions can be drawn:

1. For the layers with load-displacement behavior represented by type curves 1 and 2, the magnitude of the displacement of the movable block at which maximum load was reached has a maximum value of 0.004 in. (0.102 mm).
2. Residual load capacities equal to 60 to 70 percent of the maximum capacity were observed in mortar layers whose structural behavior corresponds to that shown by type 2 curves. This residual capacity was maintained during movable block

TABLE 3.4

MORTAR TEST RESULTS

Test no.	Maximum carrying capacity lbs	(KPa)	Displacement of the movable block at max load in.	(cm)	Remarks
1	4000	(27,800)	.015	(.0381)	
2	4000	(27,800)	.016	(.0406)	
3	1500	(10,340)	.005	(.0127)	
4	900	(6,200)	.003	(.0076)	
5	860	(5,930)	.001	(.0025)	Layer was altered during testing set-up.
6	--	--	--	--	Failed during set-up.
7	5800	(40,000)	.005	(.0127)	
8	2400	(16,550)	.003	(.0076)	
9	450	(3,100)	.001	(.0025)	
10	1000	(6,895)	.002	(.0051)	
11	3240	(22,400)	.003	(.0076)	Steel plates
12	1640	(11,600)	.004	(.0102)	Steel plates
13	1250	(8,620)	.004	(.0102)	Steel plates
14	1170	(8,070)	.004	(.0102)	Steel plates
15	2500	(17,200)	.002	(.0051)	Steel plates
16	2300	(15,850)	.003	(.0076)	Steel plates
17	2850	(19,650)	.002	(.0051)	Steel plates
18	2600	(17,900)	.075	(.1905)	Steel plates

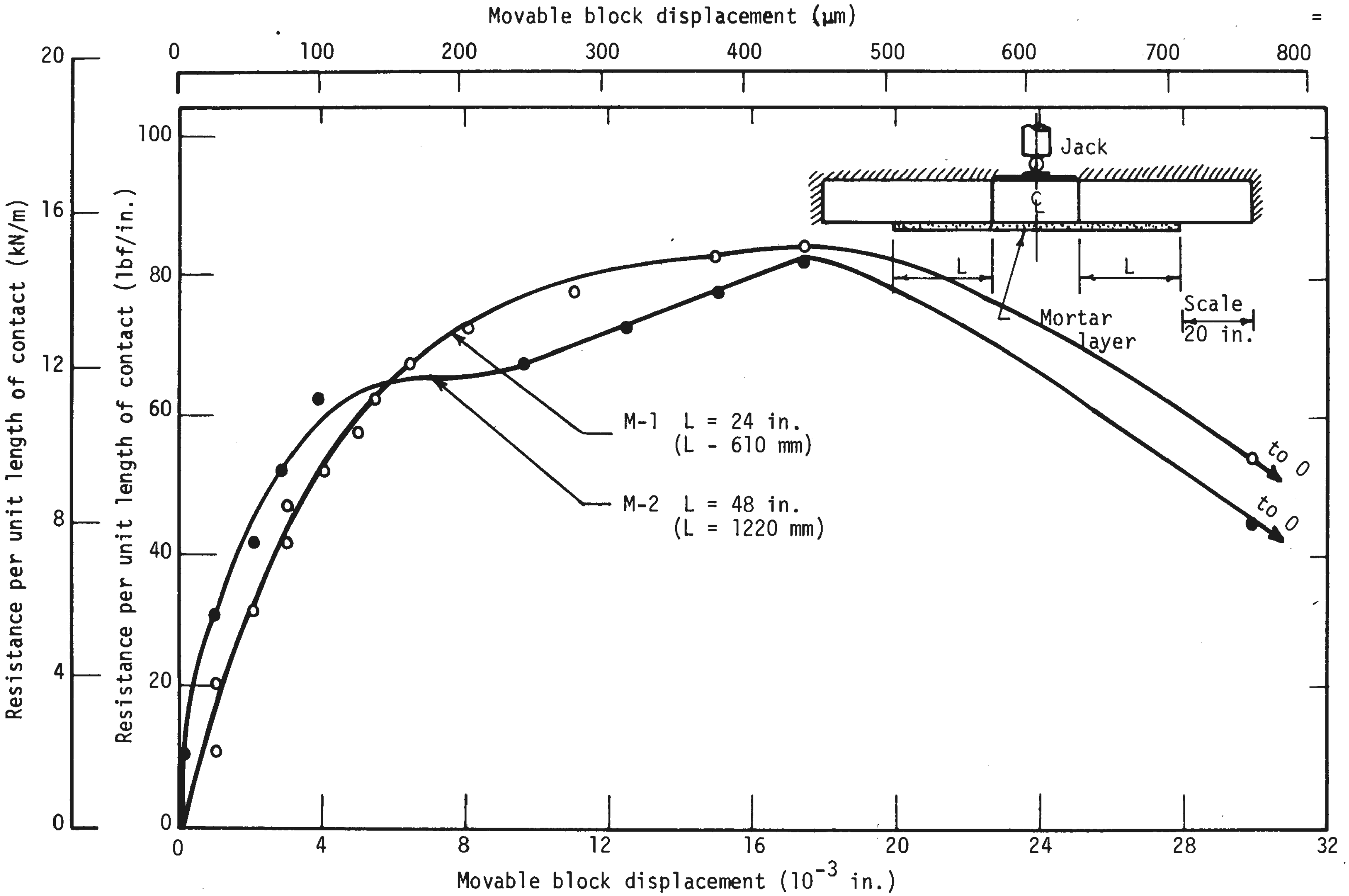


FIGURE 3.15 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

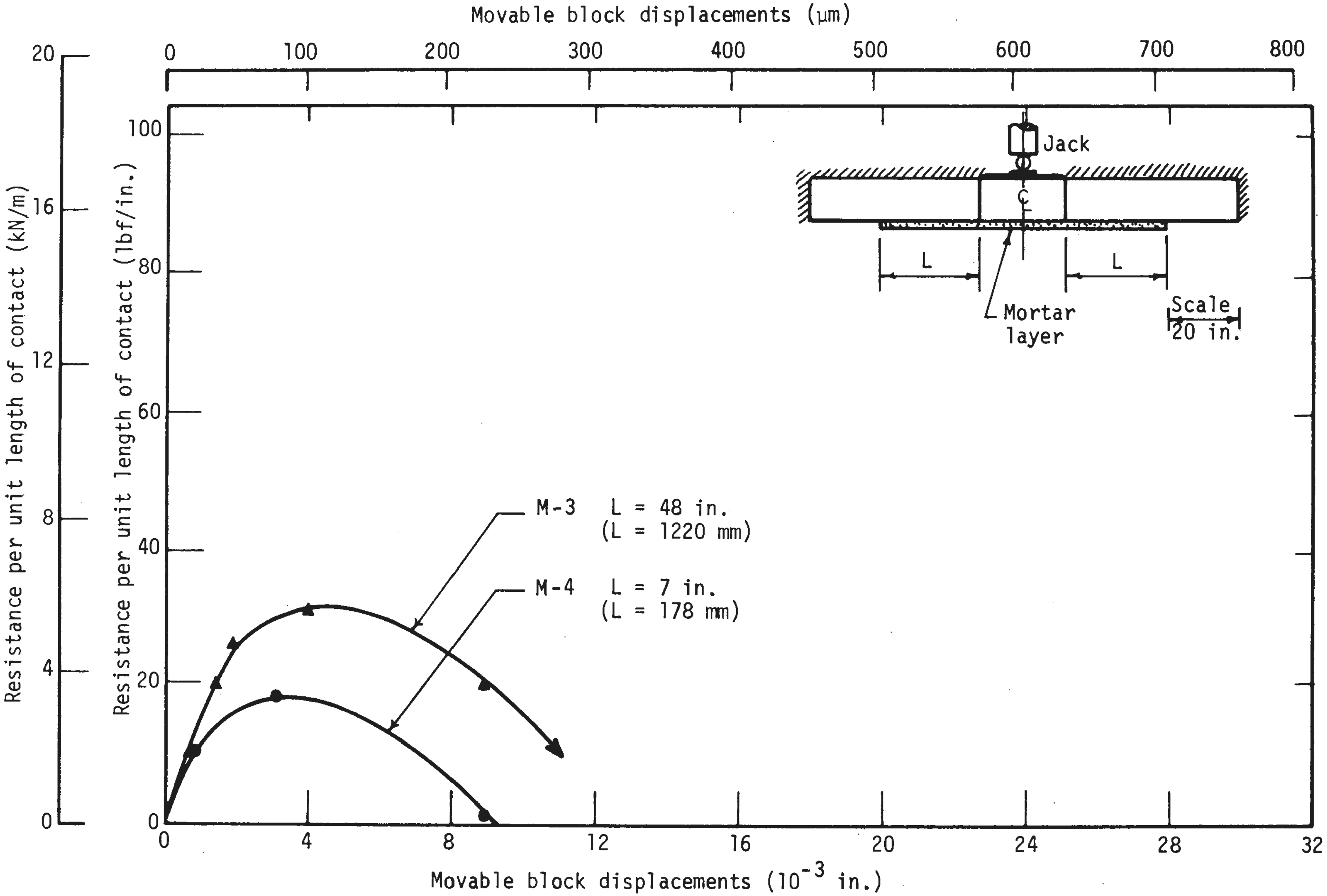


FIGURE 3.16 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

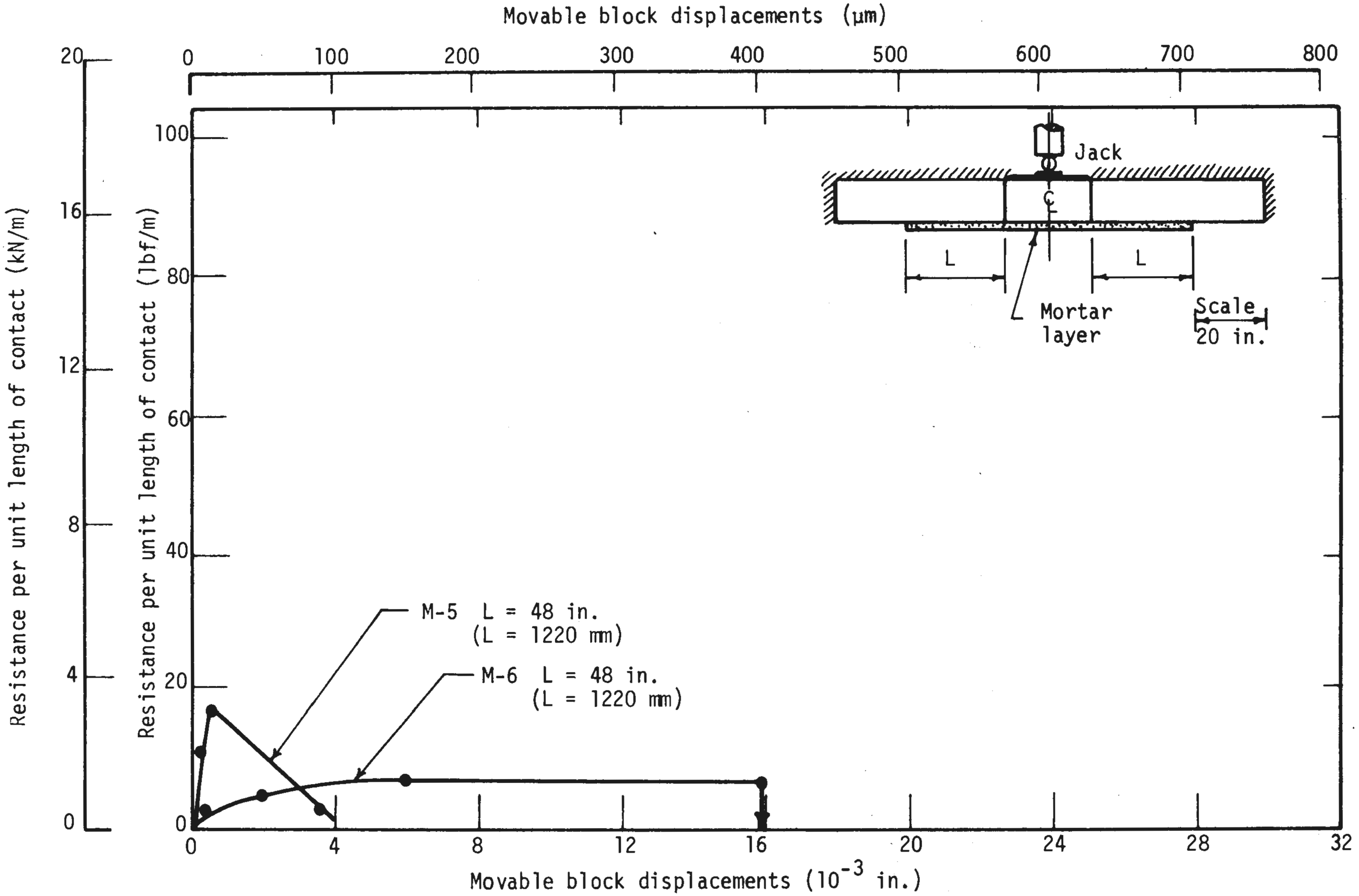


FIGURE 3.17 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

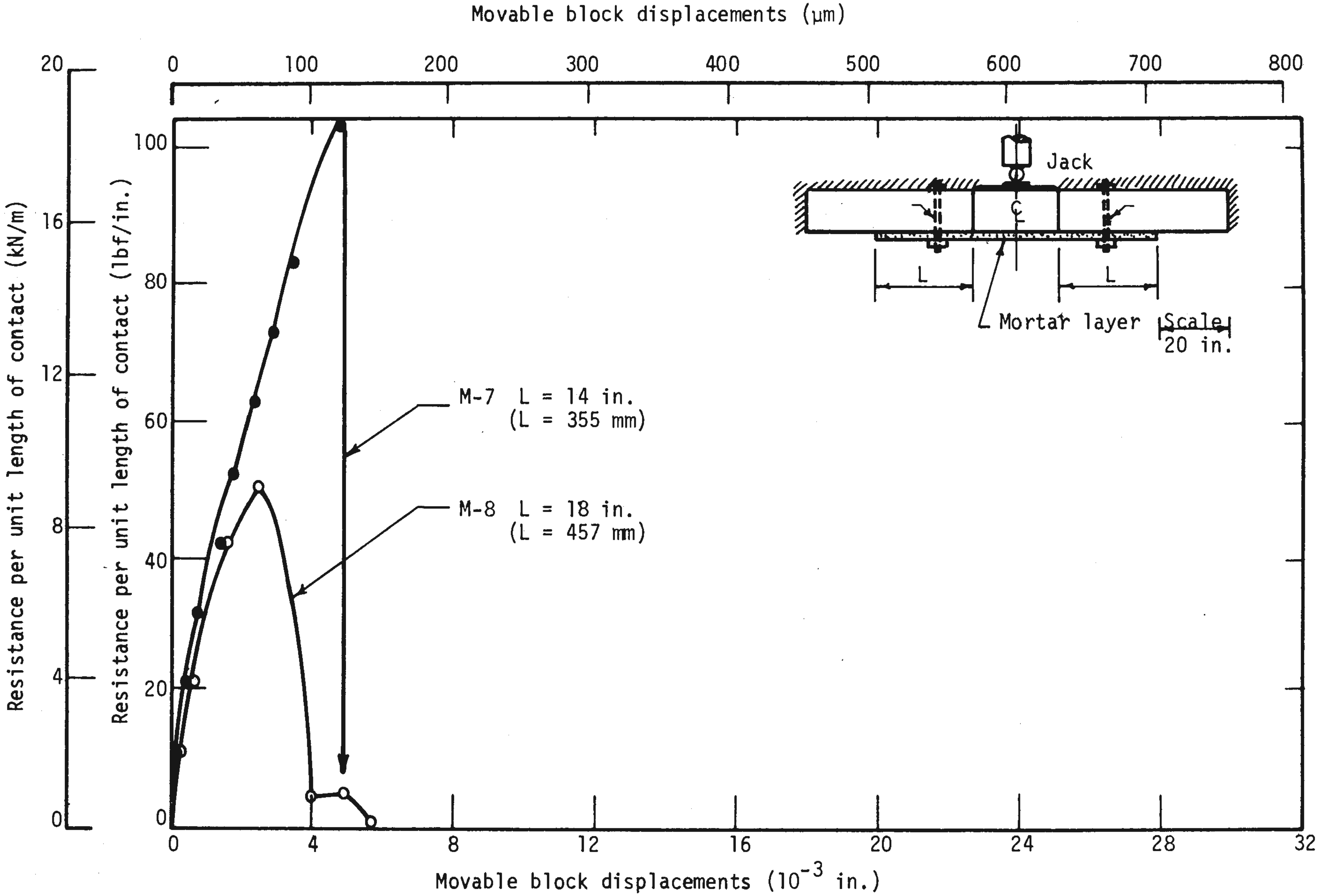


FIGURE 3.18 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

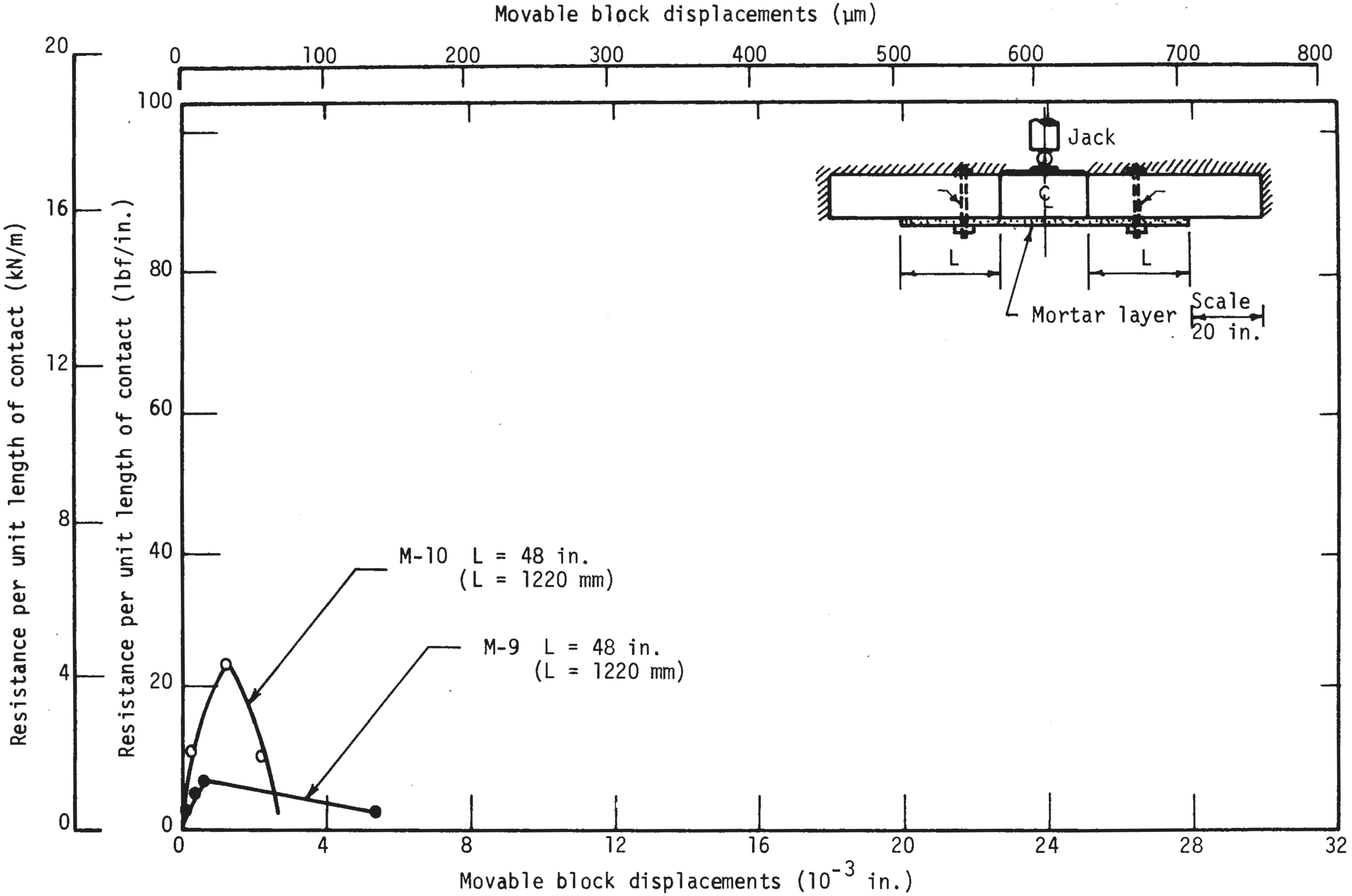


FIGURE 3.19 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

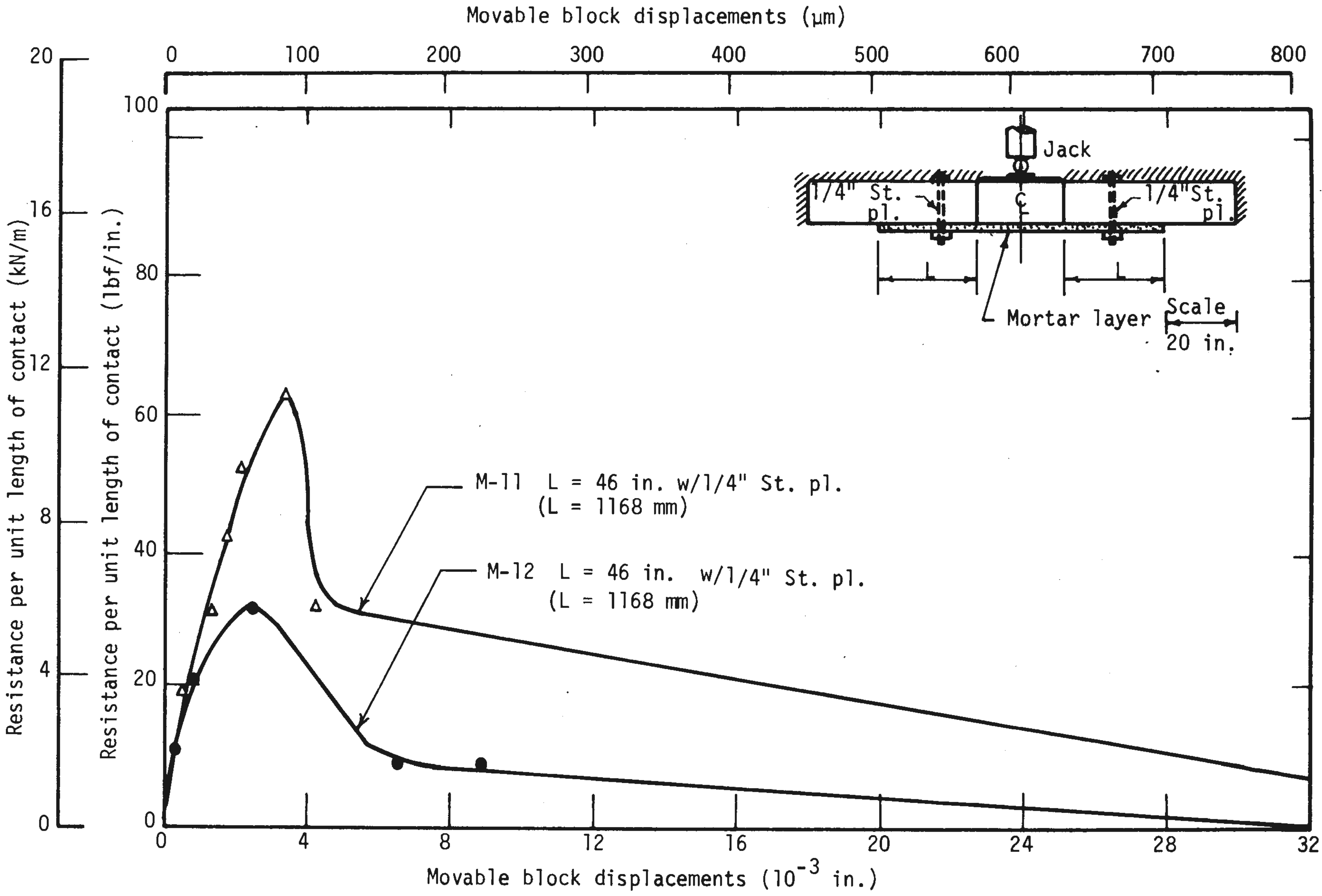


FIGURE 3.20 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

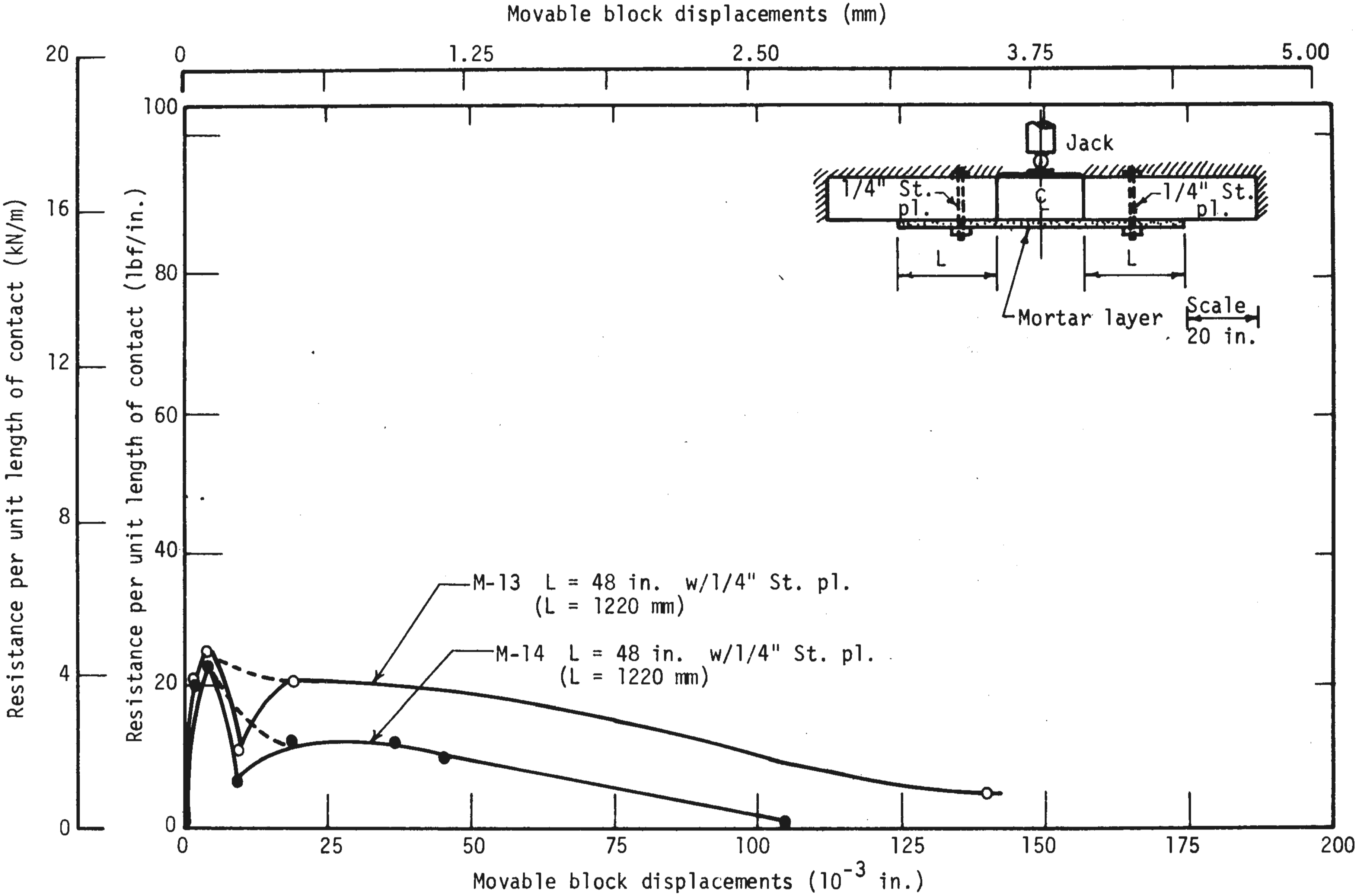


FIGURE 3.21 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

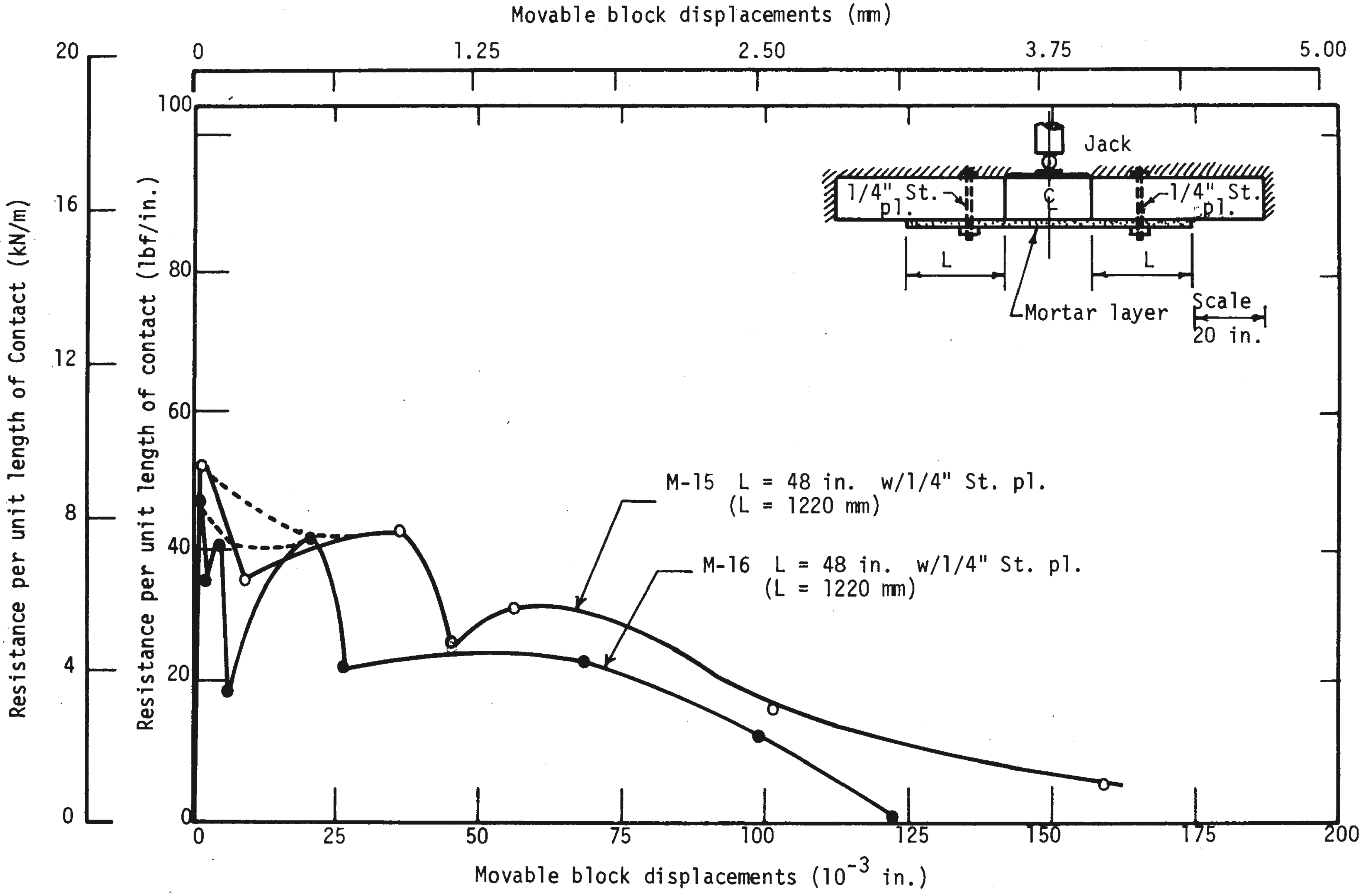


FIGURE 3.22 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

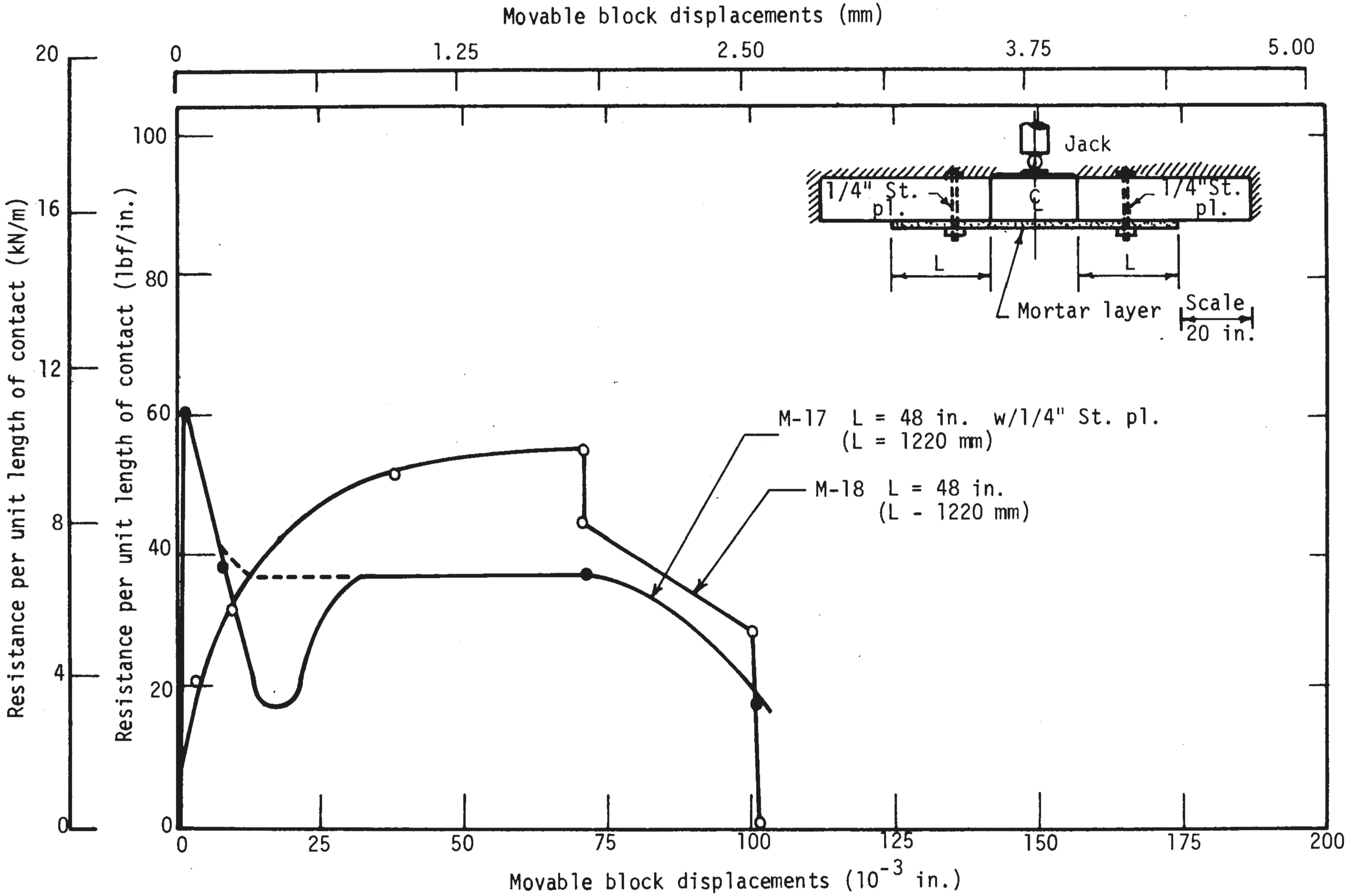


FIGURE 3.23 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

displacements 15 to 25 times greater than the average required to cause initial failure. Residual capacity of the layers was reduced to zero at movable block displacements equal to 1 in. (2.54 mm).

3. The presence of mortar in the gap between the surface slab covering the movable block and the adjacent slabs increased the magnitude of the displacements at which maximum-resistance was achieved by a factor of 4 (0.015 in.).

4. In cases where the ram induced negative moments exceeding the bending strength of mortar a crack showed up in the interior surface of the layer; cracks appeared at different distances from the movable block depending on the thickness of the layer and the adhesion strength along the mortar-surface slab contact. Rock bolts located at distances further away from the crack would not have had any influence on the resistance of the layer.

3.5.3 MORTAR LAYER DISPLACEMENTS

GENERAL

As mentioned in Section 2.4, a set of dial gages placed against the front surface of the mortar layer and attached to the floor was used to measure the relative forward displacements of the layer with respect to the floor. The pre-failure displacements measured by these dial gages for each of the mortar layers tested, are shown in Figs. 3.24 to 3.39.

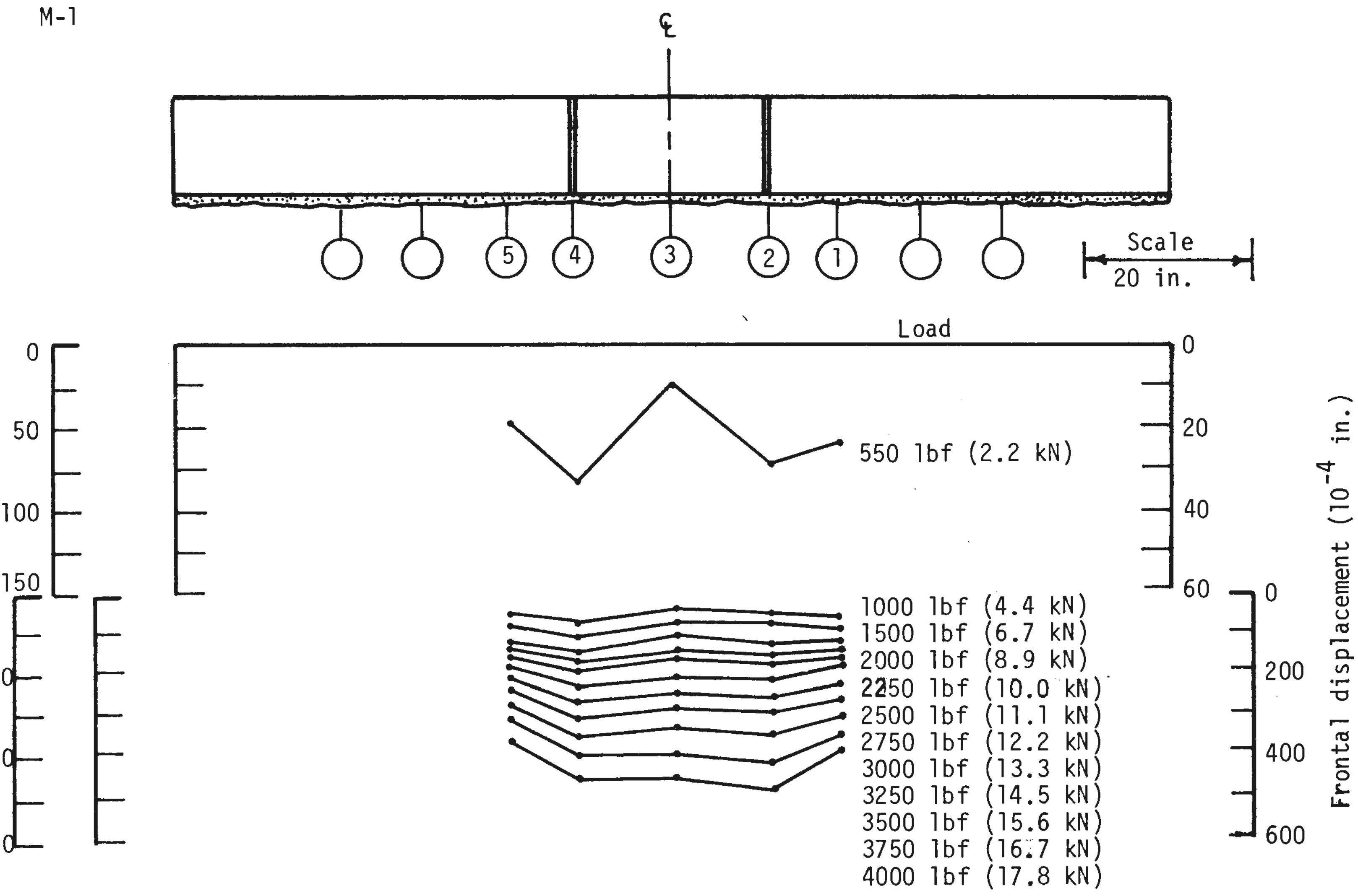


FIGURE 3.24 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

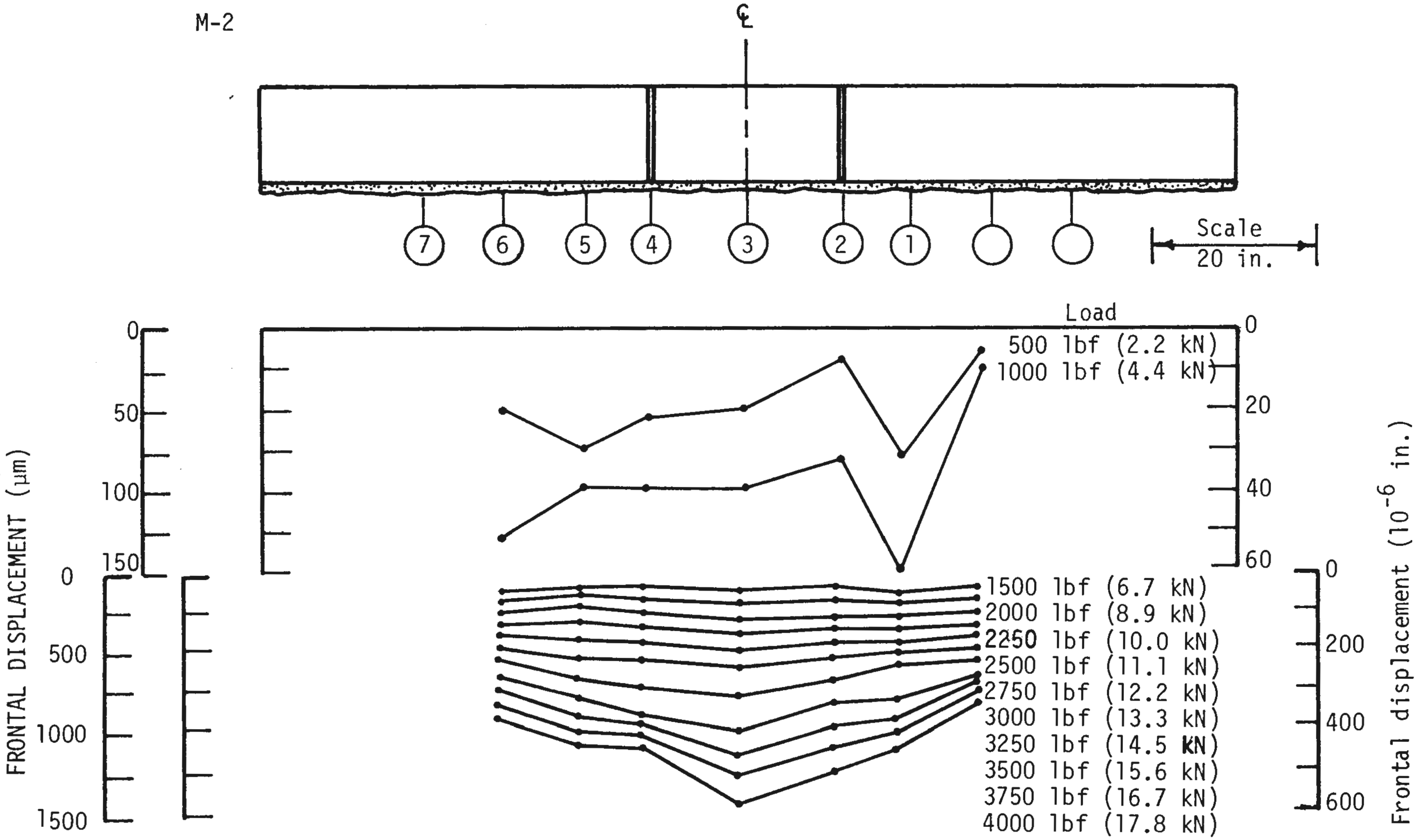


FIGURE 3.25 FRONT FACE DISPLACEMENT OF LAYER W.T.R. FLOOR

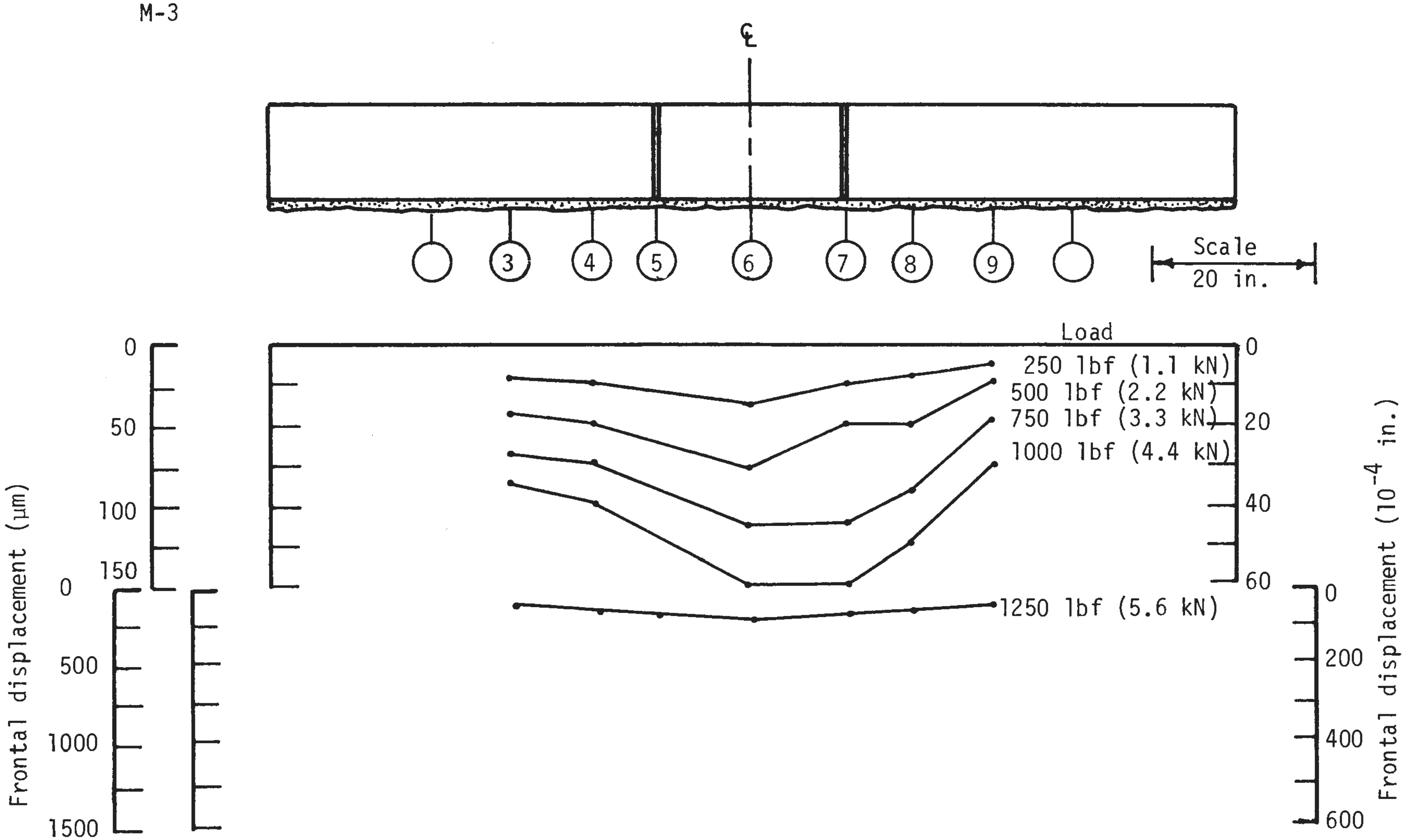


FIGURE 3.26 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

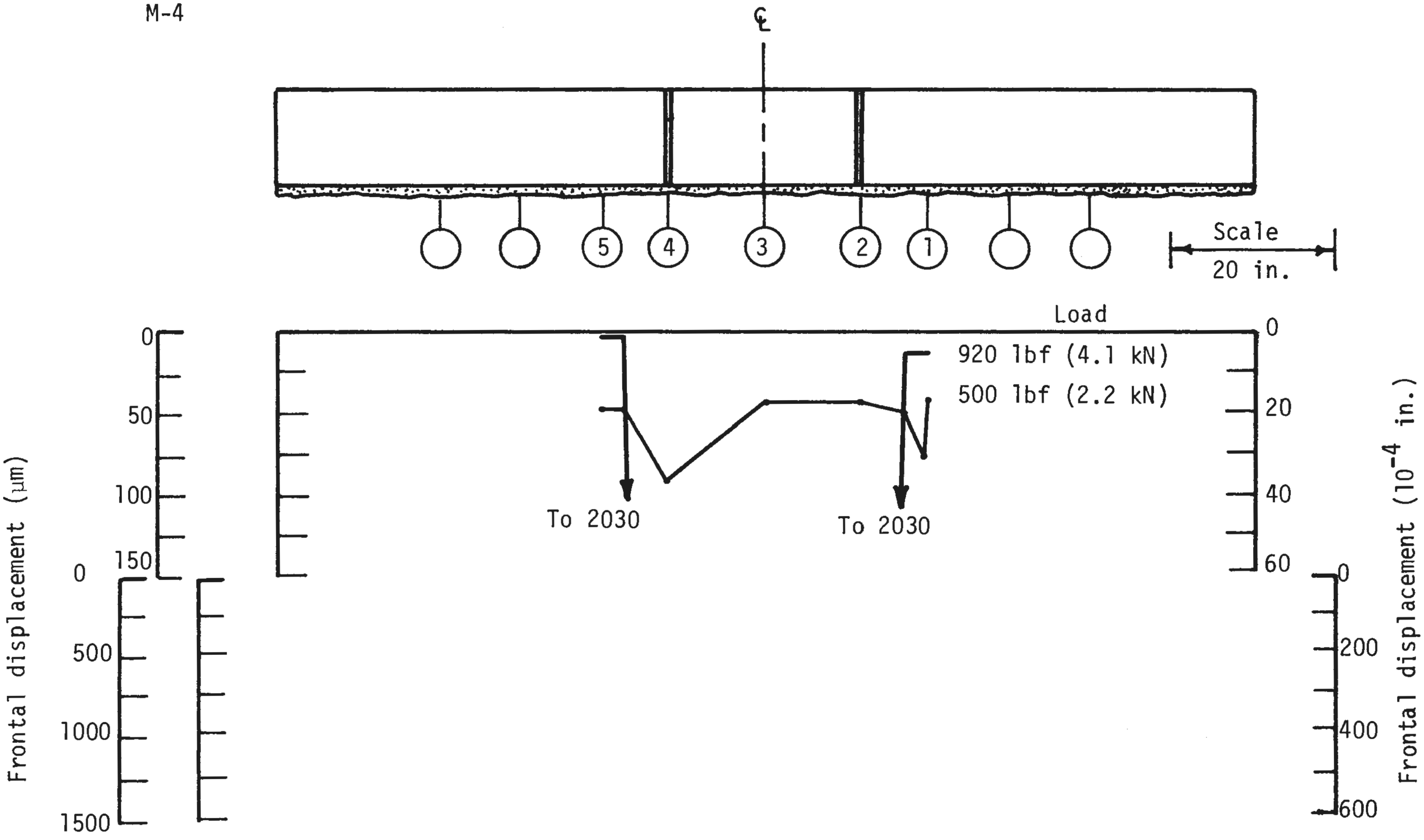


FIGURE 3.27 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

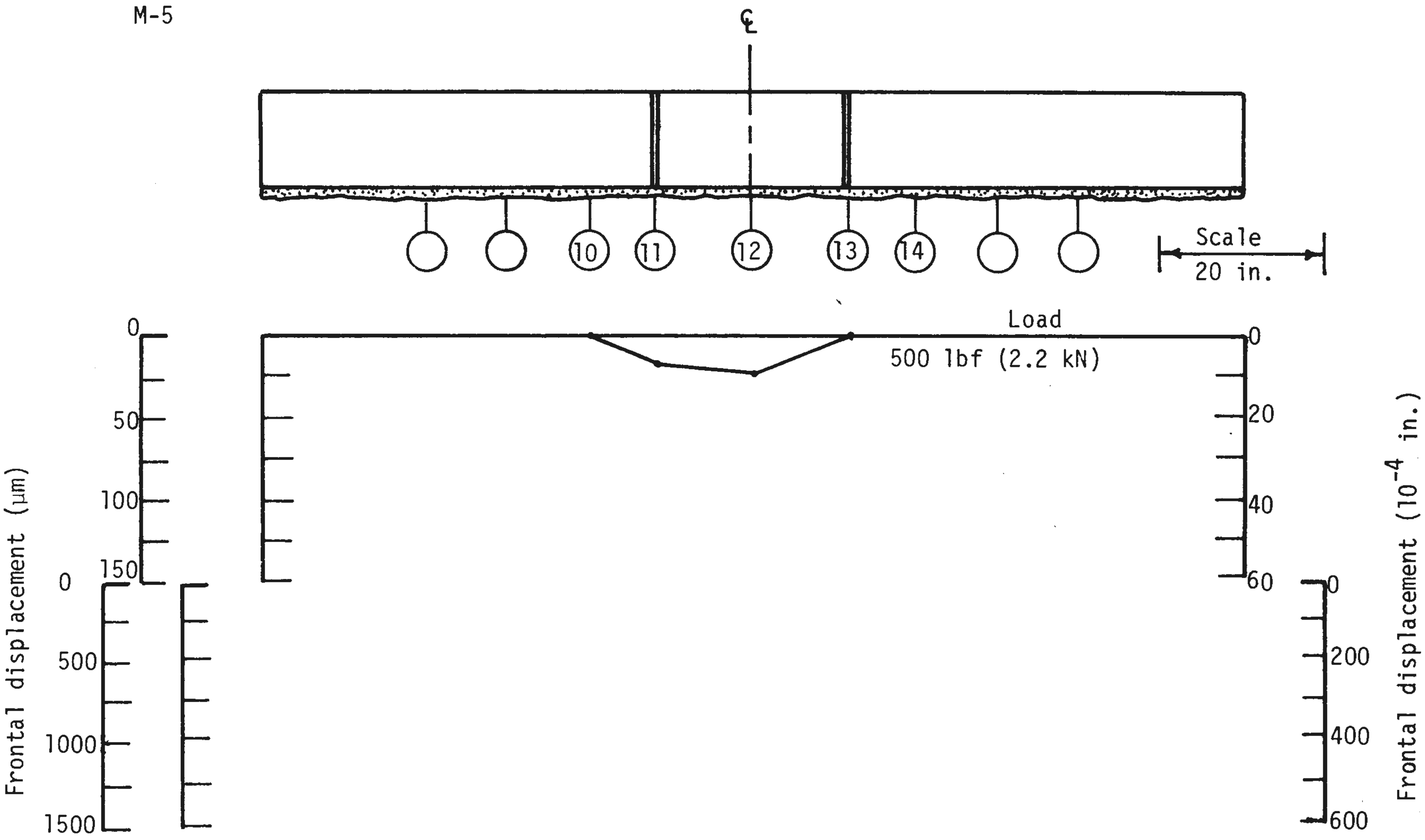


FIGURE 3.28 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

M-6

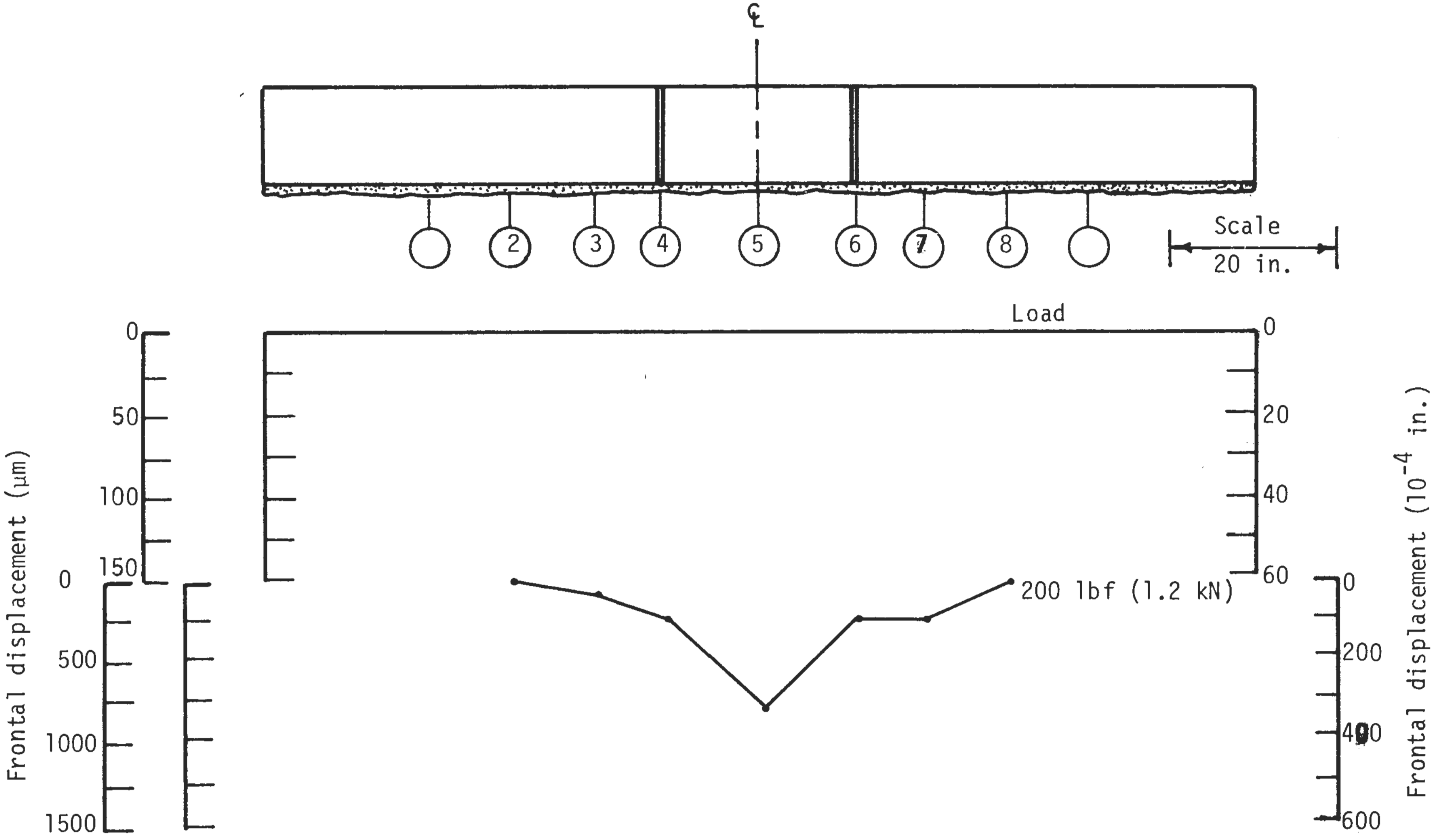


FIGURE 3.29 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

M-7

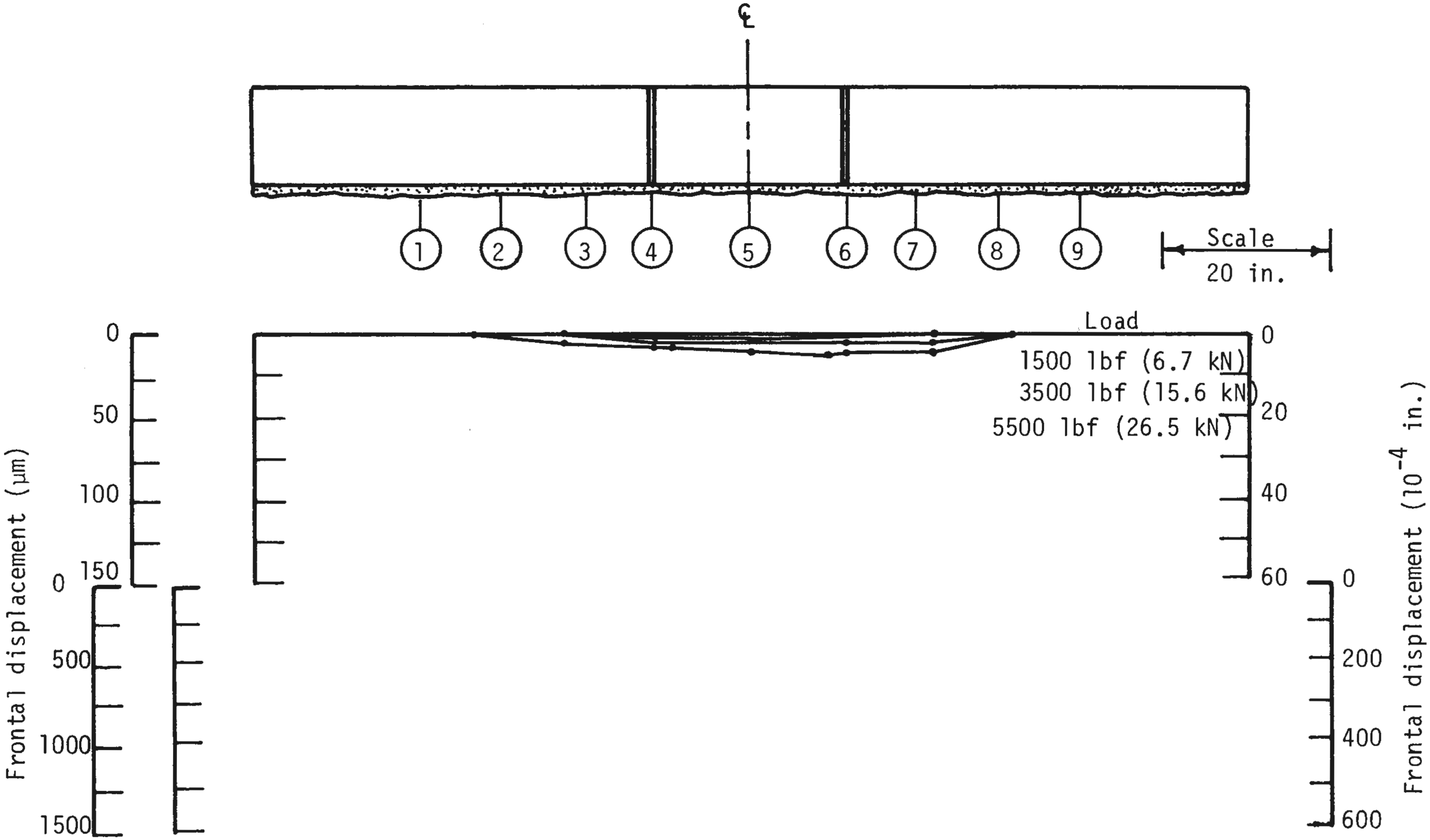


FIGURE 3.30 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

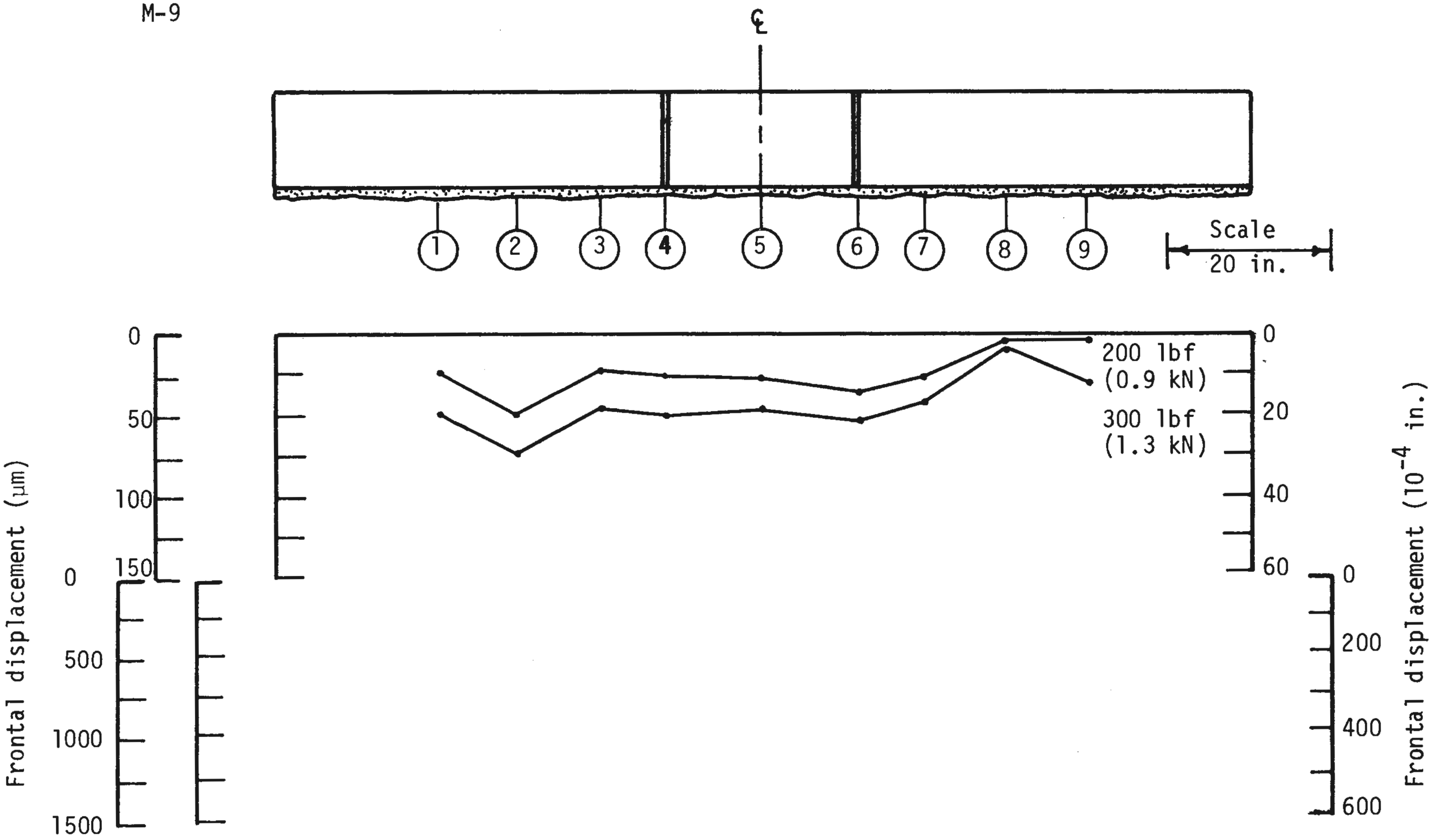


FIGURE 3.31 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

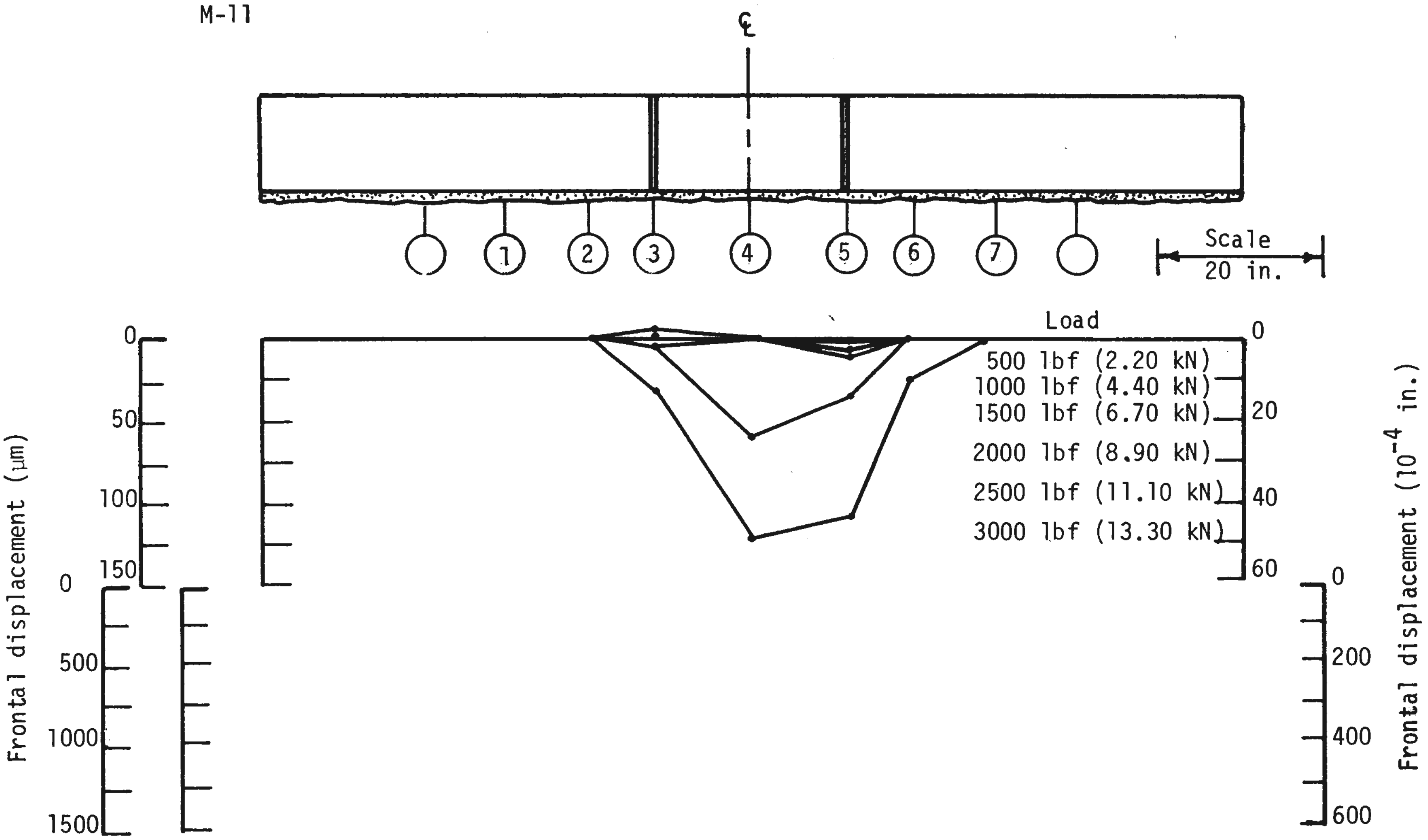


FIGURE 3.32 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

M-12

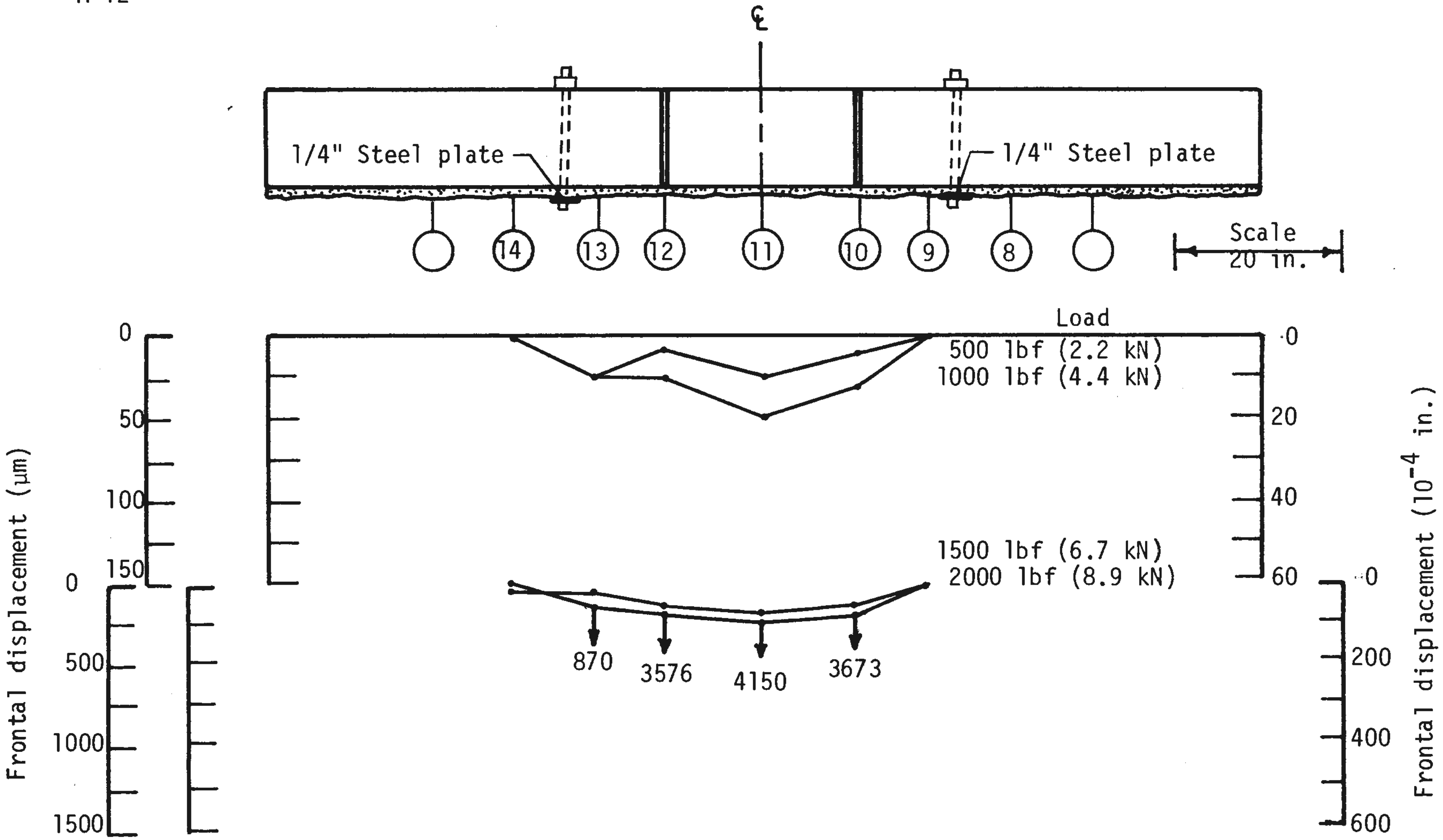


FIGURE 3.33 FRONT FACE DISPLACEMENT OF LAYER W.R.T.FLOOR

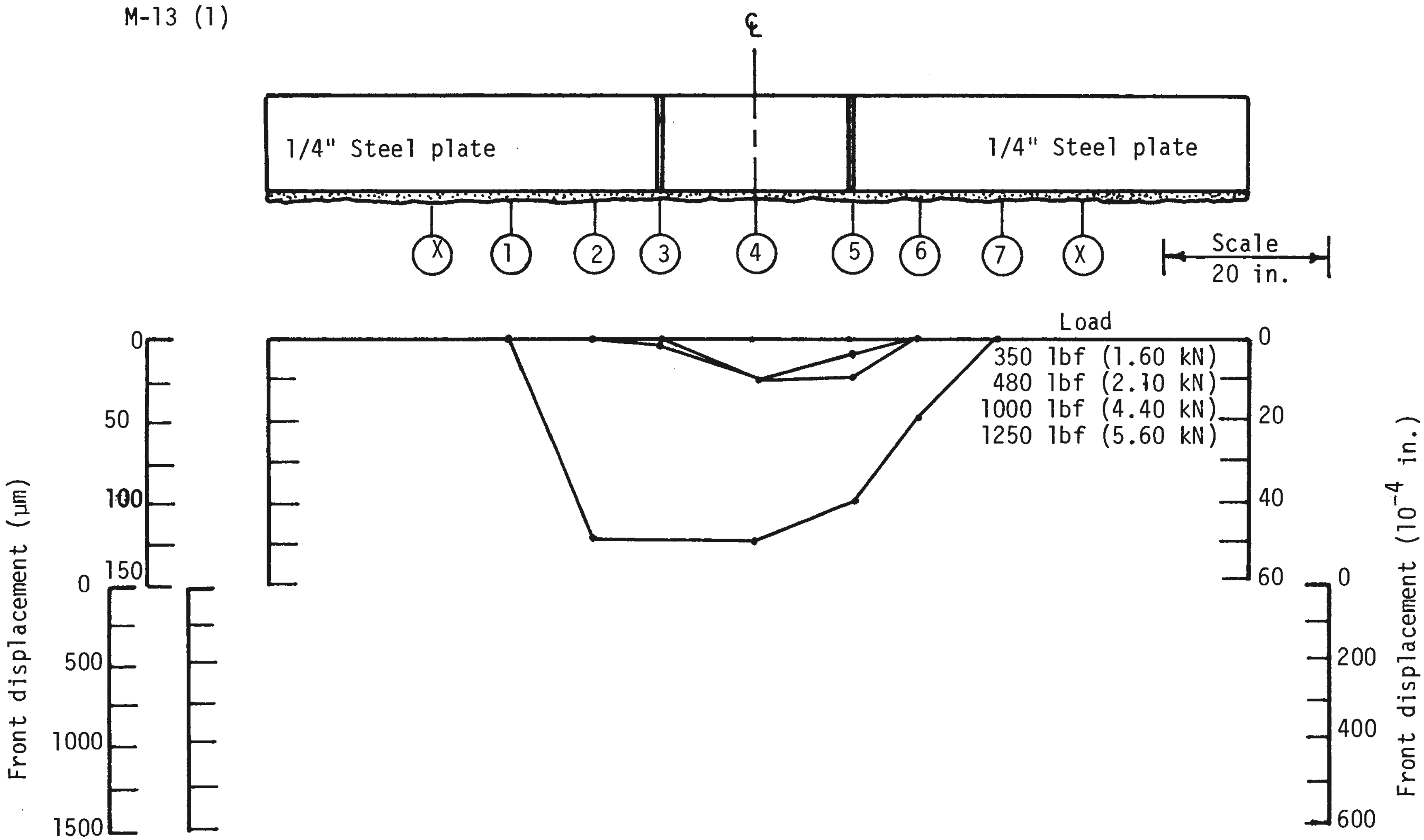


FIGURE 3.34 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

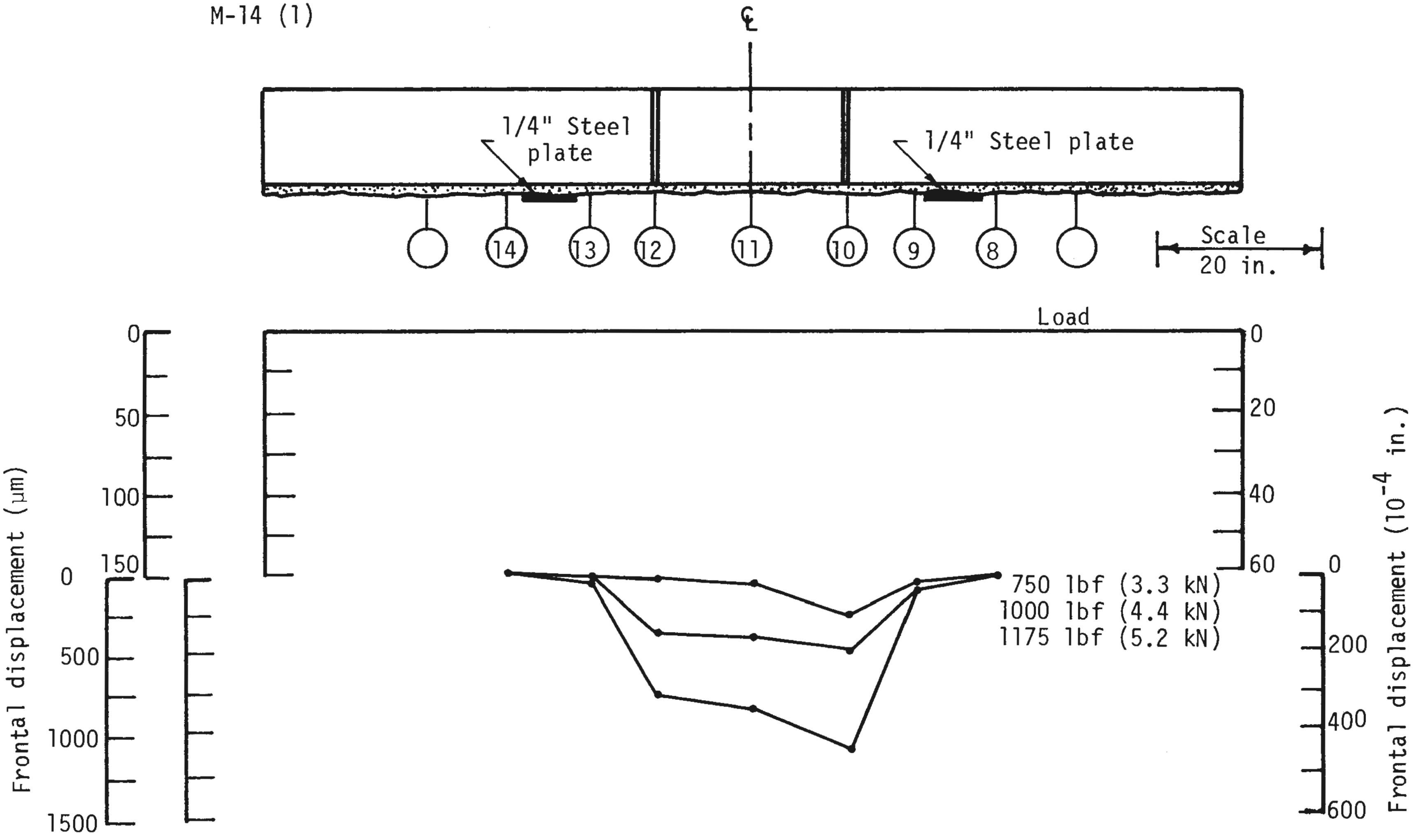


FIGURE 3.35 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

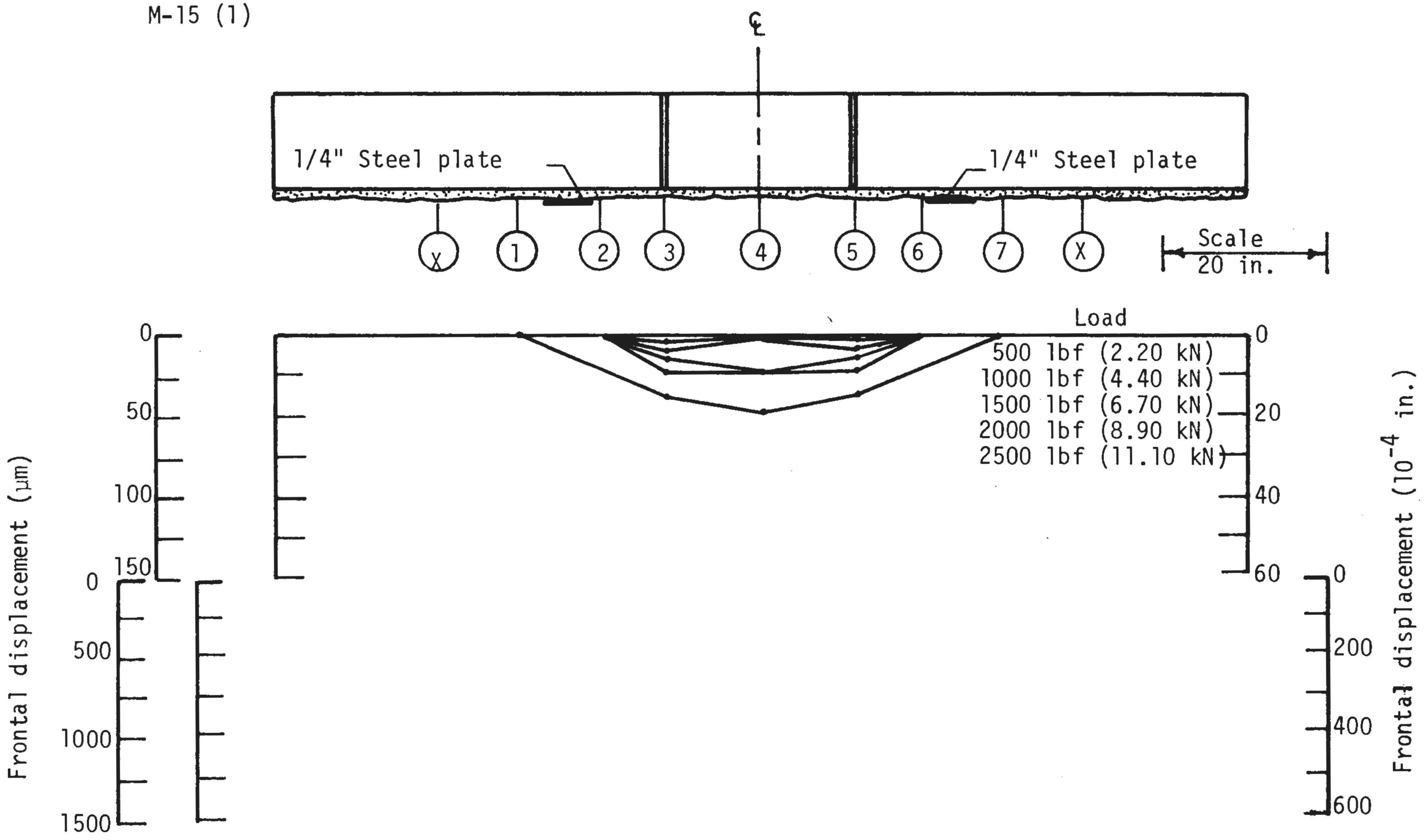


FIGURE 3.36 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

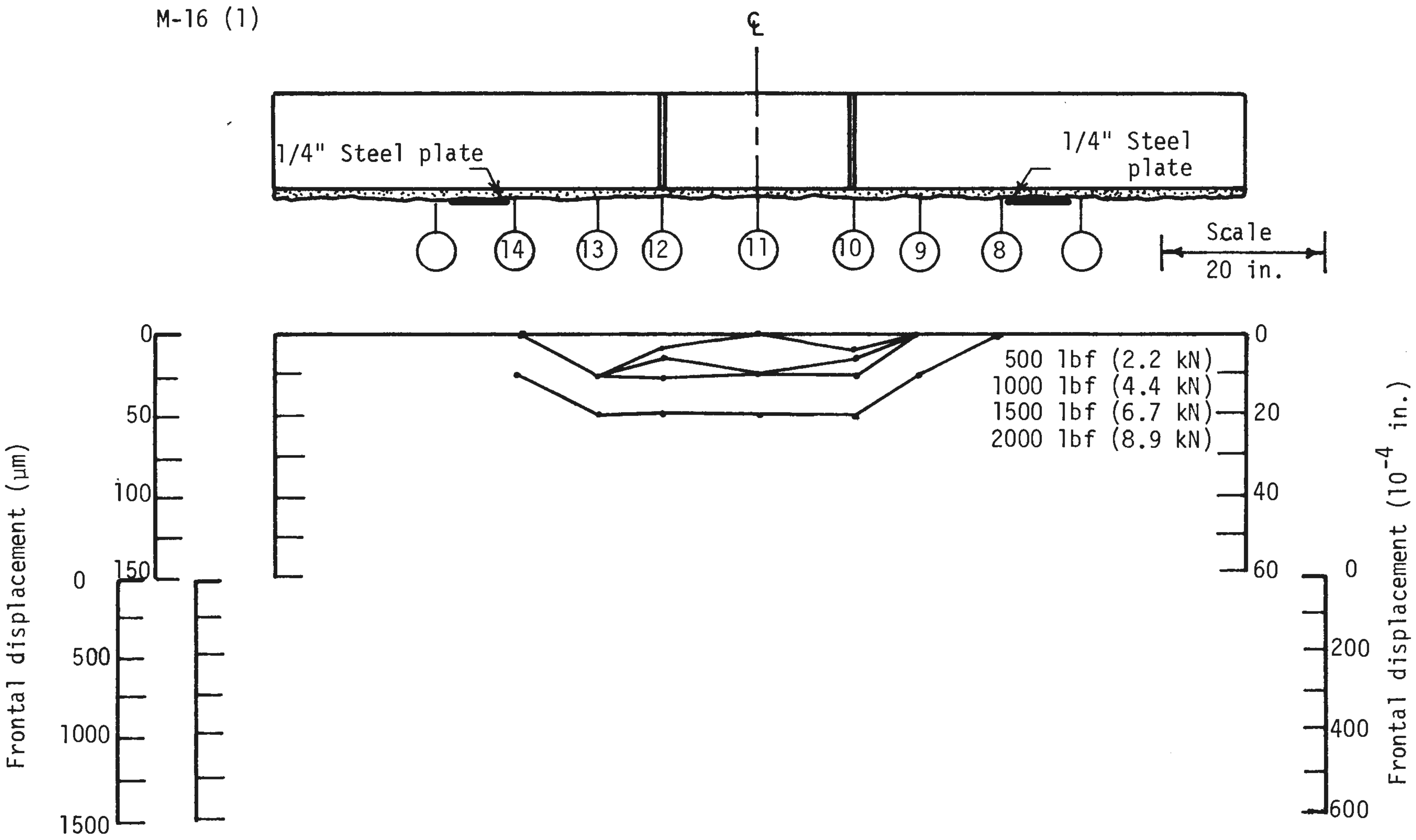


FIGURE 3.37 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

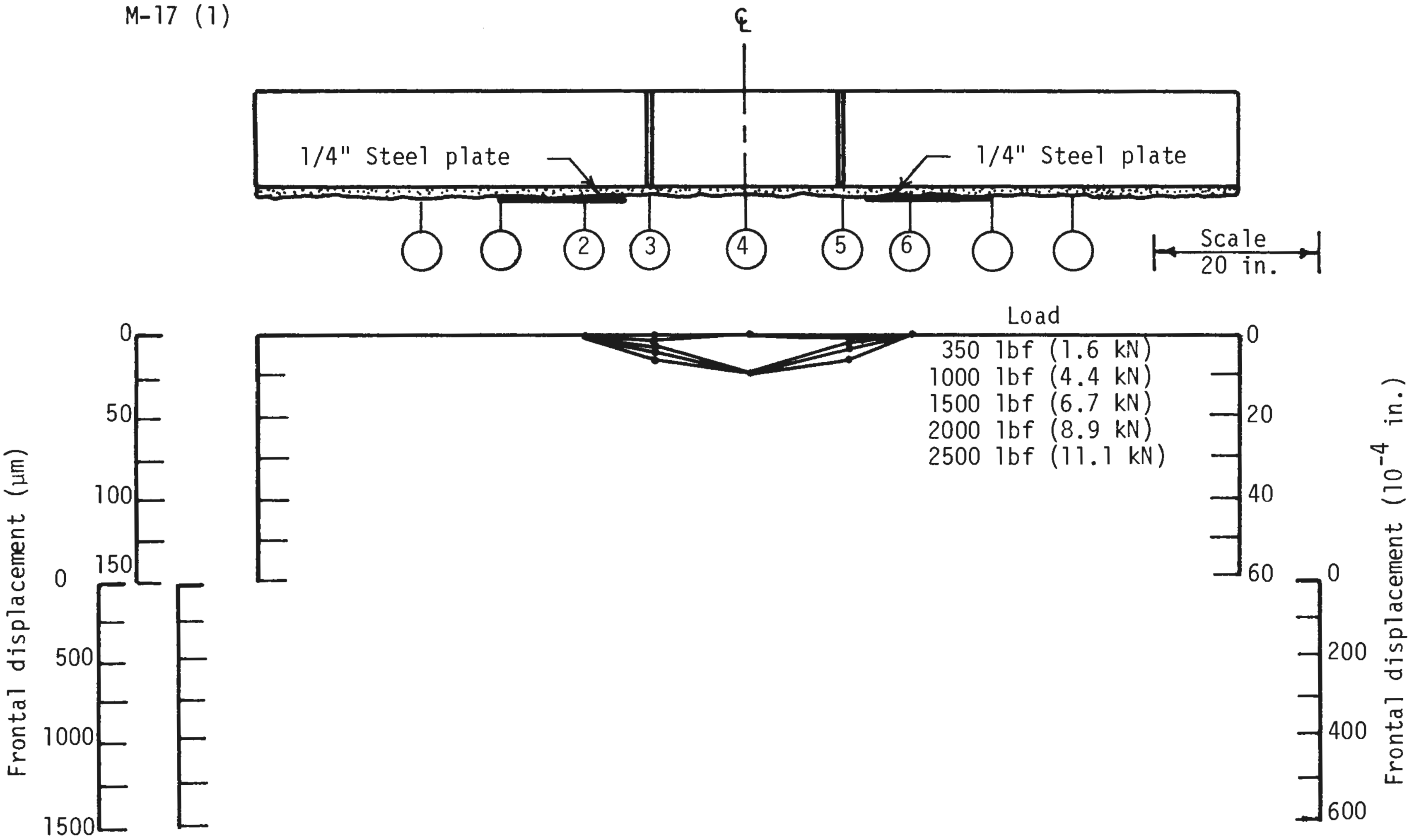


FIGURE 3.38 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

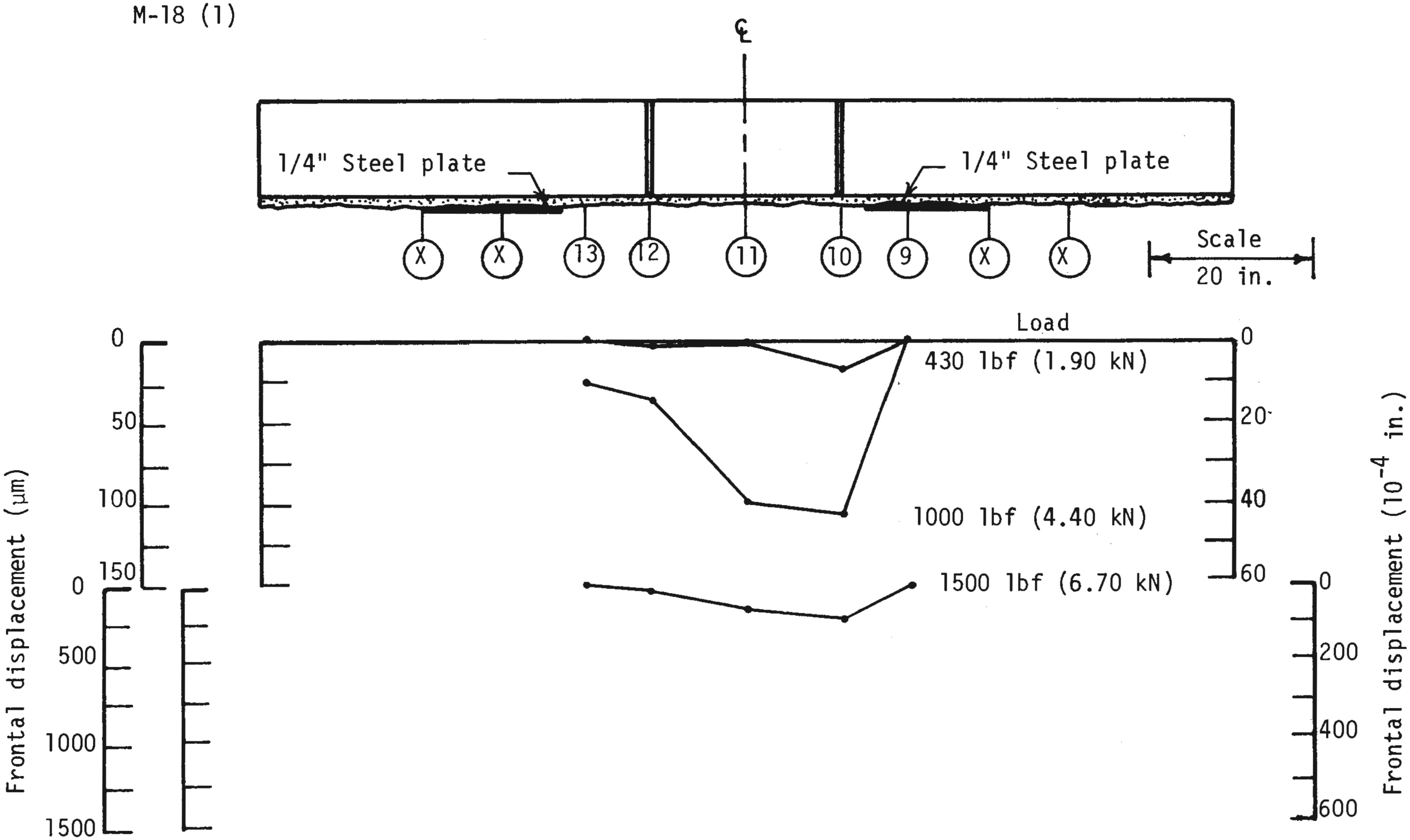


FIGURE 3.39 FRONT FACE DISPLACEMENT OF LAYER W.R.T. FLOOR

The post-failure displacements of the layers having a structural behavior similar to curve 2 in Fig. 3.14 are shown in Figs. 3.40 to 3.45.

The upper part of the figures show a schematic view looking down on the mortar layer and the covered fixed wall and movable blocks. The positions of the frontal dial gages monitoring the mortar layer displacements are also shown. The displacements recorded by each one of the dial gages at every load increment during the loading process are plotted in the figure, directly beneath the gage. A displacement profile of the front face of the mortar layer during the loading process was obtained by joining with a line the displacements measured in all the gages at the same load increment. The magnitude of the total load on the mortar layer at every load increment is shown at the right side of the displacement profile.

DISPLACEMENT PROFILE CHARACTERISTICS BEFORE INITIAL FAILURE

The characteristics of the displacement profile, before initial failure occurred, were very similar for all the tests. Initially, equal increments of load corresponded with equal increments of displacement of the front face of the mortar layer. There was an elastic relationship between the forward displacements of the mortar layer and the load in the jack.

The magnitude of the forward displacements was slightly greater along the vertical center line of the mortar layer, and decreased slightly away from the center line. The rate at which this value decreased with distance depended mainly on the stiffness of the contact between the mortar layer and the surface slabs on the fixed walls. It also depended on the

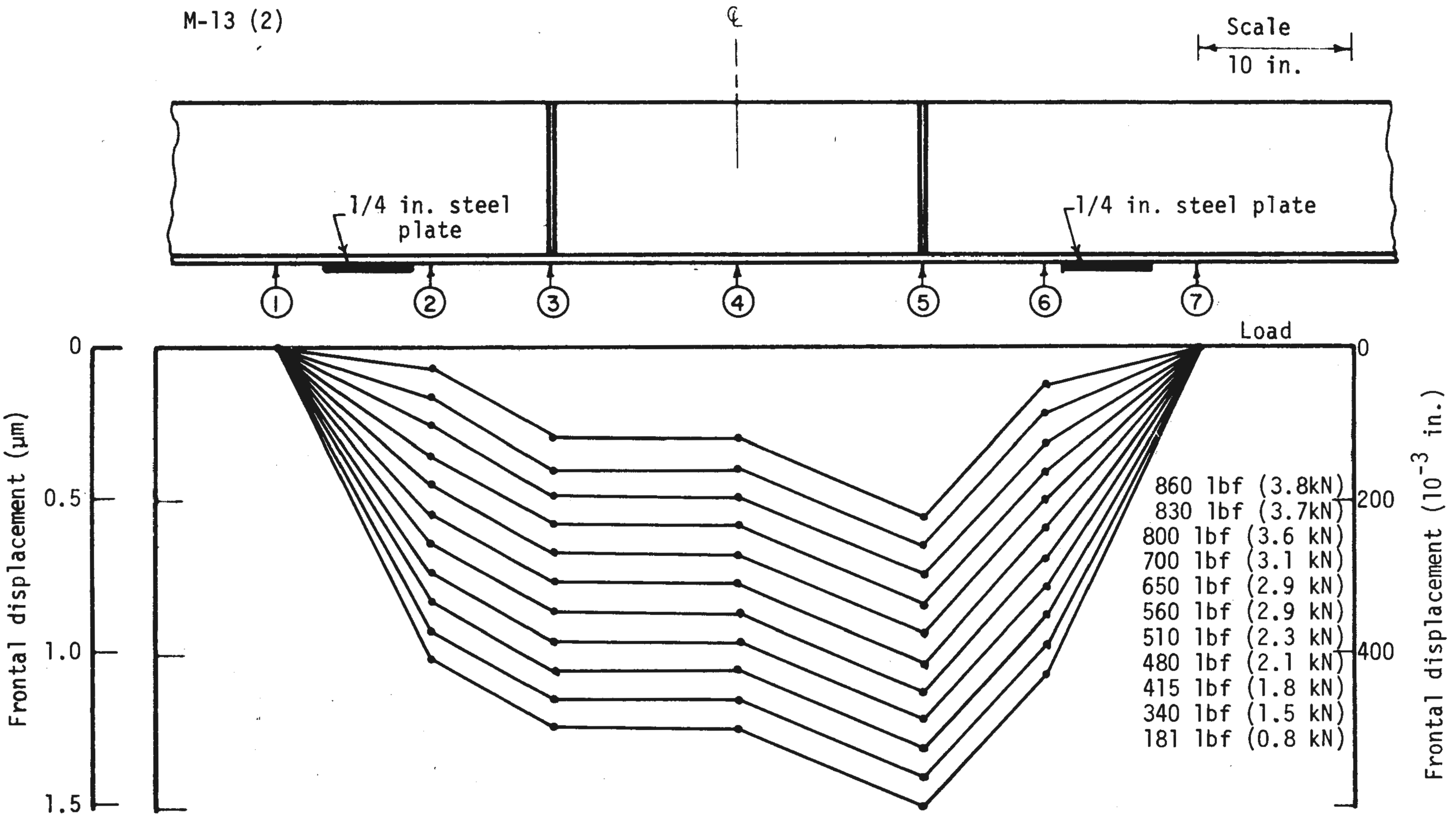


FIGURE 3.40 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

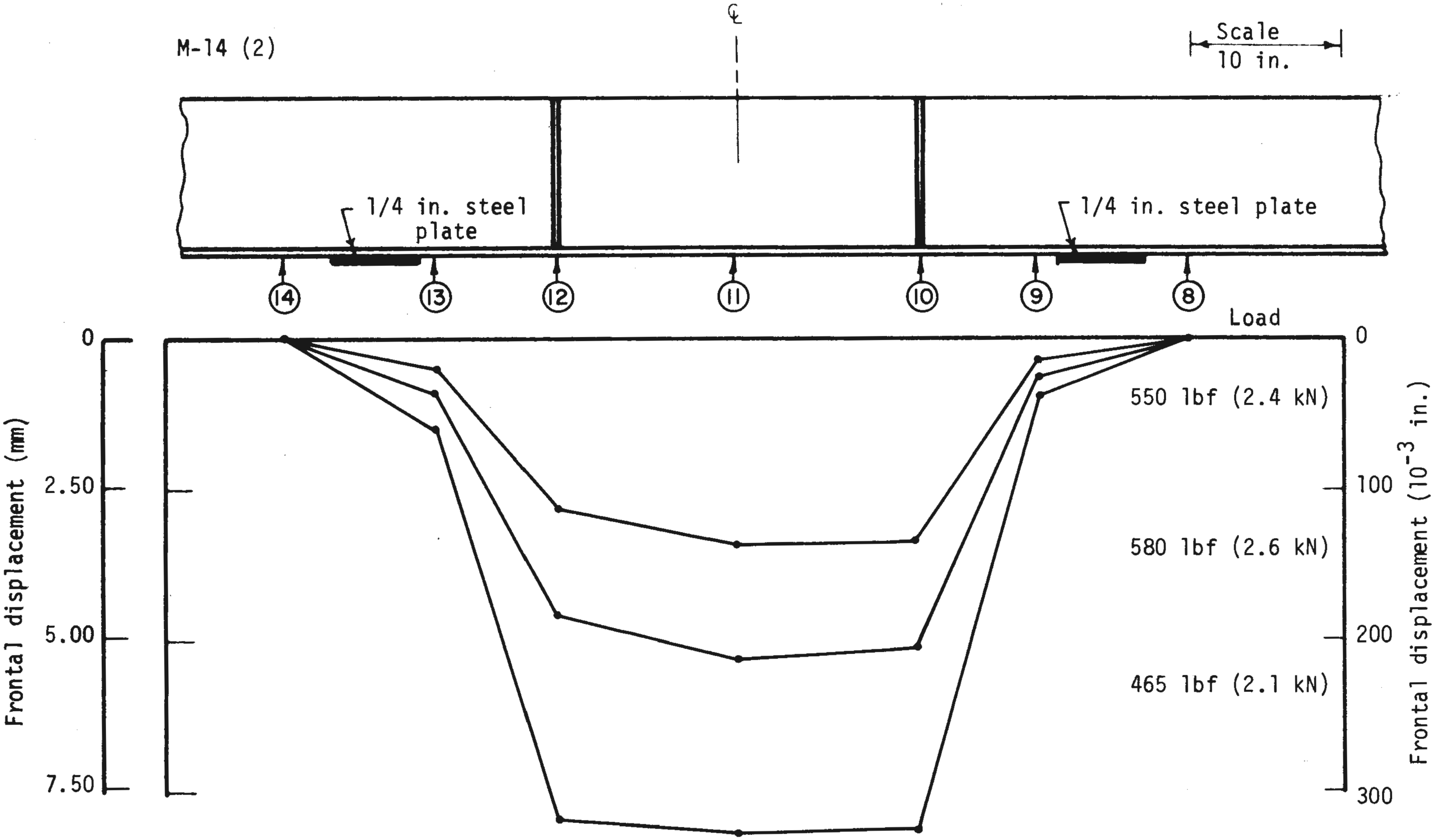


FIGURE 3.41 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

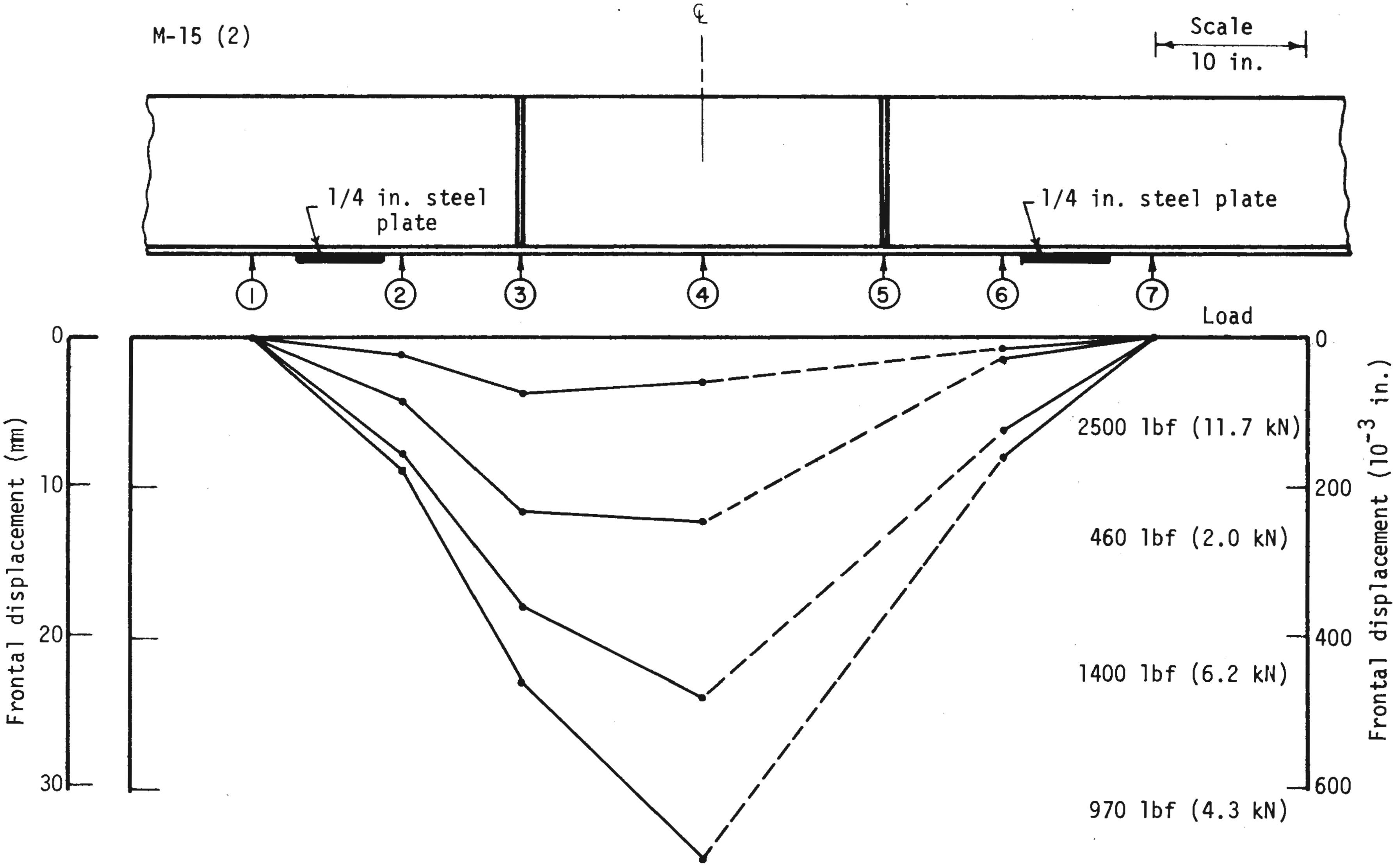


FIGURE 3.42 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

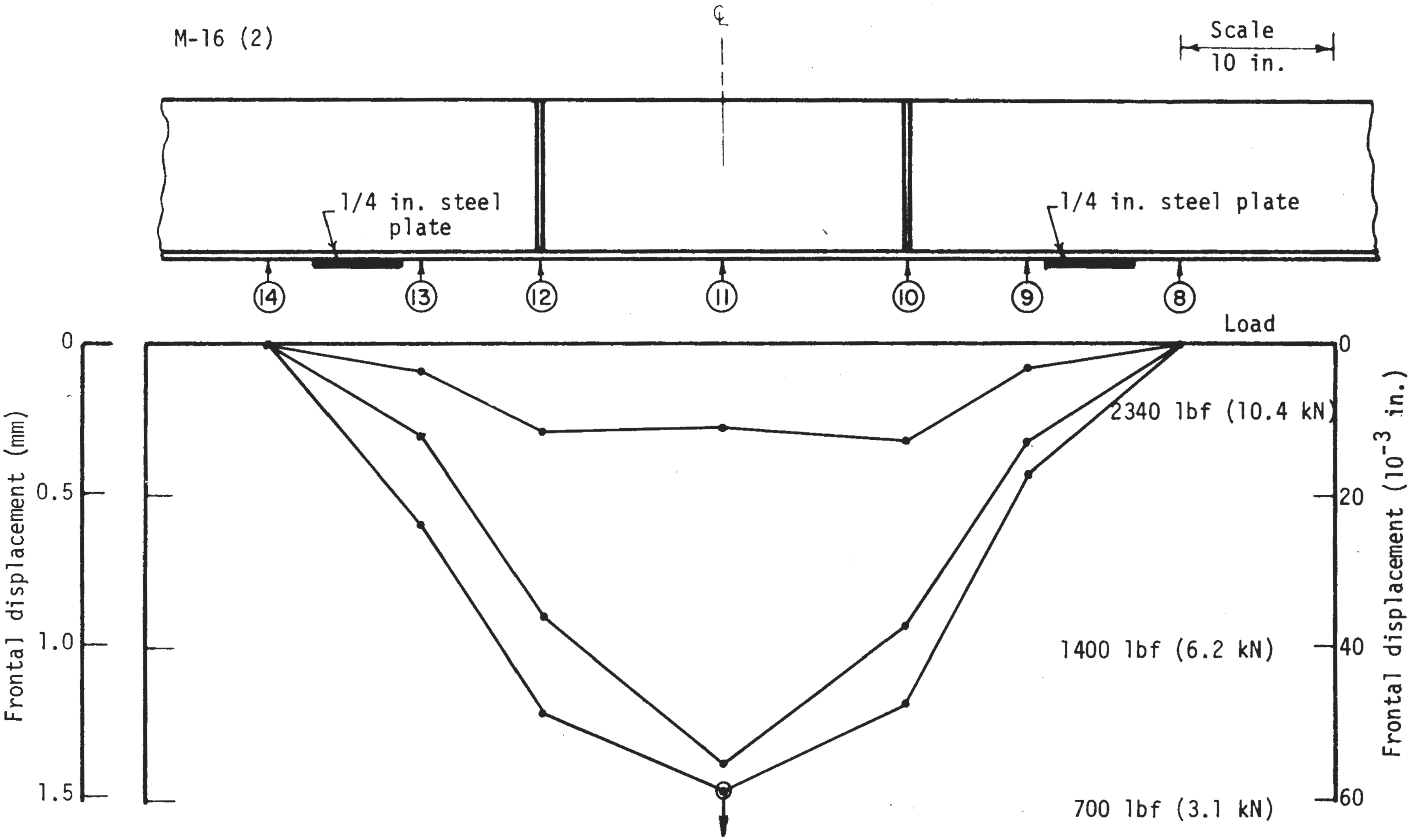


FIGURE 3.43 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

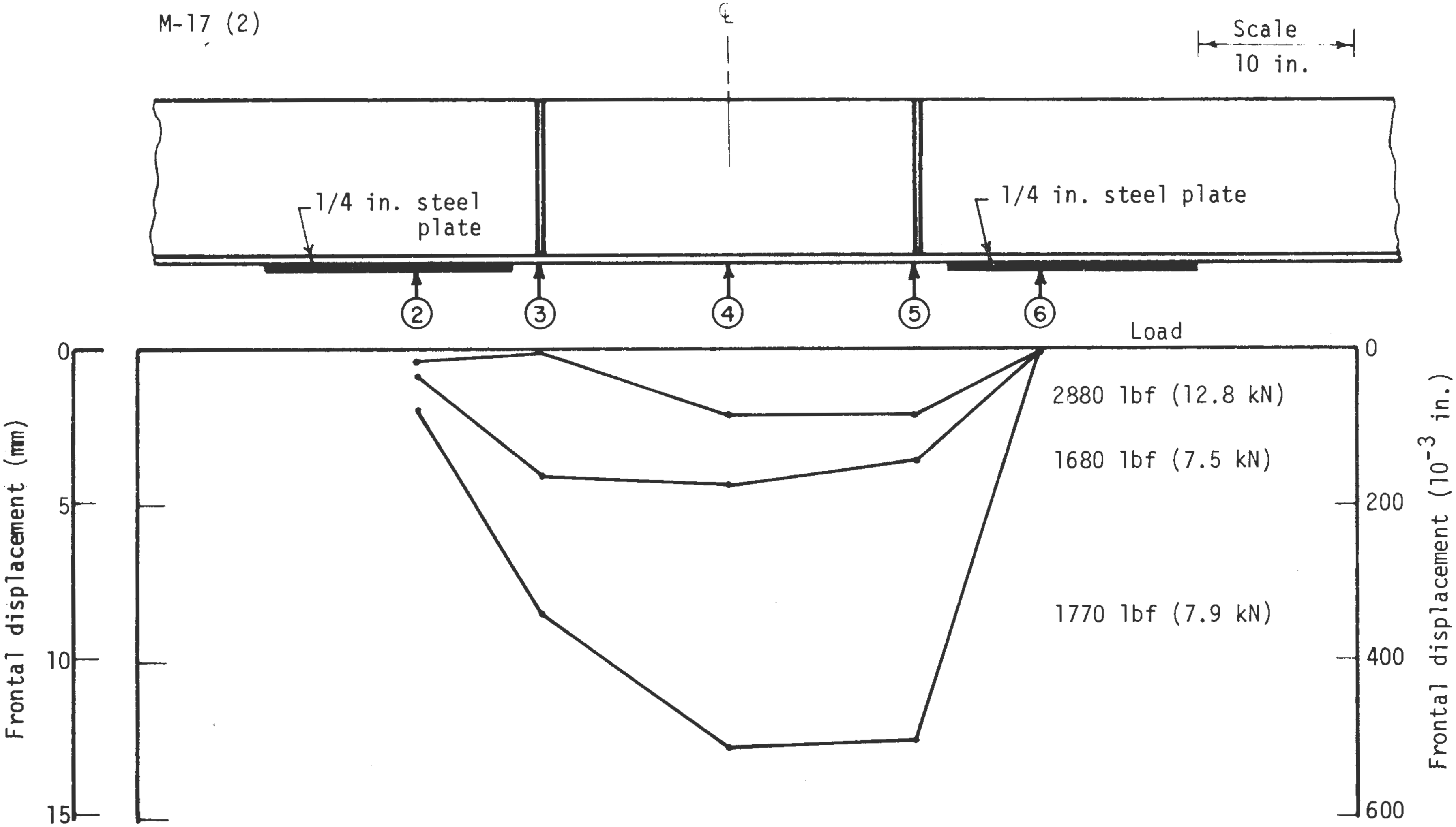


FIGURE 3.44 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

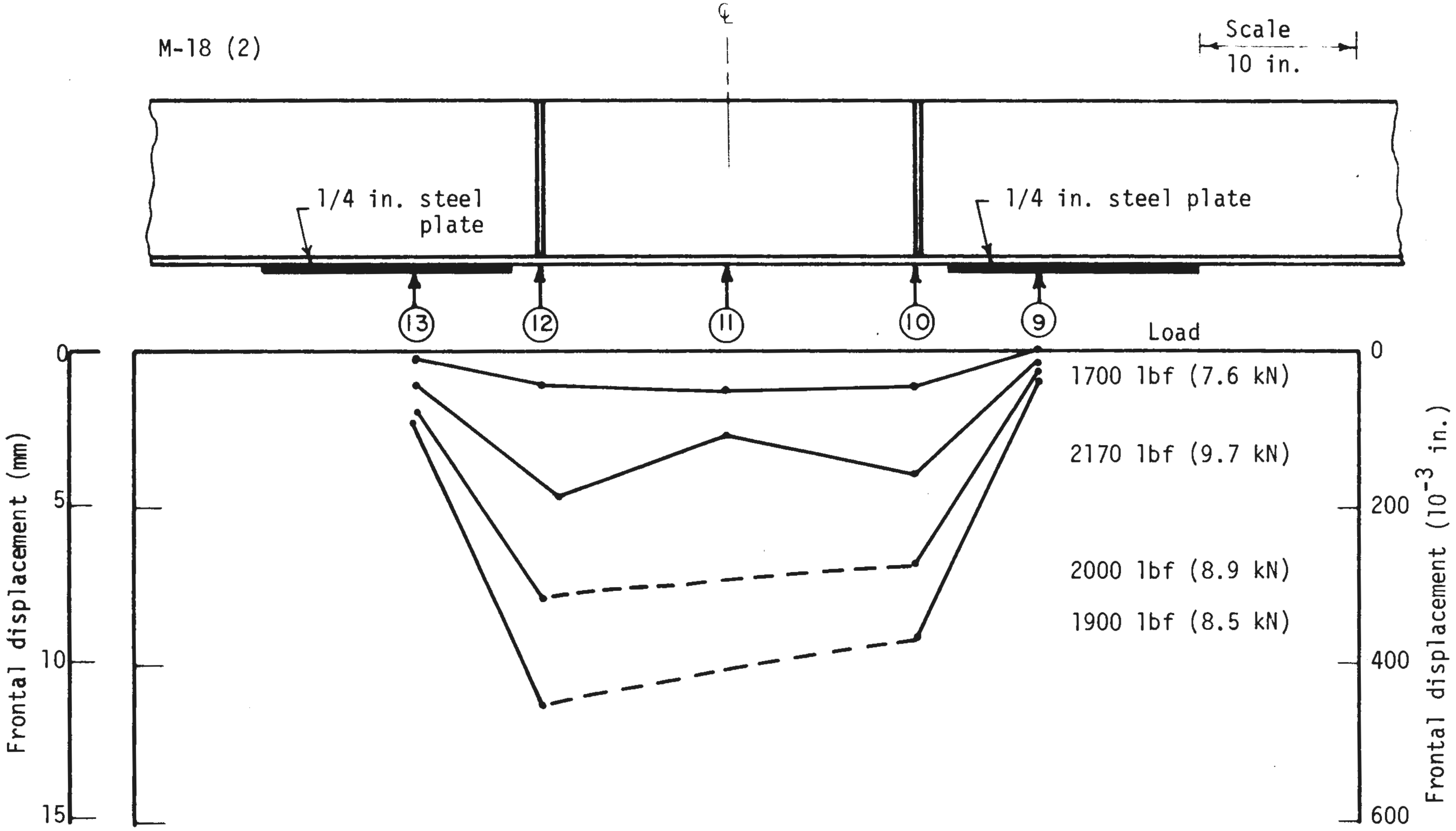


FIGURE 3.45 FRONT FACE DISPLACEMENT WITH RESPECT TO THE FLOOR

relative stiffness of the layer with respect to the movable block and on its length. For example, in test Nos. 4 and 7 which had relatively stiffer layers extending for smaller distances, 7 in. (17.8 cm) and 14 in. (35.6 cm) respectively, away from the movable block, the forward displacements along the layer were more uniform than in the other tests.

In some cases where mortar was present in the slot surrounding the movable block (test Nos. 1 and 2), the magnitude of the forward displacements of the mortar layer at failure was 3 to 4 times greater than the average value obtained in the other tests and the shape of the displacement profile was less pronounced.

DISPLACEMENT PROFILE CHARACTERISTICS AFTER FAILURE

The post-failure displacements of the mortar layers in which the structural behavior is represented by curve 1 in Fig. 3.14 occurred very rapidly and couldn't be measured. For mortar layers having load-deflections similar to curves 2 and 3 these displacements show a shape very similar to the deflection curve obtained for a simply supported beam with a centered uniformly distributed load. The forward displacements of the layer have a maximum value along the section covering the movable block and gradually reduce to zero at the points where the steel plates were located, except in test Nos. 11 and 12 where the adhesion failure propagated beyond the plates.

The rate of decrease in these displacements away from the movable block depends mainly on the stiffness of the layer and the distance between the steel plates. As expected, the post-failure displacements for the mortar layers which are represented by curve 3 in Fig. 3.14, test No. 17, are similar to those obtained in the other tests. For all tests, the general pattern and the values of the forward displacements of the mortar layers before and after failure, corresponds very closely to the structural behaviors described in the preceding section.

3.5.4 STRAINS INDUCED IN THE MORTAR LAYER DURING THE LOADING PROCESS

Whittemore Points were placed on the outside surface of the mortar layer to monitor longitudinal strains during the loading process. Figures 3.46 to 3.53 show a top view of the fixed walls, the movable block, the mortar layer and the position of the Whittemore Points. The direction of the strains along the mortar layer surface during the loading process, determined by the relative displacement of the Whittemore Points with respect to each other, is shown in the lower part of the figure. In most of the tests a zone of tensile strain was created in the outside surface of the mortary layer covering the movable block and its surroundings. Compression strains were observed in zones away from the movable block.

This state of strain in the outside surface of the mortar layer corresponds exactly with the state of strain that should develop to fit the structural behavior (profile displacements) described in previous sections. In some cases compressive strains were measured along the full length of the mortar layer (test Nos. 11 and 17) while on others both compressive and tensile strains occurred on the mortar covering the movable block (test Nos. 9 and 13). These differences in strain distribution resulted from large distances between adjacent Whittemore Points. The Whittemore Points were located in such a way that part of the mortar layer surface between them was

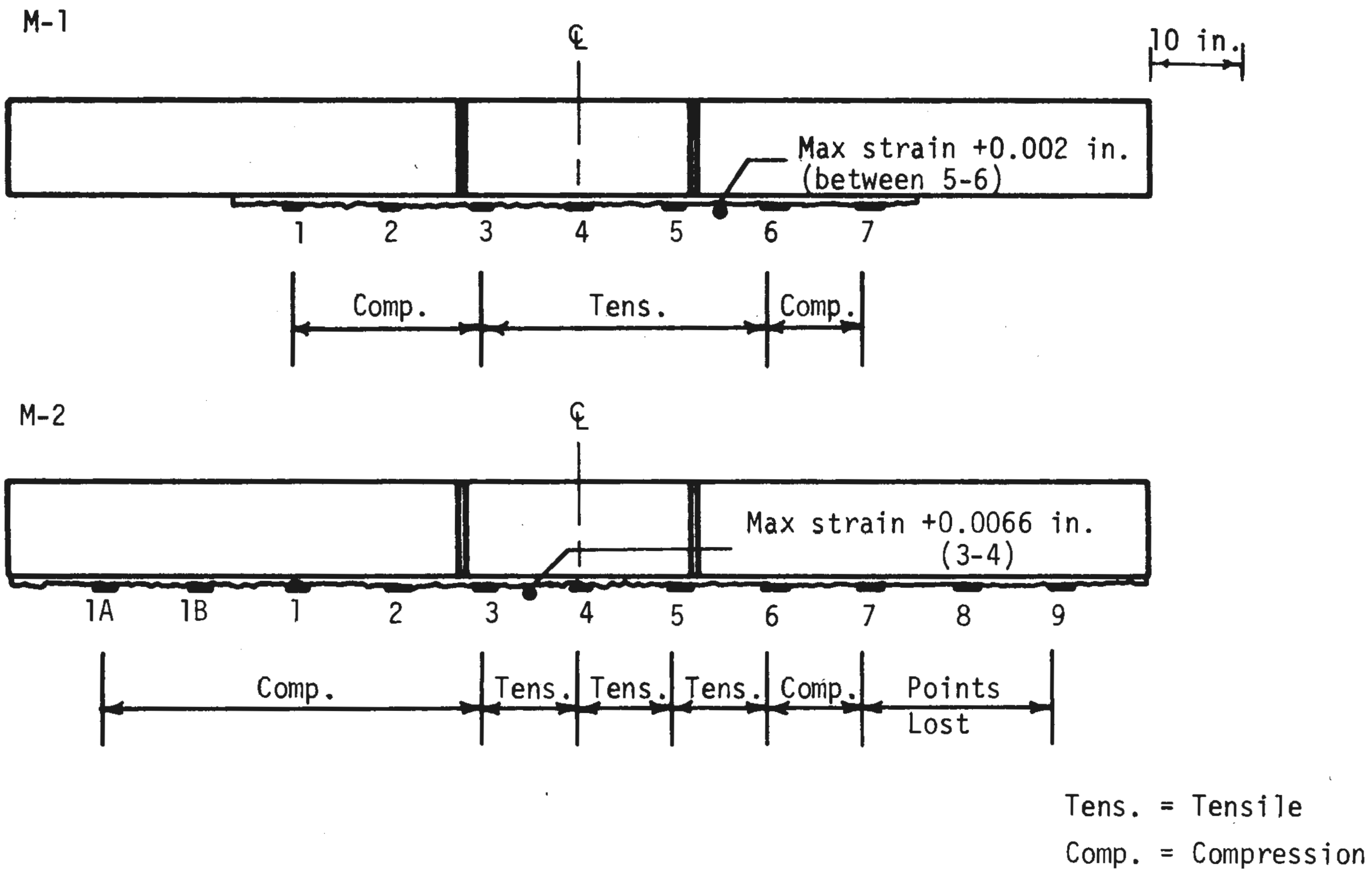
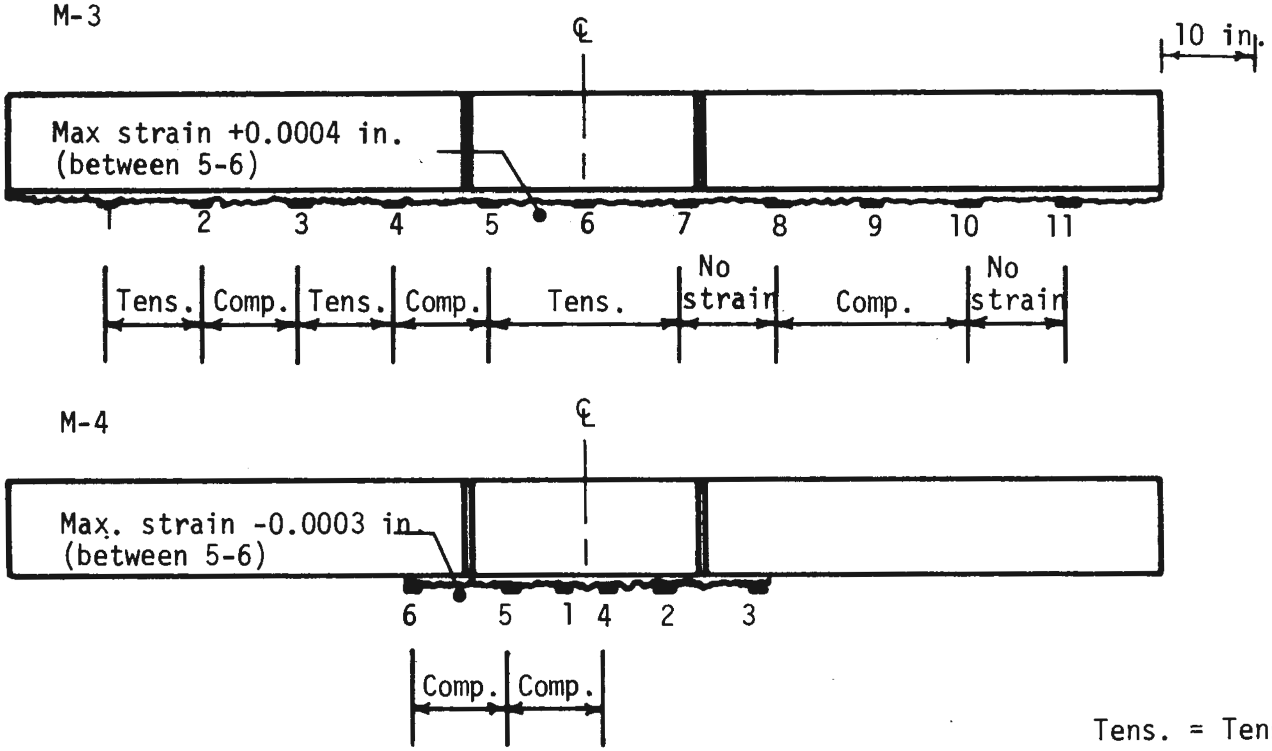


FIGURE 3.46 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER



Tens. = Tensile

Comp. = Compression

FIGURE 3.47 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

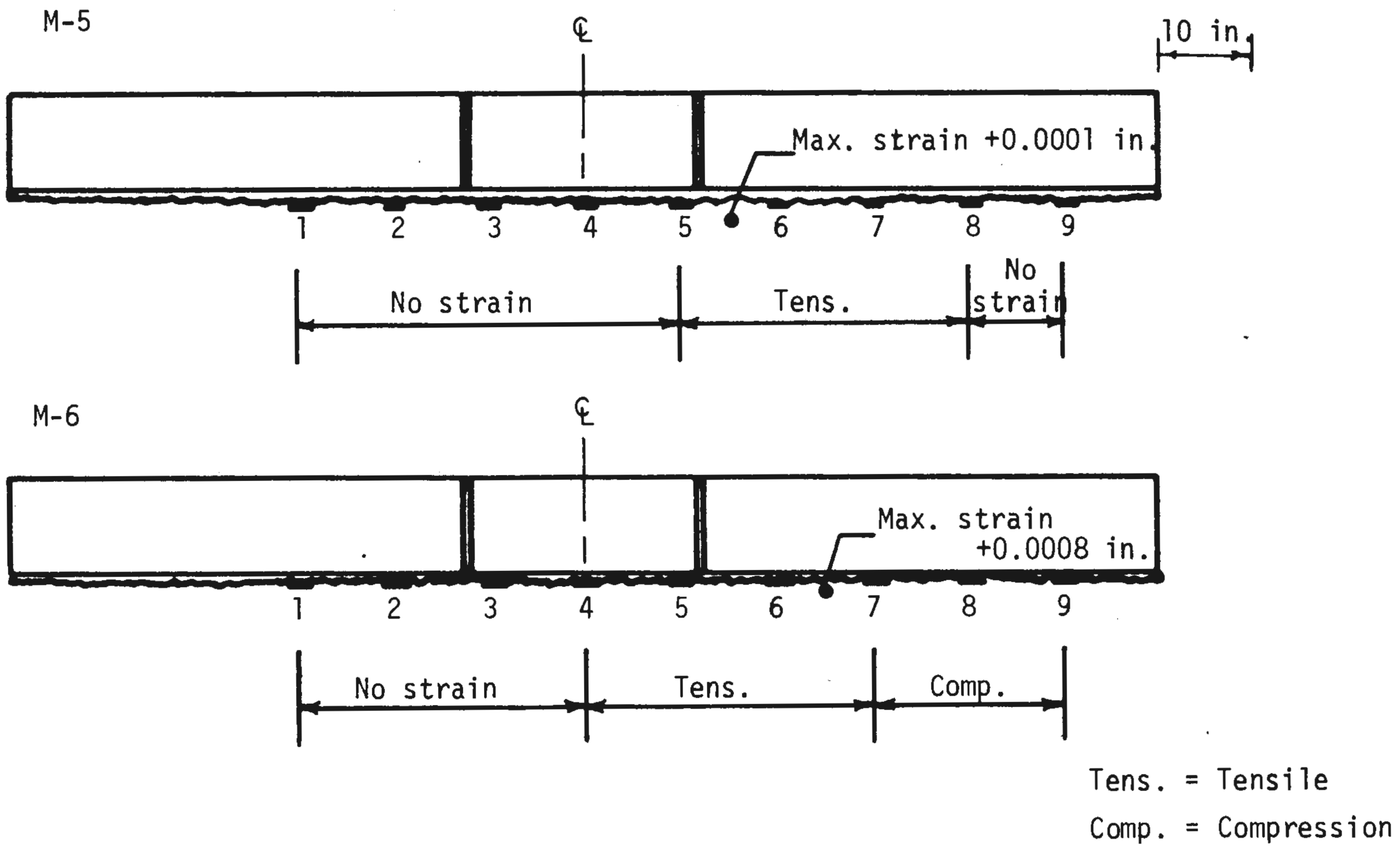


FIGURE 3.48 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

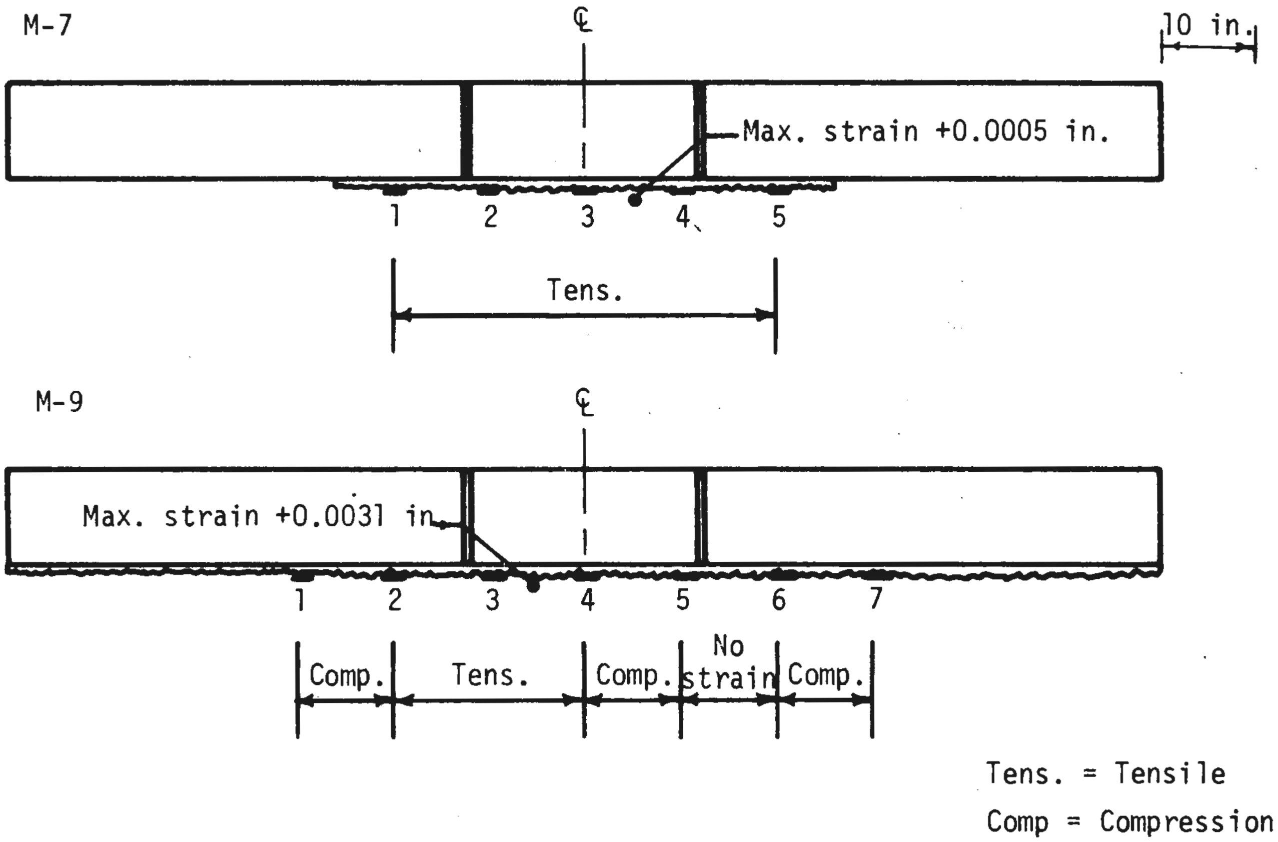


FIGURE 3.49 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

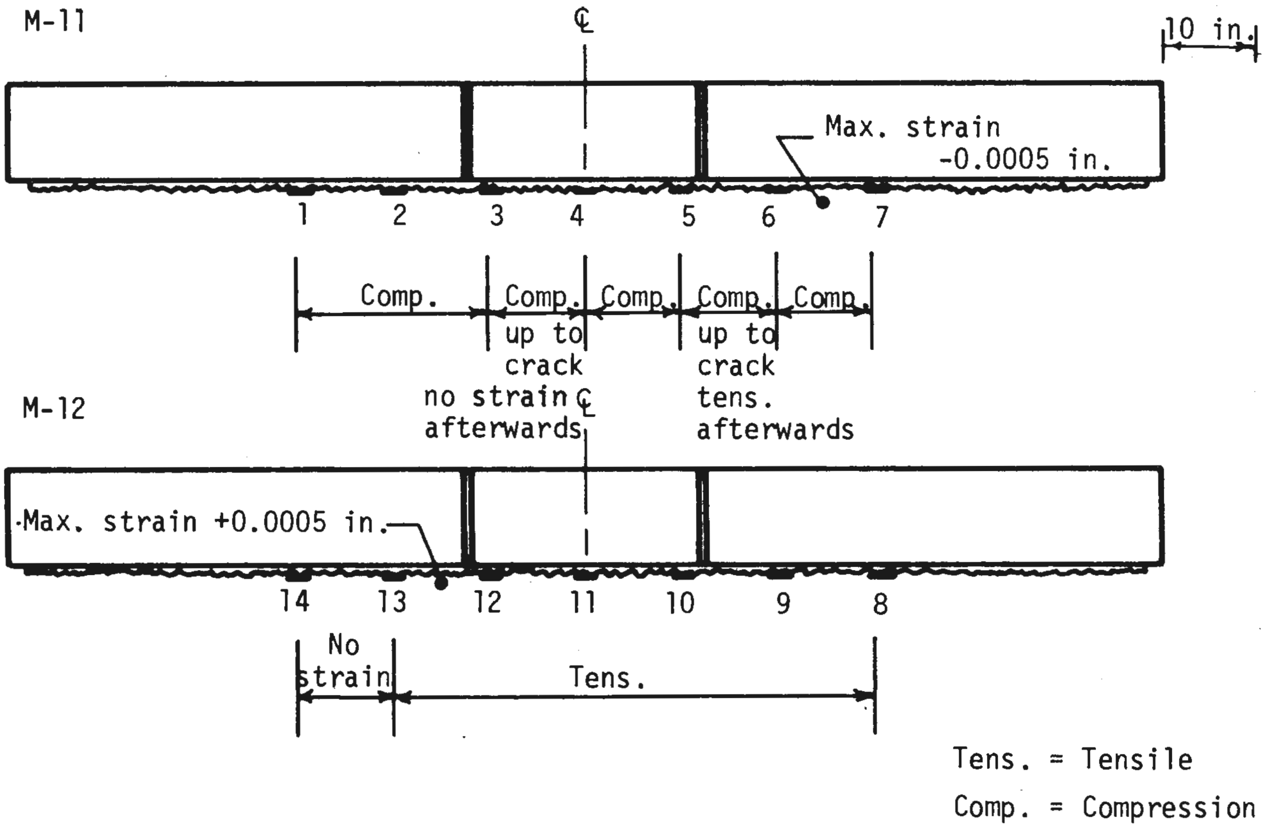


FIGURE 3.50 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

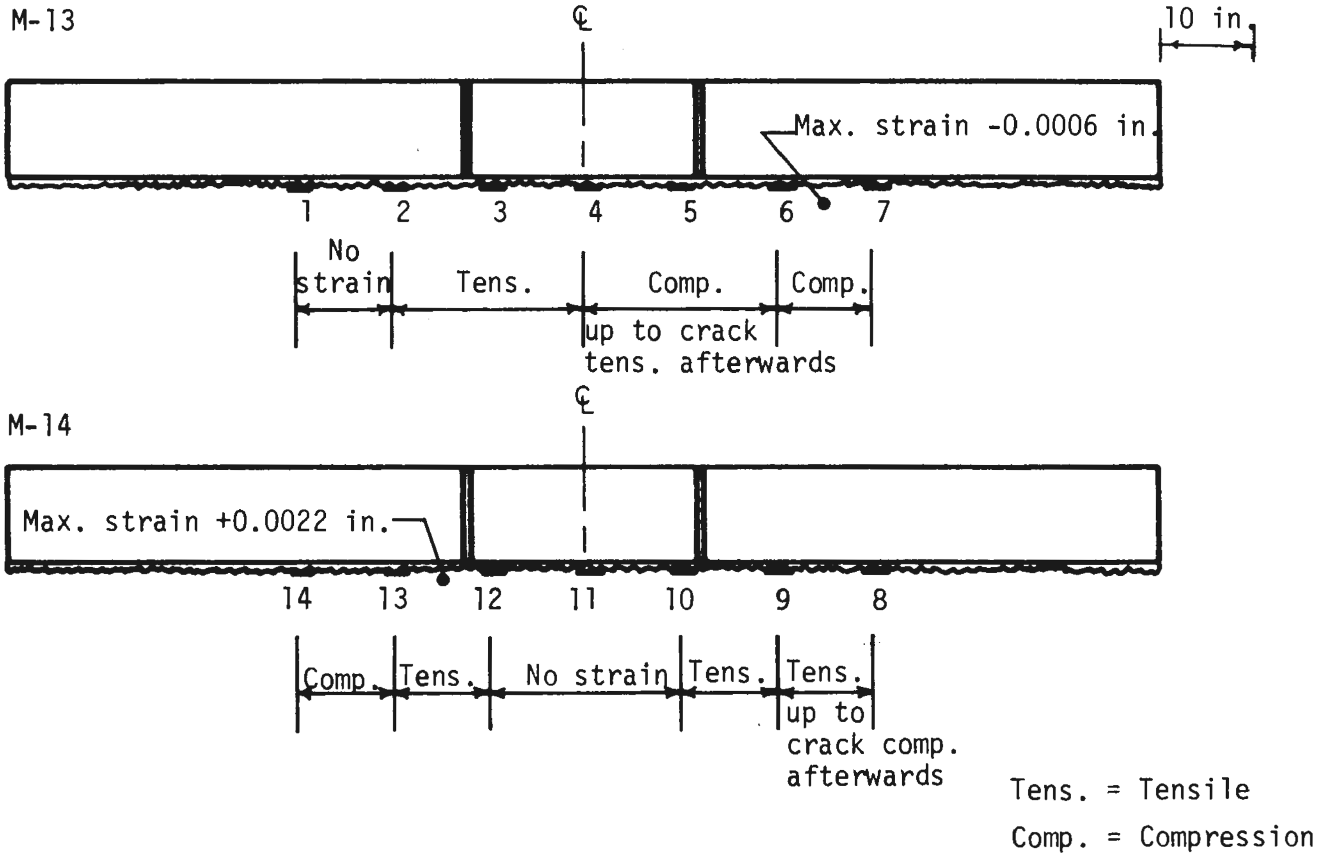


FIGURE 3.51 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

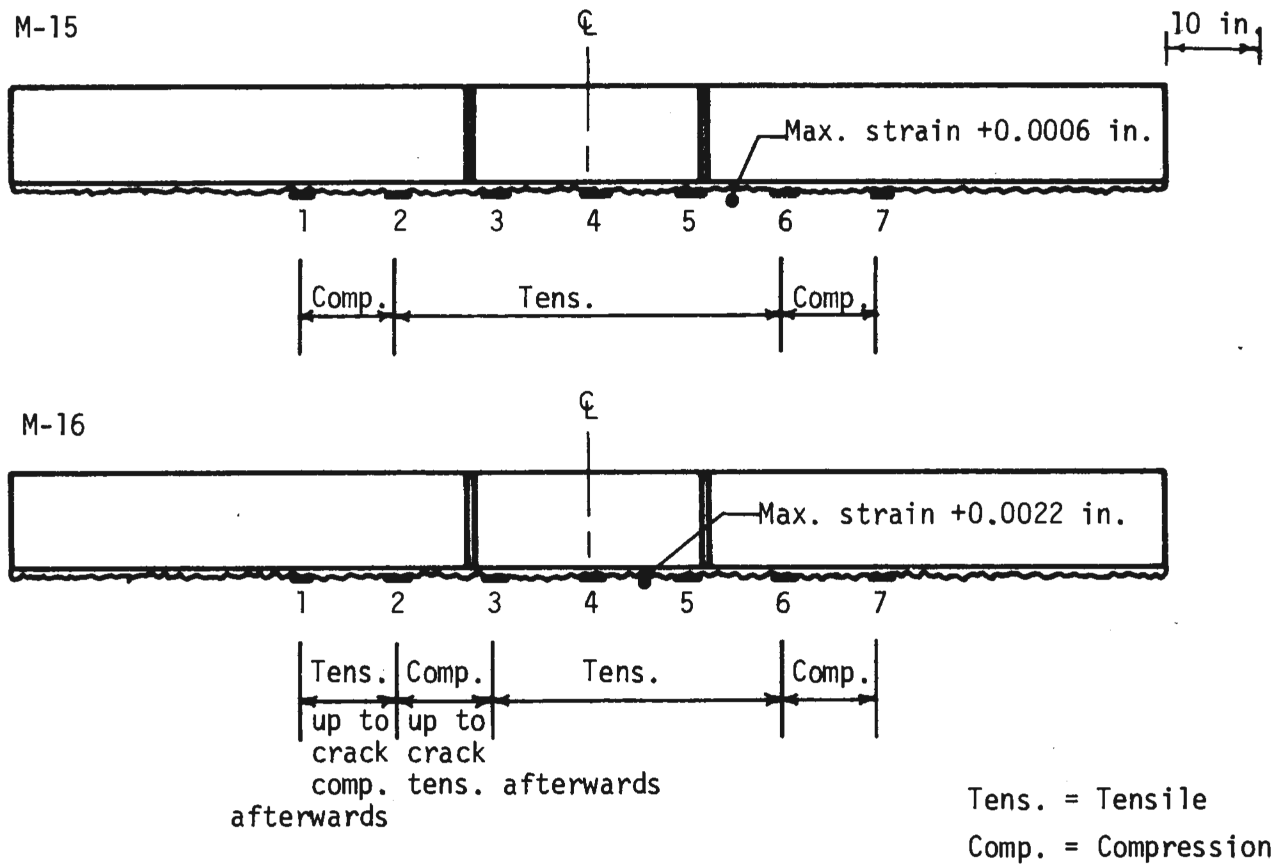


FIGURE 3.52 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTENSOMETER

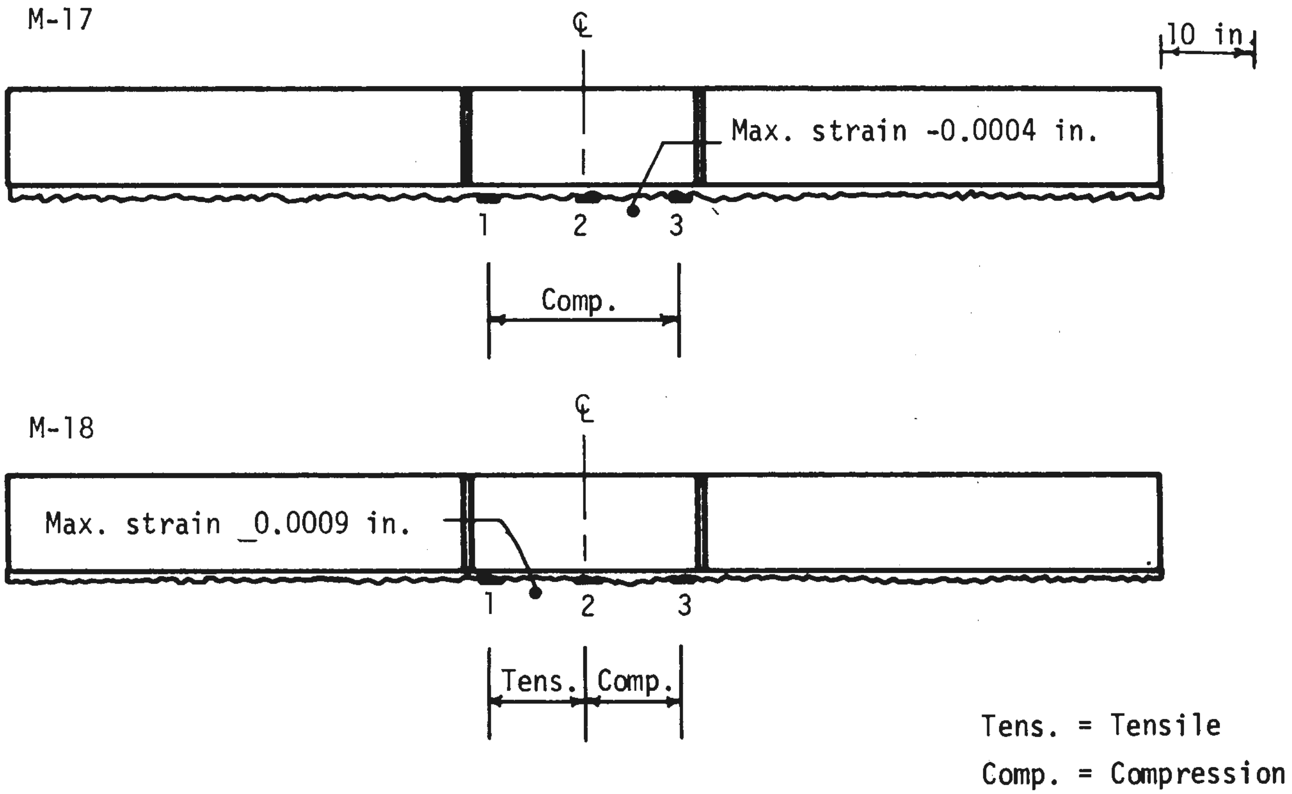


FIGURE 3.53 STRAIN DISTRIBUTION ON FRONT FACE OF THE MORTAR LAYER MEASURED BY WHITTEMORE EXTNESOMETER

subjected to compressive strains while the rest was under tensile strains, so that the relative displacement measured between the two points was the resultant of the two opposite strains. Reducing the distance between adjacent Whittemore Points would lead to a more realistic measurement of the distribution of strains in the surface of the layer.

3.6 SIGNIFICANCE OF VARIABLES

Each one of the 18 performed tests was planned in order to show the importance of a particular variable in controlling the structural behavior of the layer. During a pair of tests all variables, except one, were kept as constant as possible. Table 3.5 indicates which tests were used to compare the effects of each chosen variable. The table contains eighteen rows and columns corresponding to a specific test. The variable studied is shown in the table at the location given by the tests carried out for its comparison. For example, test Nos. 1 and 2 were carried out to determine the influence of the length of the mortar layer relative to the edge of the movable block on its structural behavior.

The importance of each variable will be discussed based on its effect in controlling the maximum and residual resistances of the mortar layer. The structural test results are discussed as follows.

3.6.1 LATERAL BOUNDARY CONDITIONS OF THE LAYER

A great number of tests (Nos. 1, 2, 4, 7, 11, 12, 17 and 18) were performed to establish the importance of this variable. The analysis and discussion of the results were divided into groups according to the

TABLE 3.5

VARIABLES COMPARED BETWEEN TESTS

Test no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1																		
2	L																	
3																		
4																		
5				L														
6				L														
7			M	L														
8							Lo											
9			M		M	M	M											
10									Lo									
11							S-8											
12							S-8											
13											S	S						
14											S	S						
15											Re	Re						
16											Re	Re						
17											S-4	S-4						
18											S-4	S-4						

LEGEND:
S = Surface conditions
Re = Reinforcement
L = Length of the mortar layer relative to the edge of the movable block.
Lo = Load rate
S-8 = Steel plates 8' apart
S-4 = Steel plates 4' apart
M = Mortar strength

structural behavior of the layers described in Section 3.6. The difference between these structural behaviors was dependent on whether or not steel plates were used as boundaries of the mortar layer.

Figure 3.54 shows the resistance-displacement relationship for test Nos. 1, 2, 4 and 7 in which the layer exhibited a structural behavior corresponding to the type 1 curve in Fig. 3.14. The slight deviation from this pattern shown by test Nos. 1 and 2 was caused by presence of mortar in the slots between the surface slabs. The higher value of the maximum layer resistance per unit length of contact, 105 lbs/in. (19 kn/m) was obtained in test No. 7 for a mortar layer extending 14 in. (35.5 cm) away from the movable block. A similar value (61 lbs/in.) was obtained on test Nos. 1 and 2 where the edge of the mortar layer was located 24 in. (61 cm) and 48 in. (122 cm) away from the movable block, respectively. The lower value of the maximum resistance was obtained in test No. 4 in which the mortar layer extended only 7 in. (17.8 cm) away from the movable block.

It could be concluded from these tests that in the absence of boundaries the length of the mortar layer beyond the movable block only affects the maximum resistance of the layer. In addition, the length of the mortar layer beyond a certain distance, between 7 in. (17.8 cm) and 14 in. (35.5 cm) for these cases, did not have any influence on the structural behavior nor support capacity of the layer. The relatively small magnitude of this limiting distance indicates that the distribution of adhesive stress between the mortar layer and the surface slab, is restricted to relatively narrow bands on each side of the movable block. However, the actual width of these bands does not necessarily range between 7 and

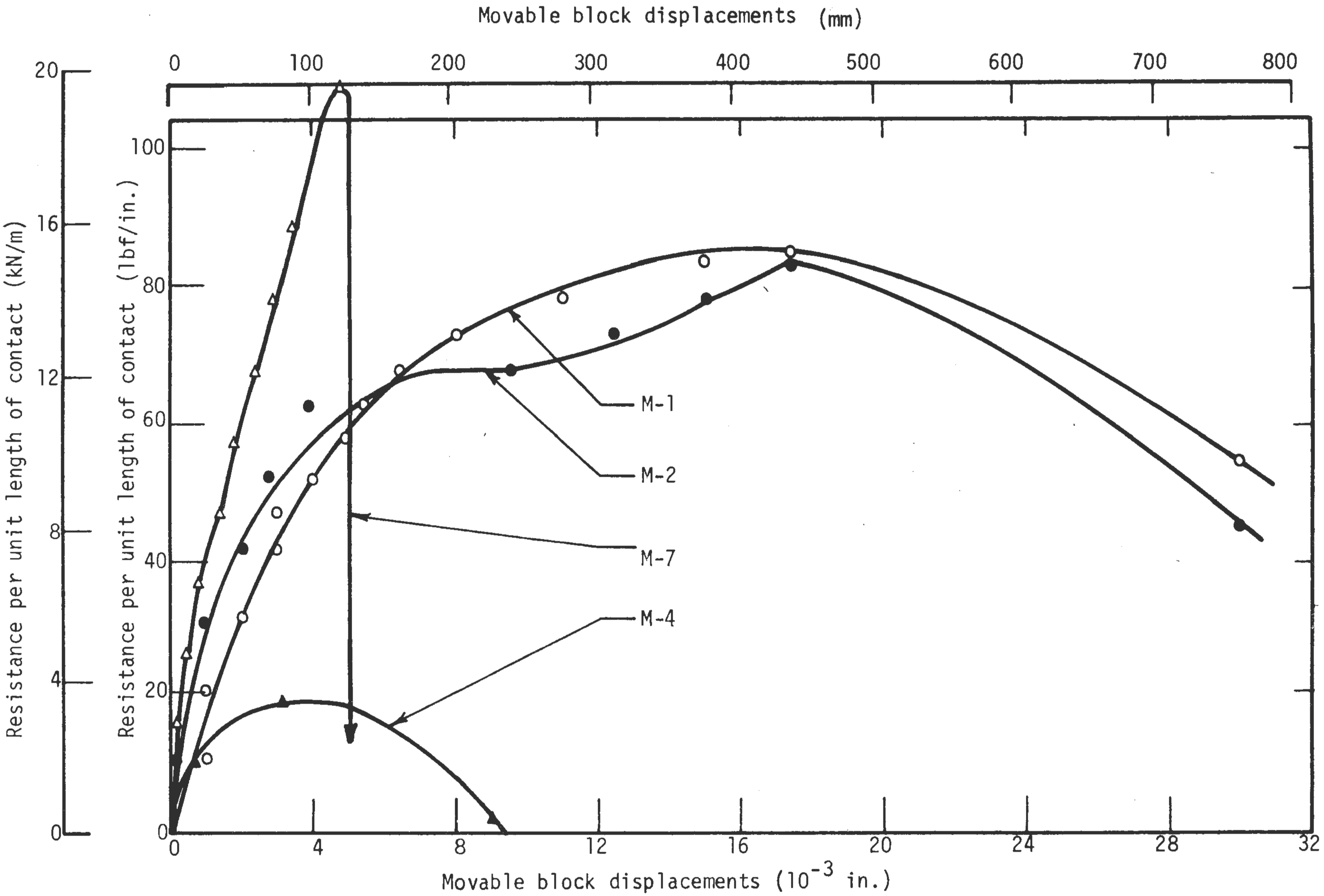


FIGURE 3.54 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

14 in., as suggested by the above test results, since independent tests indicate that the lower value obtained in test 4 may have been caused by shrinkage rather than by limiting the actual length over which adhesion could be developed. Thus the actual length over which the adhesion stress is distributed may be less than 7 in. (17.8 cm).

The resistance-displacement relationships for test Nos. 11, 12, 17 and 18 are shown in Fig. 3.55. Three of the tests, Nos. 11, 12 and 17. have a similar structural behavior corresponding to the type 2 curve in Fig. 3.14. In the other test the layer behavior is similar to that exhibited by the type 3 curve. The maximum resistance of the layer for test Nos. 11, 12 and 17 varied between 30 lbs/in. (5.5 kN/m) and 60 lbs/in. (11 kN/m) and was independent of the relative position of the steel plates with respect to the movable block.

The location of the steel plates closer to the movable block in test No. 17 increased the level of the residual resistance of this mortar layer to twice the value obtained in test Nos. 11 and 12. In addition, this residual resistance was maintained for displacements approximately twice those shown in test Nos. 11 and 12, giving more ductility to the layer.

The mortar layer in test No. 18 had a resistance in bending that was greater than the resistance in adhesion. The high resistance of the layer when behaving as a beam is attributed to the location of the steel plates in close proximity to the movable block.

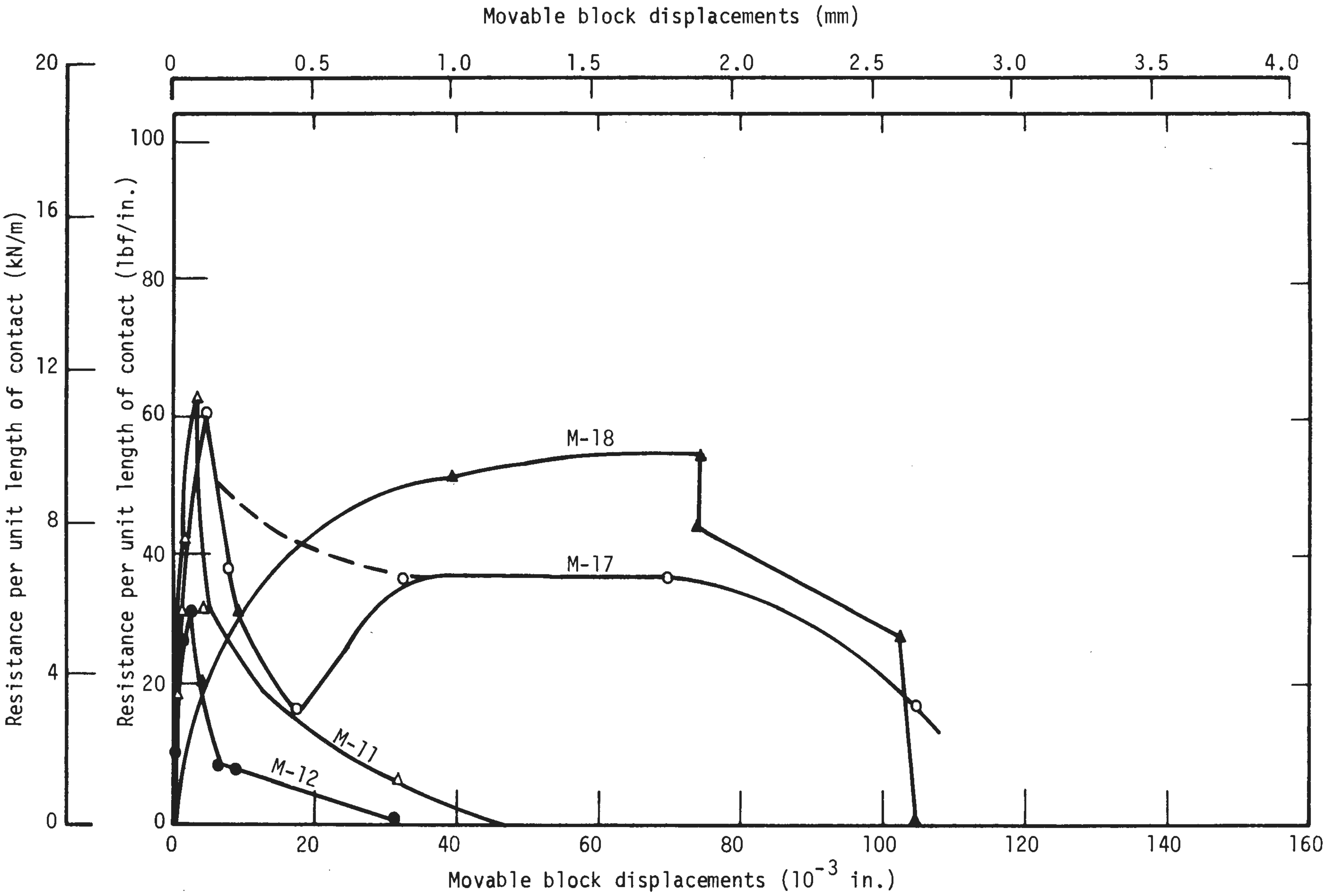


FIGURE 3.55 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

3.6.2 SLABS SURFACE CHARACTERISTICS

Test Nos. 13 and 14 were performed with mortar layers similar to the ones used in test Nos. 11 and 12 except that in test Nos. 13 and 14 filament tape was used to reduce the adhesive strength between the mortar and the surface slabs along 6-in. (15.2-cm) vertical bands on either side of and adjacent to the movable block.

The resistance-displacement relationships for tests Nos. 11, 12, 13 and 14 are shown in Fig. 3.56. All tests showed a similar structural behavior corresponding to the type 2 curve in Fig. 3.14.

The mortar layers in test Nos. 13 and 14 had approximately the same value, 22 lbs/in. (4 kN/m), of maximum resistance. Higher values of the maximum layer resistance, 30 to 60 lbs/in. (7 to 11 kN/m), were obtained in test Nos. 11 and 12. No differences were observed in the level of the residual resistance of the layers, but shorter displacements of the movable block were required to reduce completely the residual resistance of layers 11 and 12.

As indicated in these tests a direct relationship exists between the adhesive strength acting along the mortar layer-surface slab contact and the value of the maximum resistance of the layer. The variation of this adhesive strength does not show any influence on the residual resistance value. The higher rate of reduction for the residual resistance with respect to the movable block displacements, was caused by the poor constraint offered by the steel plates in test Nos. 11 and 12.

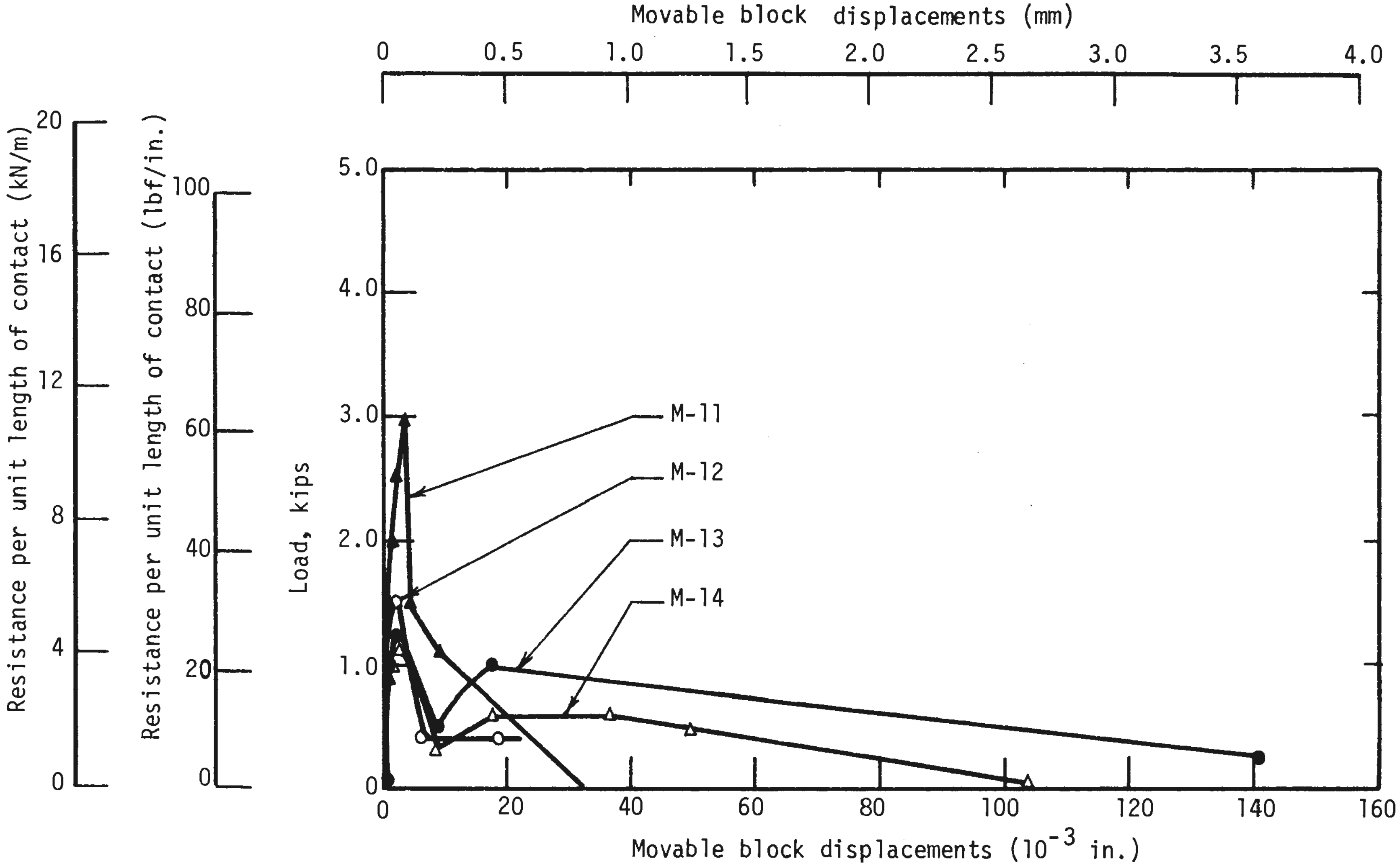


FIGURE 3.56 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

3.6.3 MORTAR STRENGTH

The mortar strength of the layers used in test Nos. 3, 7 and 9 was successively reduced, see Table 3.3, by decreasing the time of curing.

As seen in Fig. 3.57, the resistance-displacement relationships for these tests are similar to that shown by type 1 curve in Fig. 3.14.

The highest value of the maximum unit resistance was obtained in test No. 7 and decreased successively for test Nos. 3 and 9. These results indicate that the strength of the mortar in the layer directly affects its maximum unit resistance. This is expected since the adhesive strength of the mortar layer depends in part on the time of curing.

3.6.4 USE OF REINFORCEMENT (IN THE MORTAR LAYER)

Test Nos. 11, 12, 15 and 16 were performed in order to determine the effect of mesh reinforcement on the structural behavior of the layer.

As seen in Fig. 3.58 the structural behavior of the layers in these tests is similar to that shown by the type 2 curve in Fig. 3.14. The maximum unit resistance is very close for test Nos. 11, 15 and 16 and has an average value of 50 lbs/ft (9 kN/m). The lowest value of this resistance, in test No. 12, was probably caused by pre-test cracking of the mortar layer. The tests indicate that there is no significant difference in maximum resistance of mortar layers with or without reinforcement.

A considerable difference exists, however, in the residual resistance of the reinforced and non-reinforced mortar layers. The reinforced layers exhibit higher residual resistance and lower rates of reduction of this resistance with displacement of the movable block. The reinforcement

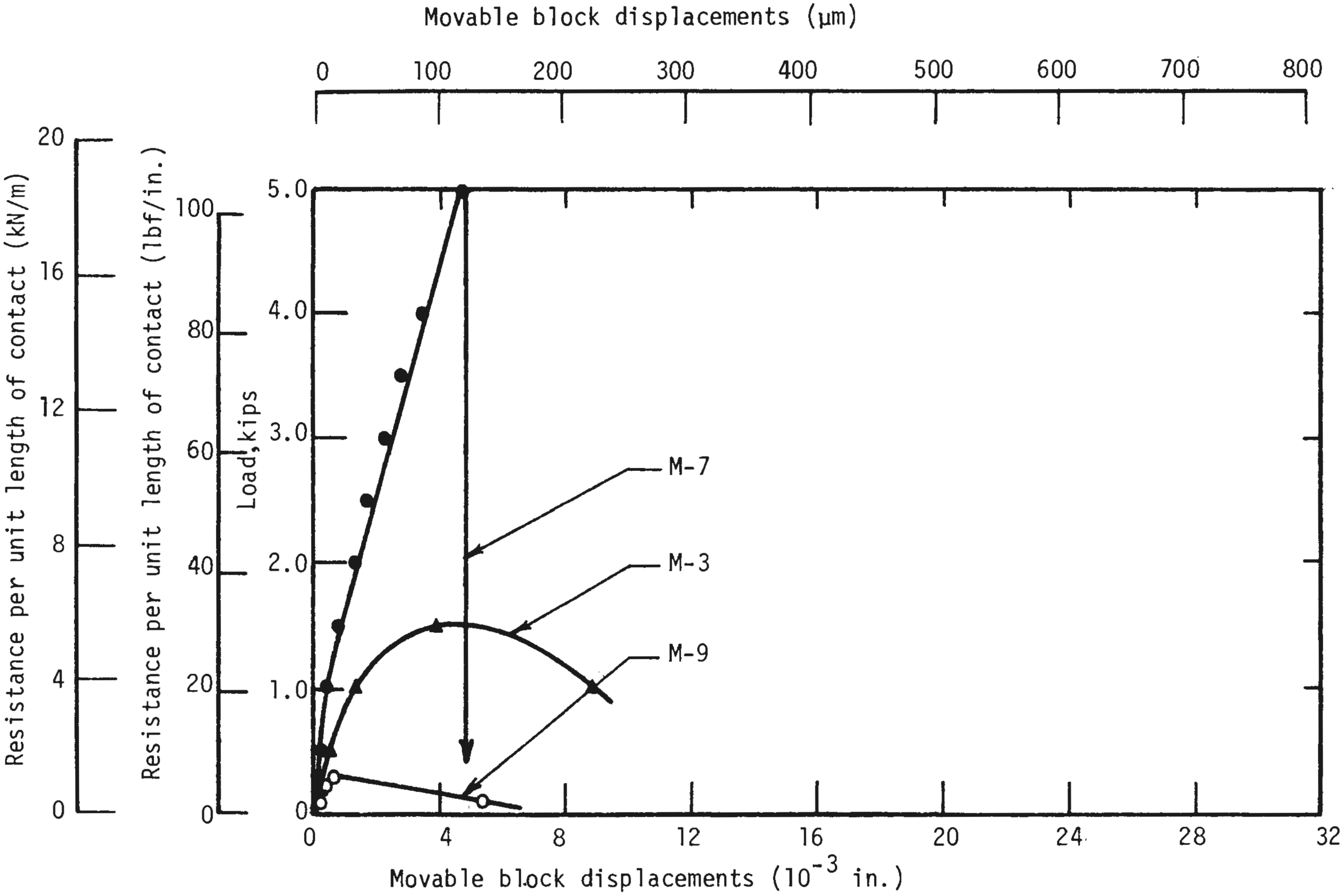


FIGURE 3.57 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

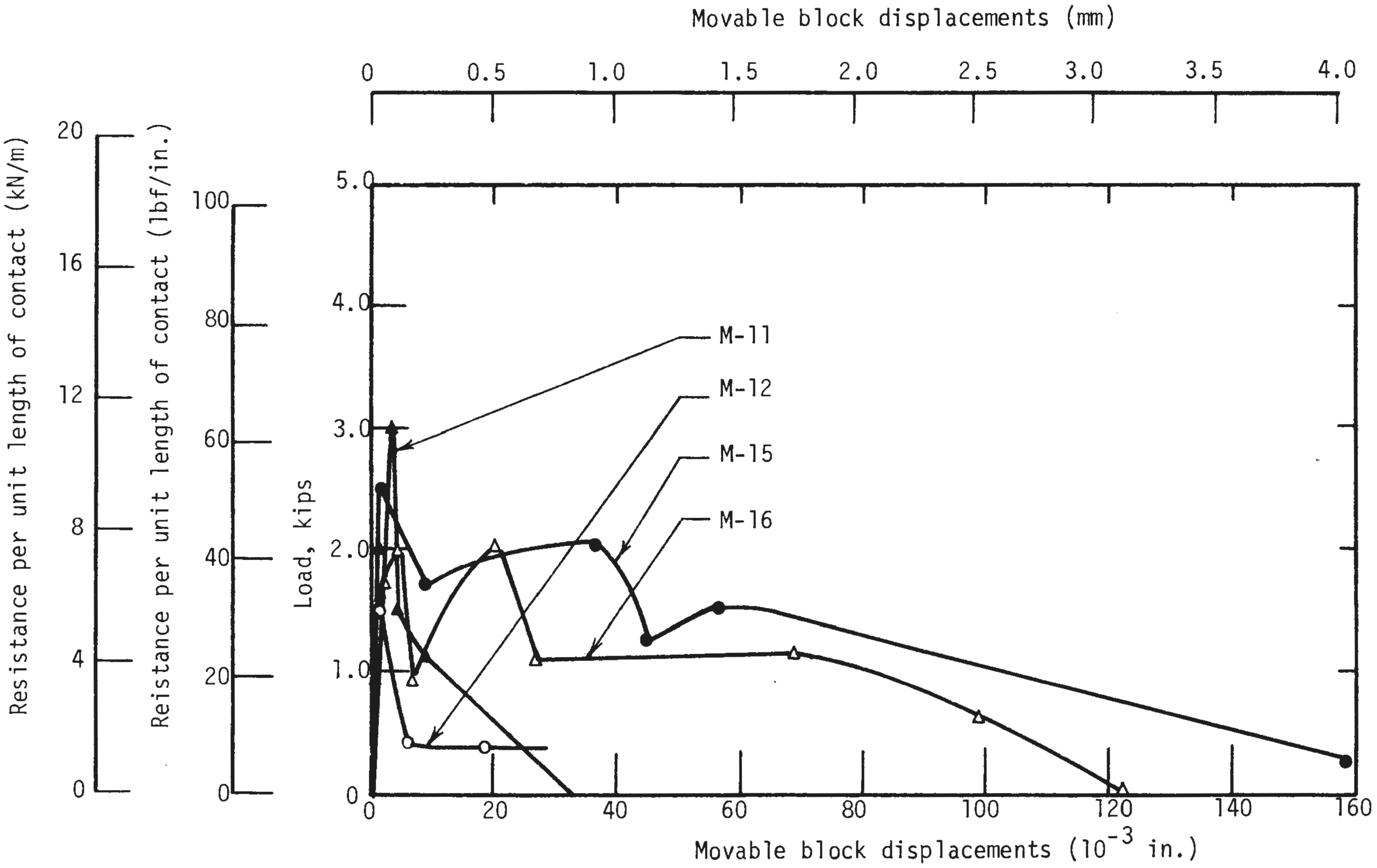


FIGURE 3.58 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

controls the residual resistance of the layers since it increases their stiffness and ductility. The maximum resistance offered by the reinforced layer may develop after separation from the surface slab if the reinforcement increases the moment capacity of the layer to a level above its adhesion strength.

3.6.5 RATE OF LOADING

Two sets of tests carried out with 3-day old layers (Nos. 7 and 8) and 7-hour old layers (Nos. 9 and 10), were used to determine the influence of the rate of loading on the structural behavior of the layer. The structural behavior of all the tests was very similar to that shown by the type 1 curve in Fig. 3.14.

For test Nos. 7 and 8 the maximum resistance of the mortar layers were 110 lbs/ft (19 kN/m) and 50 lbs/ft (9 kN/m), respectively, the higher one corresponding to test No. 7 performed with the smaller rate of loading 2 lbs/sec (8.9×10^{-3} kN/sec).

For the other set of tests, Nos. 9 and 10, the maximum resistances of the mortar layers were 22 lbs/ft (4 kN/m) and 5 lbs/ft (2 kN/m) respectively. The higher value was obtained for test No. 10, in which the layer was loaded with the maximum rate of loading, equivalent to an impact load. The inconsistent differences shown by these results indicate that changes in the rate of loading do not have a systematic influence in the structural behavior of the mortar layers or in the values of the maximum resistance.

3.6.6 THICKNESS OF THE LAYER

As previously explained, the same thickness of the mortar layer was used for all tests in this preliminary program, therefore no special tests were conducted to investigate its influence on the structural behavior of the layer. The small variation of this value (3/4 to 1-1/2 in.) between the mortar layers made it impossible to determine the effect of thickness on the structural behavior of the layer. However, from the same results obtained from these tests and knowledge of the structural behavior of uniformly loaded beams, it can be concluded that the residual resistance of the layers which follow type 2 and 3 curves, is directly proportional to the third power of its thickness.

The influence of the mortar thickness on the maximum resistance of the layer could not be established since all of the mortar layers exhibited the same mode of failure (adhesion).

3.7 CONCLUSIONS

3.7.1 PERFORMANCE OF THE TESTING DEVICE

The performance of the test device was checked by careful observation of the behavior of the apparatus and its effect on test results. For example, in the first two tests mortar penetrated the slots surrounding the movable block and thus altered the structural behavior and capacity of the layer. It was decided, for future tests, to prevent penetration of mortar in to these slots so that only the surface conditions and strength of the mortar would be tested. This was accomplished by filling the slots with a low frictional material such as cotton or a caulking compound. It was also observed during these first two tests that the surface slabs were displacing with respect to the fixed walls in a zone close to the movable block. Additional bars tying these concrete slabs to the fixed walls were provided to prevent this movement.

Forward movement of the fixed walls was monitored with dial gages as explained in Section 2.4. After the first three tests additional prestress forces were applied to the fixed walls, reducing their forward movement to a negligible level.

After minor adjustments during the first few tests the device was found to perform satisfactorily. The friction forces on the movable block were less than 50 lbs (222.5×10^{-3} kN) when the block was displaced without a mortar layer present. There was no appreciable tilting or rotation of the movable block and the rams used to apply the loads could be controlled with sufficient accuracy.

3.7.2 SUMMARY OF THE EFFECTS OF THE VARIABLES ON THE STRUCTURAL BEHAVIOR OF THE LAYER

The same mode of failure--separation of the mortar layer from the surface slabs--was present in all the tests carried out in this preliminary program.

Two typical structural behaviors were observed for the mortar layers tested. In both, a very stiff, elastic relationship existed between the resistance of the layer and the displacements of the movable block, before the maximum, or peak, resistance of the layer was reached.

However, for further displacements the resistance of the mortar layer in one case dropped immediately to zero. This occurred in short layers and layers not having boundaries and sufficient adhesion to provide end restraint and development of a simply supported beam. In the other case, the resistance of the mortar layer was gradually reduced with further displacement of the movable block. The post-maximum resistance offered by the mortar layer has been called residual resistance.

The structural behavior of the mortar layers tested in this preliminary program was controlled by the lateral boundaries of the layer. Whenever steel plates were used in the tests, a boundary to the adhesive failure propagation was created, thus enabling the layer to behave as a simply supported beam and to provide some residual resistance. When no steel plates were used, the adhesive failure propagated in most cases to the layer boundaries, producing an instantaneous failure.

The maximum resistance of the mortar layers was directly related to: 1) the strength of the mortar in the layer, 2) the adhesion characteristics of the surface slab, and 3) the length of the mortar layer on the walls close to the movable block.

The residual resistance of the mortar layer depended mainly on: 1) the strength of the mortar, 2) reinforcement of the layer, 3) the length of the beam, and 4) the thickness of the layer.

In the ranges tested, the rate of loading had no significant effect on the peak or residual resistance of the mortar layers.

CHAPTER 4

SHOTCRETE TESTS

4.1 INTRODUCTION

For the shotcrete tests the same planar geometry of the testing device was used. However, the methods of layer application were completely revised; the necessary equipment for placing of the shotcrete had to be selected, prepared and tested. The preparation of the testing device and testing of the applied shotcrete layers followed the same procedures used for the testing of the mortar layers. The displacements of the shotcrete layer and of the movable block were again measured by dial gages, but the measurement of surface strains was discontinued for the reasons given in Section 3.5.4. The same electronic recording instruments were utilized for measurement of the load and displacement of the rams. The subsequent data and results are presented in a manner similar to that used for the mortar tests.

Measurement of the displacement occurring between the fixed wall and the surface slabs were made during two of the shotcrete tests. This relative displacement had not been measured in the mortar tests.

The variables studied during the shotcrete tests included all of those investigated in the mortar tests; i.e., the effects of a change in adhesion conditions, layer strength, reinforcement and boundary conditions were investigated. In addition to these, the effect of the thickness of the layer was also included.

4.2 SHOTCRETE OPERATION

4.2.1 PREPARATION OF TESTING DEVICE

Prior to shooting, the testing device was prepared to: 1) facilitate the shooting operation, 2) set up the required test conditions, 3) facilitate the preparation of the shotcrete layer for testing; and 4) minimize the effects of other variables on test results.

Several measures were taken to facilitate the shooting operation. The entire testing device was surrounded by plywood wingwalls which would confine the rebound to a small area. These wingwalls are shown in Fig. 4.1 Vertical guide wires were placed to assist the nozzleman in spraying the shotcrete to the required thickness. These wires were installed at distances corresponding with the desired thickness of the layer. They can be seen in Figs. 4.1 and 4.2. Finally, the floor in front of the test wall was covered with canvas tarps to facilitate clean-up after shooting.

The required adhesion condition was obtained by preparing the concrete surface slabs before shooting. For those tests in which a good bond between the shotcrete and the slabs was desired, the surface of the slabs was roughened with a wire brush. The relative roughness of the surface was then measured and recorded by the device discussed in Appendix B. For those tests representing low adhesion, the slab surface was covered with nylon filament tape. The entire area of the test (2 ft x 10 ft) including the movable block was covered with tape. The tape was cut along the joints between the movable block and fixed wall. The tape-covered strip can be seen across the upper movable block in Fig. 4.3.

FIGURE 4.1 FRONTAL VIEW OF TESTING DEVICE WITH PLYWOOD WINGWALLS

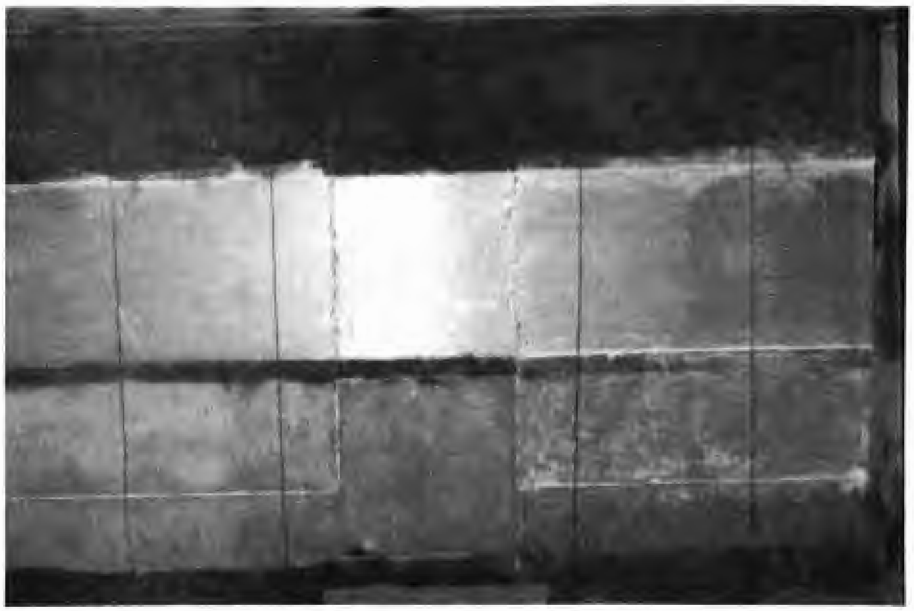


FIGURE 4.2 CLOSE-UP SHOWING VERTICAL SCREED WIRES AND TAPED SURFACE

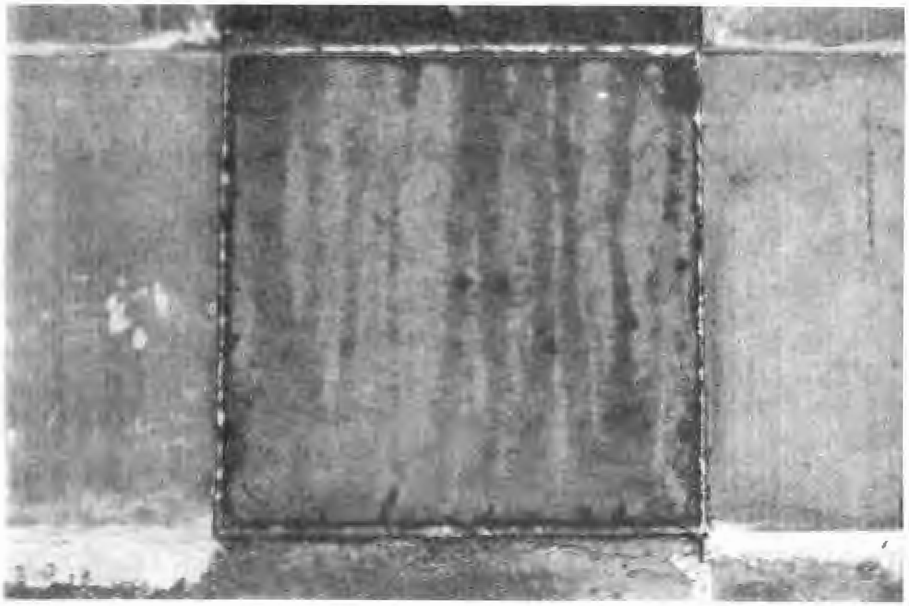


FIGURE 4.3 FRONTAL VIEW OF COTTON-FILLED MOVABLE BLOCK-SURROUNDING SLOTS

The surface of the movable block was made flush with that of the fixed wall to assure a uniform thickness of shotcrete.

To reduce the difficulty in removing excess shotcrete and disturbance to the shotcrete layer before testing, several measures were taken before the shotcrete was applied. Filament tape or oil was used to cover those areas of the wall where the shotcrete was to be removed. For tests with fiber reinforced shotcrete,the test strips were framed with wood boards so that excess shotcrete could be removed without chiseling. This reduced greatly the disturbance to the layer during trimming.

For many tests, steel plates were used as boundaries of the shotcrete layer. These plates were held by rods which passed through the wall, the surface slab, and the shotcrete layer. Drilling of holes through the shotcrete to accommodate these rods was avoided by extending the rods out of the surface of the wall before shooting. The rods were then covered with tape to preserve their threads.

To provide the same testing conditions except for the parameter being studied, great care was taken in the preparation of the test wall. The presence of shotcrete within the joints between the movable block and fixed wall was eliminated by placing cotton in the open slots (see Fig. 4.3). To provide a uniform surface,the same type of tape and surface preparation were employed to minimize the variation of surface roughness, and, therefore, its effect on testing.

4.2.2 SHOTCRETE MIX

All tests were conducted using dry-mix shotcrete. The same mix proportions were used in all the shootings with the exception of test Nos. 15 and 16 in which fiber was added. The basic mix design is shown in Table 4.1.

TABLE 4.1

DRY MIX PROPORTIONS WITHOUT FIBER

	Per 1/2 C.Y.		Percent
	lbs	(kg)	
Sand	575	(261)	40.8
Gravel	575	(261)	40.8
Cement	250	(116)	17.8
Accelerator	7.5	(3.4)	0.6

The grain size distributions of the sand and gravel making up the shotcrete are shown in Fig. 4.4. The uniformity coefficient of the sand was 2.19 while that of the pea gravel was 1.41. The combined gradation curve for the sand and gravel is also included in Fig. 4.4. Type 1 portland cement was used along with Sigunite dry-powder accelerator. The accelerator was added in a proportion of 3 percent by weight of cement.

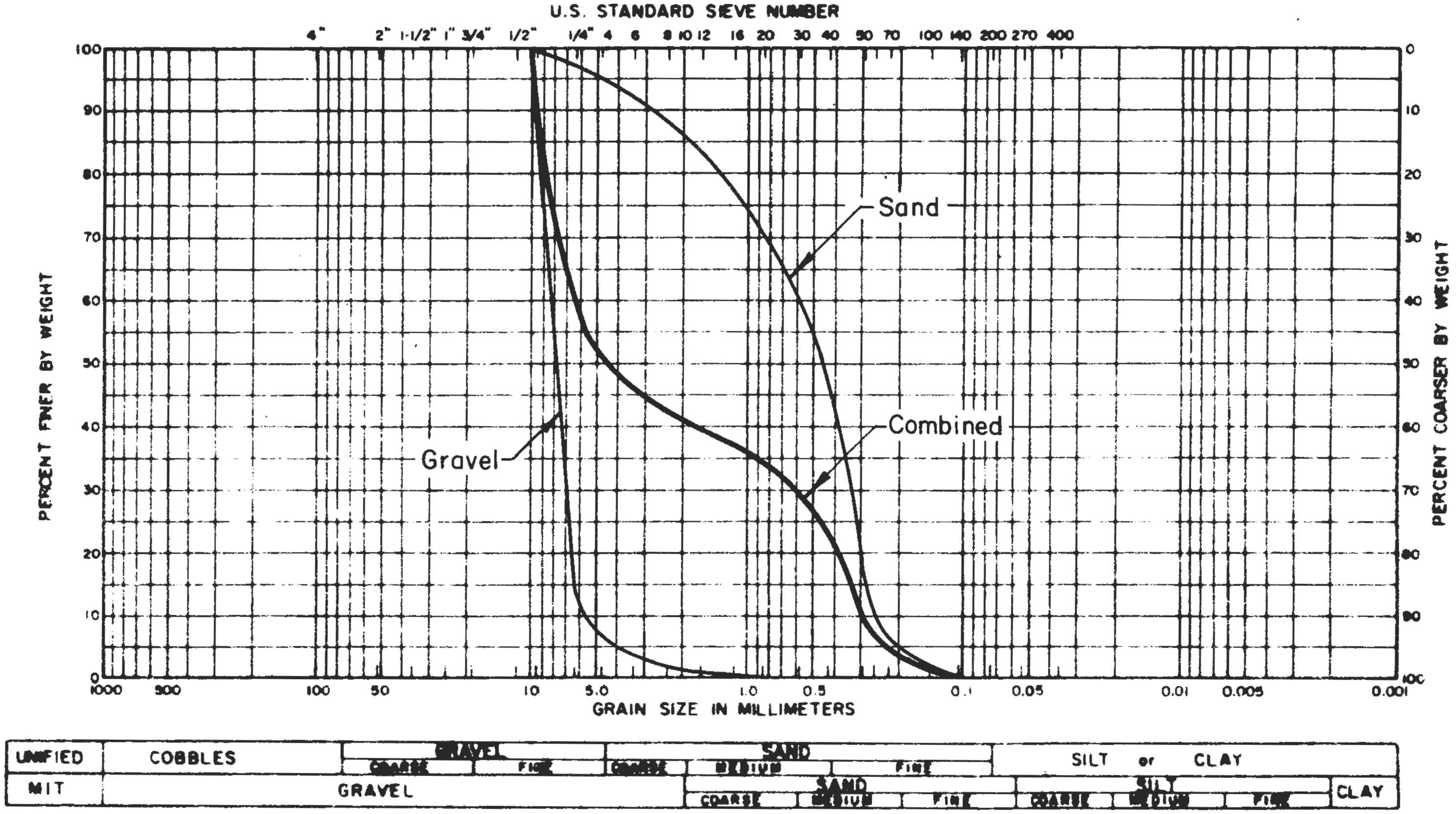
The mix design for test Nos. 15 and 16, in which fiber was used, is shown in Table 4.2. The percent of fiber added was approximately 3 percent by weight and 1 percent by volume. U.S.S. Fibercon steel fiber, 0.010 in. x 0.022 in. x 1 in. (0.0254 cm x 0.0559 cm x 2.54 cm) was used in the mix.

TABLE 4.2

DRY MIX PROPORTIONS WITH FIBER

	Per 1/2 C.Y.		Percent
	lbs	(kg)	
Sand	575	(261)	39.6
Gravel	575	(261)	39.6
Cement	250	(116)	17.2
Fiber	43	(19.5)	3.0
Accelerator	7.5	(3.4)	0.6

Water was added to the dry-mix materials at the nozzle. A preliminary measurement of the amount of water injected at the nozzle indicated that the water-cement ratio of the shotcrete as it left the nozzle was approximately 0.50.



Torpedo sand:	Pea gravel:
Natural water content: 10.0%	Natural water content: 1.7%
% Passing #200 sieve: 1.0%	% Larger than 3/8" (10 mm) 1.0%
D60/D10 = 2.19	D60/D10 = 1.41

FIG. 4.4 GRADATION CURVES.

4.2.3 EQUIPMENT

The equipment used to place shotcrete consisted of a mixer, a belt conveyor, and a dry-mix shotcrete machine. The mixer was an electric, rotating drum type mixer having a 1/2 C.Y. (0.382 m^3) capacity. The material, after leaving the mixer, was conveyed to the gun by a gasoline-powered, belt conveyor. The gun, a Reed Model LASC II, was used to spray the shotcrete onto the surface of the model. The material was conveyed to the nozzle in a 2 in. (5.08 cm) diameter hose having a length of 100 ft (30.4 m). A stepped-balloon nozzle having a length of 1 ft was used to direct the material onto the wall. The water was delivered by an ordinary garden hose and regulated by a screw valve at the nozzle. The water ring had an inside diameter of 2-1/2 in. (6.35 cm) and contained four holes 3/16 in. (0.476 cm) in diameter, symmetrically placed around it. A photograph of the nozzle can be seen in Fig. 4.5. The arrangement of the equipment is shown schematically in Fig. 4.6, and pictured in Figs. 4.7 and 4.8. In both Figs. 4.7 and 4.8, the shotcrete machine is shown at the extreme left.

In the first several tests, the accelerator was added at the gun using a screw-feed accelerator dispensor. However, difficulty in the operation of this device made it necessary to manually add the accelerator to the material as it passed on the conveyor.

4.2.4 SHOOTING PROCESS

Since the mixer had only a 1/2 C.Y. (0.382 m^3) capacity, the

FIGURE 4.5 NOZZLE CLOSE-UP

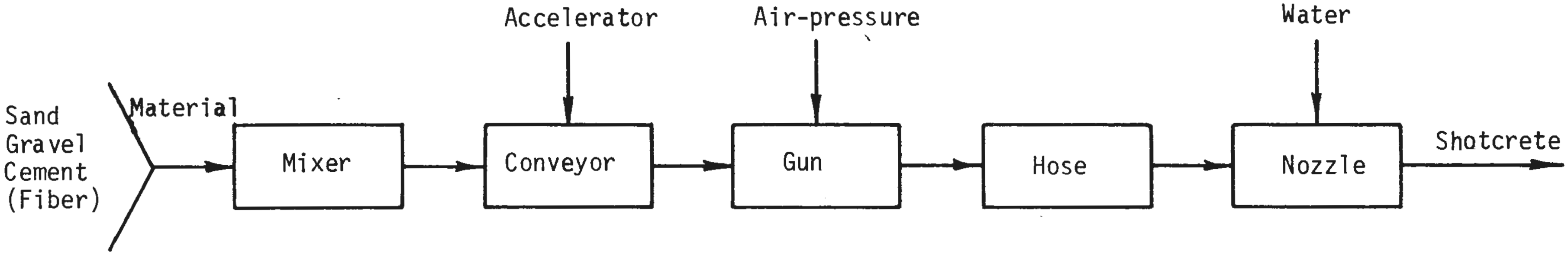


FIGURE 4.6 SCHEMATIC ARRANGEMENT OF THE SHOTCRETE EQUIPMENT

FIGURE 4.7 ARRANGEMENT OF SHOOTING EQUIPMENT

FIGURE 4.8 CLOSE-UP VIEW OF BELT CONVEYOR AND POWERED GUN

shotcrete had to be prepared in several batches. To provide a nearly continuous shooting operation, the material for each batch was pre-weighed and stored in drums. This assured a minimum batching time during gunning of the model.

For each batch the required amounts of sand, gravel, cement, and, for test Nos. S-15 and S-16, fiber were loaded into the skip and then dumped simultaneously into the mixer. When fiber was added, a sieve with 1 in. (2.54 cm) square opening was used, as shown in Fig. 4.9, to break up any entangled balls of fiber. The batched materials were always mixed a minimum of 3 minutes. The rate of material transported to the gun was controlled by the speed of the conveyor and was set so that the time of the material in the hopper remained essentially the same. The accelerator was manually added onto the conveyor.

The first batch was gunned against a plywood practice wall, as shown in Fig. 4.10, which was located away from the testing device. This allowed the nozzleman and gunman to adjust the air pressure and rotation speed of the machine so that a smooth, continuous flow of material would be delivered to the nozzle while shooting the surface of the model. During this time a 2 ft x 2 ft x 3 in. (61.0 cm x 61.0 cm x 7.62 cm) test panel was also gunned to obtain samples for strength tests. An empty test panel is shown in Fig. 4.10, the shooting of the test panel is shown in Fig. 4.11, and a filled panel is shown in Fig. 4.12.

After the completion of the practice shooting, the shooting operation was then moved to the test wall. The wall was first cleaned using an air-water jet from the nozzle. This removed any dust accumulated on the

FIGURE 4.9 FIBER SCREENING USING 1-IN. (2.54 CM) SIZE SIEVE

FIGURE 4.10 WARM-UP SHOOTING AGAINST PLYWOOD WALL

FIGURE 4.11 STRENGTH-SPECIMENS PANEL BEING FILLED UP

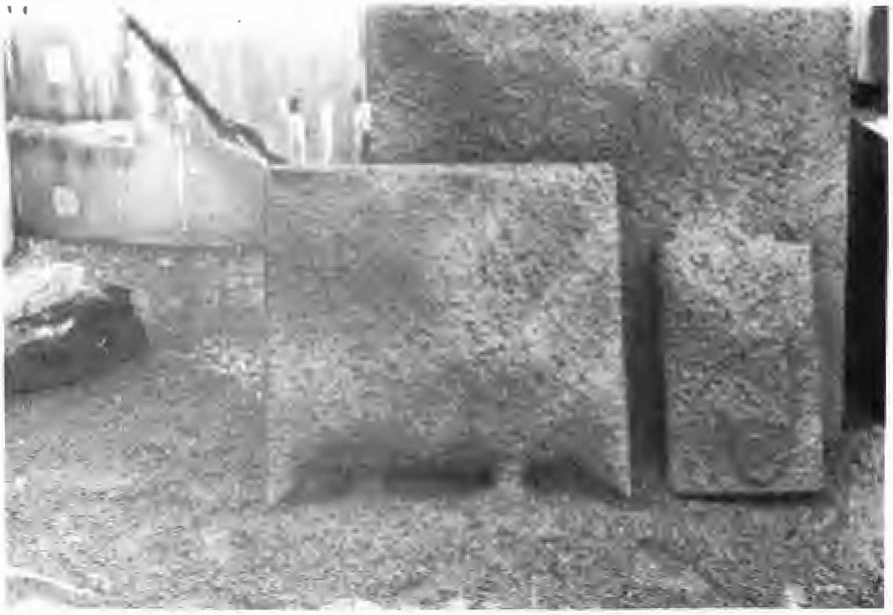


FIGURE 4.12 FINISHED STRENGTH-SPECIMENS PANEL

surface of the slabs and prepared them for receiving shotcrete. The first material delivered to the nozzle was shot against one of the wingwalls so that the air pressure and water could be adjusted without placing poor quality shotcrete. After these adjustments were made, the stream of material was directed against the test wall surface. The shooting began in the lower right corner of the test wall and followed the path shown in Fig. 4.13. The nozzleman used the guide wires to obtain a uniform thickness. For all shootings, the shotcrete was placed in a single layer. However, additional materials were placed over indentations in the first layer to obtain a relatively uniform thickness. The time between the shooting of the first layer and patching of thin areas never exceeded 30 minutes.

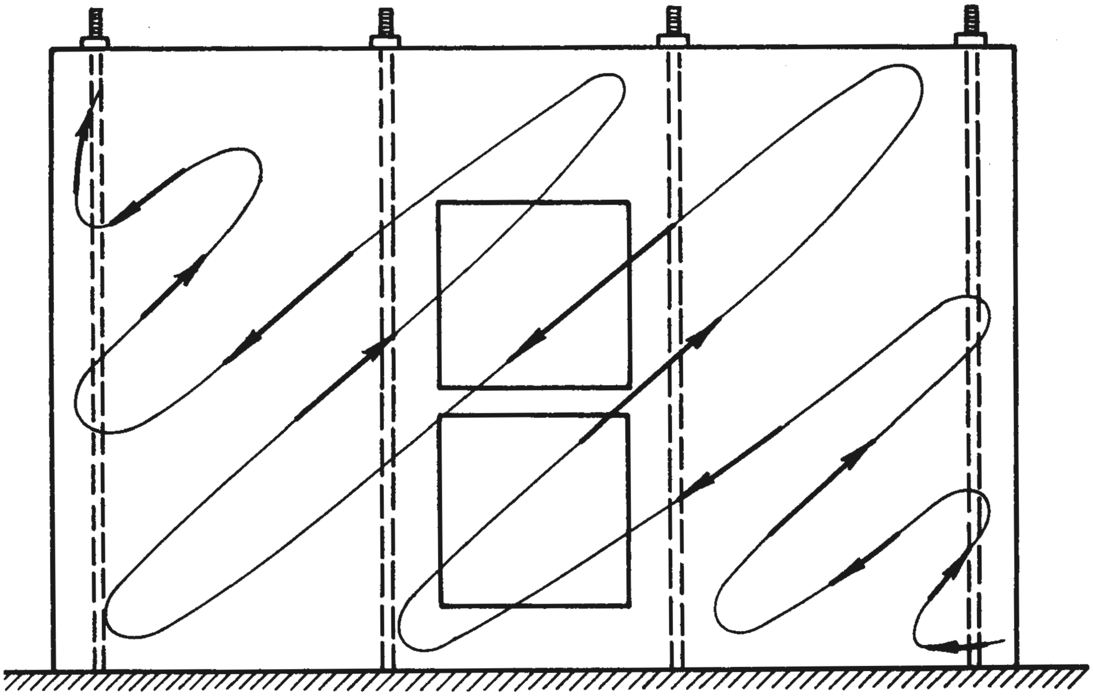


FIGURE 4.13 PATTERN OF SHOOTING

During shooting, the air pressure at the gun ranged from 60 to 75 psi (4.22 to 5.27 kg/cm^2). These pressures produced a material delivery rate (including water) of 400 to 450 lbs/min (181 to 204 kg/min). The same air pressure was used for all shootings in order to obtain approximately the same compaction and thus the same strength in all of the tests. The rate of water flow to the nozzle during one shooting was approximately 24.0 to 27.0 gal/min (1.51 to 1.70 ℓ/min).

After the entire wall was covered with a layer of shotcrete, a second test panel was gunned. This panel, like the first, was used to obtain samples for strength tests which were performed simultaneously with the large scale test. In addition, for test Nos. S-13 to S-16, another test panel was shot to obtain samples for adhesion tests. For test Nos. S-13 and S-14, a 1-ft x 1-ft x 3-in. (30.5 cm x 30.5 cm x 7.62 cm) concrete slab was used for the adhesion test panel. To reduce the difficulty of cutting the adhesion test samples, a concrete slab was pre-cut to the desired sample size. A 4 x 6 array of 2 in. x 2 in. x 3 in. deep (5.08 cm x 5.08 cm x 7.62 cm) concrete blocks, joined together by brittle plaster, was used for test Nos. S-15 and S-16. The shotcrete-slab adhesion samples were procured by cutting only the shotcrete layer. This procedure permitted samples to be obtained for early adhesion tests.

4.2.5 CURING

Immediately after the shooting, the plywood wingwalls were removed and the shotcrete layer was trimmed around the top and bottom of each movable block and fixed wall slabs. For all tests, except those containing steel fibers, the trimming was accomplished by chiseling along the boundaries of the test layer. The removal of the surrounding material was facilitated by placing the tape or oil on those areas to be trimmed. For the steel fiber shotcrete tests, boards were placed horizontally along the extreme upper and lower boundaries of the layers. These boards were easily removed and an evenly trimmed edge was obtained. Only the 3-in. (7.62-cm) wide strip between the two test layers had to be removed using a hammer and chisel. The guide wires were left embedded in the shotcrete to avoid disturbance to the test layer. Figure 4.14 shows a non-fiber reinforced shotcrete layer after it was trimmed.

After trimming, burlap was placed over the shotcrete layer and moistened. The burlap was then covered with plastic sheets to retain the moisture. Periodically the burlap was rewetted to provide a constant moist curing environment for the shotcrete. A photo of burlap and plastic placed over test layers can be seen in Fig. 4.15.

The 2-ft x 2-ft x 3-in. (61.0 cm x 61.0 cm x 7.62 cm) shotcrete panels were placed in a concrete curing room in which humidity and temperature conditions were similar to those surrounding the shotcrete in the model. Panels were kept in the room until it was time for preparation and testing.

The adhesion test panels were covered and cured in the same manner as shotcrete on the test wall; they were covered with burlap and plastic, and periodically moistened. This was done so that the adhesion of the test specimens would match as closely as possible that existing on the test wall. These panels were also cured until just before testing.

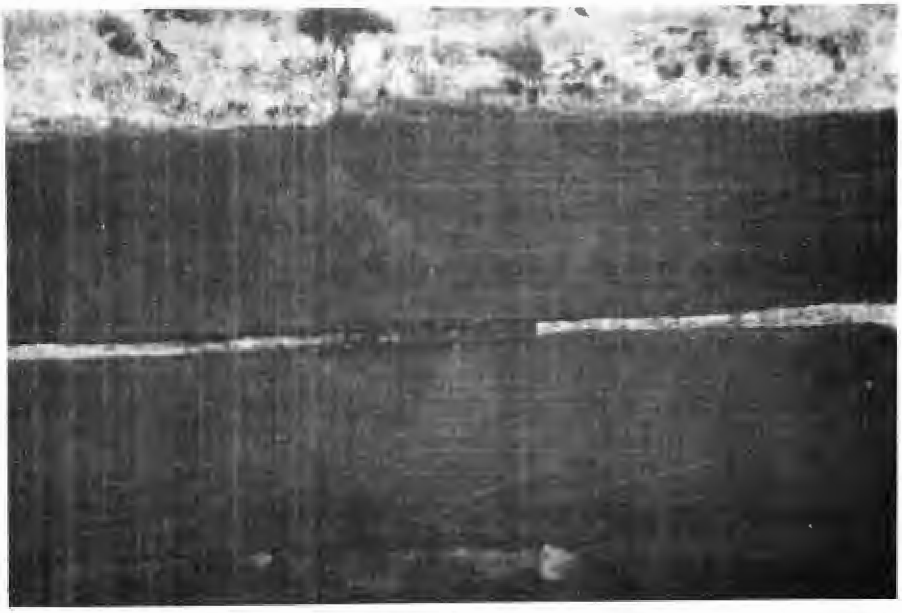


FIGURE 4.14 FRONTAL VIEW OF SHOTCRETE LAYERS IMMEDIATELY AFTER TRIMMING

FIGURE 4.15 FRONTAL VIEW OF SHOTCRETE LAYERS DURING CURING PROCESS

4.3 SHOTCRETE TEST PROGRAM

The shotcrete test program was set up using the same hypothetical model of thin layer behavior shown in Fig. 3.5. Based on the results of the mortar tests, modes of failure were predicted for the shotcrete layers. The same variables, but including reinforcement, were reassessed in terms of the structural behavior of shotcrete rather than mortar.

All shotcrete layers covered the full width of the model. This application assured that adhesive stress would be fully mobilized along the portion of the fixed walls bordering the movable block. In addition, full coverage of the surface of the model permitted a wide range in the spacing between the steel plates which formed the lateral boundaries of the layer. For all tests a loading rate of 5 lbs/sec (22.2 N/sec) was used in applying the load from the ram to the movable blocks.

The parameters selected for study in the shotcrete tests included: 1) lateral boundaries of the layer, 2) adhesive strength, 3) shotcrete strength, 4) thickness of the shotcrete layer, and 5) reinforcement. The manner in which these parameters were varied and the values assigned to them in the 16 shotcrete tests are summarized in Table 4.3 and described in the following sections.

4.3.1 LATERAL BOUNDARY CONDITIONS OF THE LAYER

In most tests the lateral boundaries of the shotcrete layers were established by steel plates simulating rock bolts or boundaries of openings in actual tunnels. Steel plates were not used in five of the shotcrete tests (test Nos. S-1, S-2, S-3, S-5 and S-7 - Table 4.3) This case

TABLE 4.3

MATERIAL PROPERTIES OF SHOTCRETE LAYERS

COLUMNS 1	2	3	4	5	6	7	8
Test no.	Thickness in./mm	Adhesion psi/kPa	Comp. strength psi/MPa	Flexural strength psi/MPa	E 10^6psi/GPa	Length in./m	Rock bolt at ft/m
S-1	1.82 46.23	180 1241	3580 24.7	565 3.9	3.64 25.10	48 1.22	None --
S-2	1.70 43.18	180 1241	3580 24.7	565 3.9	3.64 25.10	48 1.22	None --
S-3	2.18 55.37	187 1289	4890 33.7	-	3.08 21.2	48 1.22	None --
S-4	2.11 53.59	20 138	4890 33.7	-	3.08 21.2	48 1.22	8 2.44
S-5	5.26 133.60	185 1276	3830 26.4	740 5.1	4.70 32.4	48 1.22	None --
S-6	4.70 119.38	20 138	3830 26.4	740 5.1	4.70 32.4	48 1.22	8 2.44
S-7	2.78 70.61	60 470	910 6.3	250 1.7	2.30 15.9	48 1.22	None 2.44
S-8	2.95 74.93	10 69	910 6.3	250 1.7	2.30 15.9	48 1.22	8 2.44
S-9	2.65 67.31	154 1062	2400 16.5	450 3.1	3.70 25.5	48 1.22	4 1.22
S-10	3.07 77.98	37 255	2400 16.5	450 3.1	3.70 25.5	48 1.22	4 1.22
S-11	5.24 133.10	45 310	718 5.0	80 0.3	0.86 5.9	48 1.22	8 2.44
S-12	5.46 138.68	20 138	718 5.0	80 0.3	0.86 5.9	48 1.22	8 2.44
S-13	1.80 45.72	185 1276	2850 19.7	141 1.0	7.34 50.6	48 1.22	8 2.44
S-14	1.06 26.92	187 1289	2850 19.7	141 1.0	7.34 50.6	48 1.22	8 2.44
S-15	3.66 92.96		3450 23.8	930 6.4	-- --	48 1.22	8 2.44
S-16	4.43 112.52		3450 23.8	930 6.4	-- --	48 1.22	8 2.44

would represent a tunnel in which bolts were not installed or were placed only locally. In nine of the tests, Nos. S-4, S-6, S-8 and S-11 to S-16, the steel plates were located at 8 ft (243.2 cm) apart. Finally, for two of the shotcrete layers tested, Nos. 9 and 10, the distance between the steel plates was equal to 4 ft (121.6 cm) or 1 ft (30.4 cm) from the edge of the movable block.

These steel plates were used to provide a restriction to propagation of an adhesion failure and to evaluate the residual resistance of the layer acting as a beam. Variation in the spacing of the steel plates was not expected to have an effect on mode of failure or the maximum resistance of the shotcrete layer.

4.3.2 SHOTCRETE STRENGTH

The variation in shotcrete strength was obtained by testing the layers at different times after application of the shotcrete.

The strength of the shotcrete in the layer was estimated by performing standard compression and flexural tests on shotcrete specimens obtained from the sample panels. These tests were conducted at approximately the same time as the model tests and were used for strength control. In some of the model tests, strength tests were also carried out on shotcrete samples cut from the failed shotcrete layer. A comparison of the strength results from the two sets of samples indicates that the shotcrete in the panel is representative of the shotcrete placed on the surface of the model. Columns 4, 5 and 6 of Table 4.3 show the compressive and flexural strengths and the initial tangent modulus of the shotcrete in the test panels.

The average values of adhesive strength for shotcrete cured 7 days varied from 180 psi (1241 KPa) for roughened surface slabs to 20 psi (138 KPa) for the surface slabs covered with filament tape. When the shotcrete was cured for 7 hours, the average values of adhesive strength ranged between 77 psi (531 KPa) and 10 psi (69 KPa).

The variation in adhesive strength with time of curing represented by the unconfined compressive strength and surface conditions is shown in Fig. 4.18. In this figure the average values of the adhesive strength for both the roughened and taped surfaces are plotted against the compressive strength of the shotcrete. The greatest difference in adhesive strength occurred between samples having roughened concrete and taped surfaces at 7 days and between samples having rough surfaces but tested at 7 days and 7 hours. The test results further show that adhesive strength is insensitive to time of curing for poor bonding conditions. The adhesive strength of the shotcrete on the roughened concrete surfaces was approximately twice that on the taped surfaces at 7 hours.

The tensile load vs deformation data obtained from the adhesive tests indicate that the stiffness in adhesion is very high and that the mode of failure is very brittle (Fig. 3 - Appendix C). Almost no displacement occurred at the contact during the loading process before failure, and after failure had occurred the resistance immediately dropped to zero.

Finally, the adhesion failure did not always occur along the shotcrete-concrete contact but sometimes took place along laminations in the shotcrete. The adhesive strength values obtained in these cases were not used in computing the average adhesive strength of the layer.

The compressive strength of the shotcrete varied from a maximum of 4890 psi (33.7 MPa), in test Nos. S-3 and S-4, to 718 psi (5.0 MPa) in test Nos. 11 and 12. Variations in the strength of shotcrete having approximately the same curing time are related to variations in the shooting process and in its ingredients.

4.3.3 ADHESIVE STRENGTH

The adhesive strength between the shotcrete and concrete surface slabs covering the walls was varied directly by changing the adhesive characteristics of the surface slabs, and indirectly by varying the shotcrete strength.

Column 3 in Table 4.3 shows the average values of the adhesive strength between the shotcrete layers and the surface slabs obtained from the tests on the 2-in. x 2-in. x 6-in. (5.08-cm x 5.08-cm x 15.2-cm) samples cut from sections of the test layer. In most of the cases, the samples were taken from either the slab on the movable block or from locations close to the edge of the fixed walls where little or no disturbance of the layer took place during testing. Figure 4.16 shows a typical facing slab covered with shotcrete from which the adhesion test specimens were cut. The samples were prepared so that the interface between the shotcrete and concrete slab was located in the middle of the prism.

The test apparatus used, the procedure followed, and all of the results obtained in the adhesion testing program are described and summarized in Appendix C.

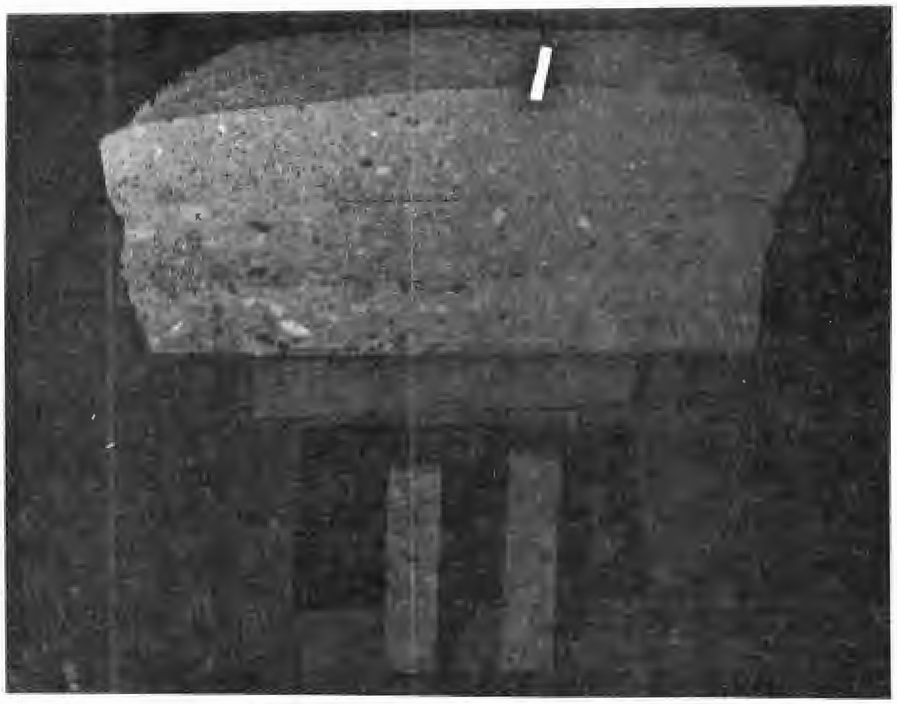


FIGURE 4.16 COMBINED SHOTCRETE-SLAB SECTION AND CORRESPONDENT ADHESIVE TEST SAMPLES

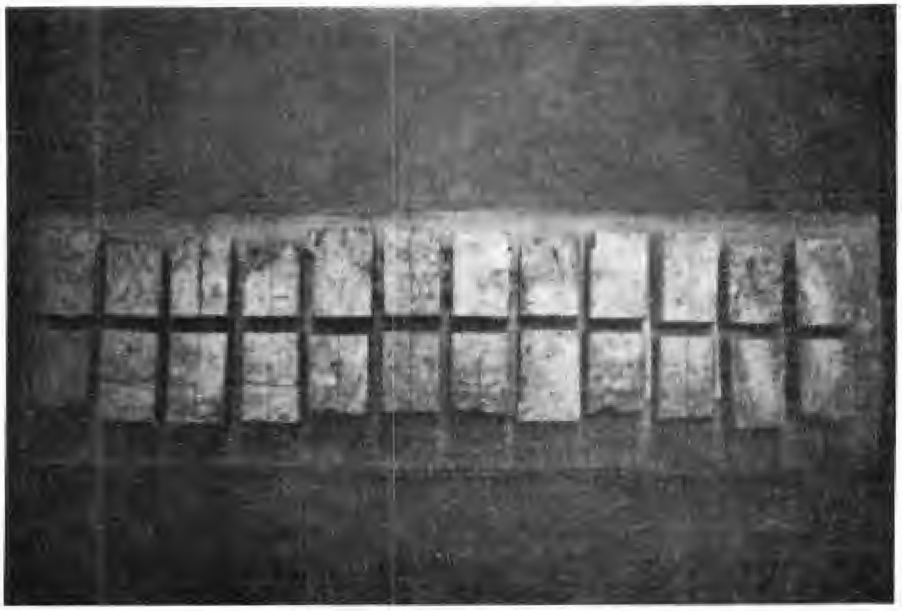


FIGURE 4.17 ADHESIVE TEST SAMPLES AFTER TESTING

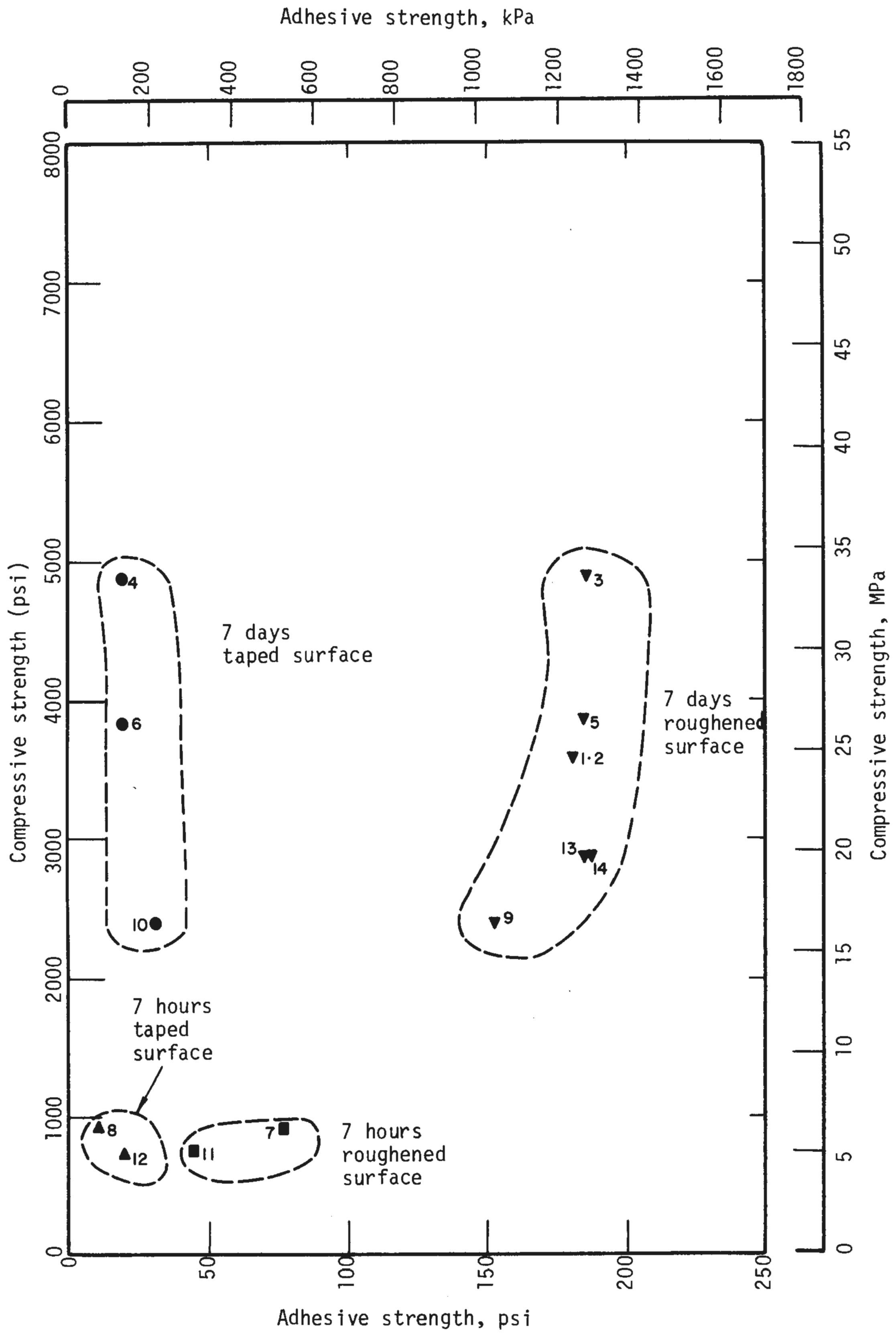


FIGURE 4.18 ADHESIVE STRENGTH VS COMPRESSIVE STRENGTH OF THE SHOTCRETE LAYERS

4.3.4 THICKNESS OF THE LAYER

Column 2 in Table 4.3 shows the average thicknesses of the shotcrete layers. These thicknesses are typical of those used in practice for thin linings, and ranged from a maximum of 5.46 in. (13.9 cm) in test No. S-12 to a minimum of 1.06 in. (2.69 cm) in test No. S-14. These values represent the average thickness measured along the failure cracks in the layer. The measurements show a remarkable uniformity in the thickness of all the layers shot (±0.1 in.) (0.254 cm).

4.3.5 USE OF REINFORCEMENT

Two of the tests, Nos. S-15 and S-16, were conducted on shotcrete containing steel fibers, 1-in. x 0.010 in. x 0.022 in. (2.54-cm x 0.254 mm x 0.559 mm). In each test 144 lbs (65.3 kgms) of steel fiber corresponding to 3 percent by weight or 1 percent by volume of the entire batch were added to the mix.

The presence of steel fibers added to the materials in the above proportions has been shown to increase the tensile strength of the shotcrete (Parker, et al., 1975) or at least improve its ductility. It was therefore expected that reinforcing with the steel fiber would affect the residual resistance of the shotcrete layer without changing its mode of failure or maximum resistance.

4.4 TEST RESULTS

The shotcrete layer test results were plotted and analyzed in the same manner as those obtained in mortar tests. The load in the jack representing the resistance of the shotcrete layer was plotted against the "net" displacement of the movable block. The relative forward displacement of the shotcrete layer was obtained for each load increment by subtracting the displacement of the "fixed" walls of the test device with respect to the floor. The displacement of the wall was quite small (0.001 in.; 0.025 mm) compared with the displacement of the movable block.

4.4.1 MODES OF FAILURE

The two basic modes of failure shown in the conceptual model in Section 3.3 were observed in the shotcrete layers. Column 2 of Table 4.4 shows the mode of failure for each shotcrete test.

A diagonal tension failure occurred in tests S-1, S-2, S-13 and S-14. (Fig. 4.19).

FIGURE 4.19 FRONTAL VIEW OF FAILED SURFACES IN TEST NOS. 1 AND 2

TABLE 4.4

SHOTCRETE LAYER TEST RESULTS

1	2	3	4	5	COLUMNS 6	7	8	9	10	11
Test no.	Failure mode	Max. load lbf/kN	Δ failure in./mm	Residual load lbf/kN	Δ residual in./mm	Length of develop (left) in./m	Length of develop (right) in./m	I $in.^4/cm^4$	EI $10^6 in.^4/m^4$	Curing time hrs
S-1	Shear	15,250 67.8	0.01 0.25	0 0	0.10 2.54	9 0.2	30 0.8	12.06 502.0	43.9 18.3	72
S-2	Adhesion -Shear	13,250 58.9	0.01 0.25	0 0	0.15 3.81	5 0.1	3 0.08	9.83 409.2	35.8 14.9	72
S-3	Adhesion	17.375 77.3	0.02 0.51	2800 12.5	0.06 1.52	48 1.2	15-1/2 0.4	20.72 862.4	63.8 25.6	144
S-4	Adhesion -Bending	2,500 11.1	0.01 0.25	2600 11.6	0.04 1.02	36 0.9	36 0.9	18.79 782.1	57.9 24.1	144
S-5	Adhesion	17,500 77.8	0.04 1.02	0 0	0.04 1.02	48 1.2	48 1.2	291.06 12114.8	1368.0 569.4	168
S-6	Adhesion -Bending	4,550 20.2	0.03 0.76	3200 14.2	0.12 3.05	36 0.9	36 0.9	207.65 8643.0	975.9 406.2	168
S-7	Adhesion	5.500 24.5	0.02 0.51	5200 23.1	0.27 6.89	24 0.6	48 1.2	42.97 1788.5	98.8 41.1	7
S-8	Adhesion -Bending	1,700 7.6	0.01 0.25	500 2.2	0.15 3.81	36 0.9	36 0.9	51.34 2136.9	118.1 49.2	7
S-9	Adhesion -Bending	20,250 90.1	0.03 0.76	0 0	0.50 12.70	12 0.3	12 0.3	37.22 1549.2	137.7 57.3	144
S-10	Adhesion -Bending	7,000 31.1	0.06 1.52	6960 31.0	0.30 7.62	12 0.3	12 0.3	57.87 2408.7	214.1 89.1	168
S-11	Adhesion	6,620 29.4	0.02 0.51	2970 13.2	0.05 1.27	36 0.9	36 0.9	287.76 11977.4	247.5 103.0	7
S-12	Adhesion	2,640 11.7	0.02 0.51	1300 57.8	0.10 2.54	36 0.6	36 0.6	325.54 13550.0	280.0 116.5	7
S-13	Shear	19,930 88.7	0.07 1.78	0 0	0.08 2.03	9 0.2	12 0.3	11.66 485.3	85.6 35.6	192
S-14	Shear	7,250 32.2	0.01 0.25	350 1.6	0.04 1.02	7 0.2	7 0.2	2.38 99.1	17.5 7.3	192
S-15	Adhesion -Bending	14,375 63.9	0.16 4.06	3840 17.1	0.36 9.14	8 0.2	3 0.08	- -	- -	168
S-16	Adhesion -Bending	4,100 18.2	0.08 2.03	1440 6.4	0.45 11.43	48 1.2	48 1.2	- -	- -	168

The type 1 curve is characteristic of diagonal tensile failures in which an immediate and complete reduction of layer resistance was observed after failure (test Nos. S-1, S-2, S-13 and S-14). A similar behavior is shown by the type 2 curve, typical of test Nos. S-3, S-5 and S-7, in which no steel plates were used and the adhesive failure propagated at least on one side to the margins of the layer. Once the maximum resistance of the layer was reached, however, it was held temporarily during additional displacement (up to 0.05 in.) of the movable block.

The type 3 and 3A curves reflect the structural behavior of the remaining layers. In these layers an adhesive failure initially developed between the shotcrete and the surface slab. However, the steel plates on the fixed block limited the lateral extent of this adhesion failure and allowed the layer to behave as a beam.

The character of the residual resistance shown by the 3 and 3A curves depends on the ductility and flexural strength of the shotcrete layer as well as the spacing between the steel plates. The type 3A curve is typical of the results obtained from tests in which shotcrete was placed against filament tape (low bond strength). The presence of the tape reduced the adhesive strength, therefore decreasing the maximum resistance of the layer. In this case the adhesive strength was nearly the same as the bending capacity of the layer. Type 3 curves were obtained when shotcrete was in contact with roughened concrete.

The resistance-displacement relationships for all the shotcrete tests are shown in Figs. 4.21 to 4.28. The maximum resistance and block

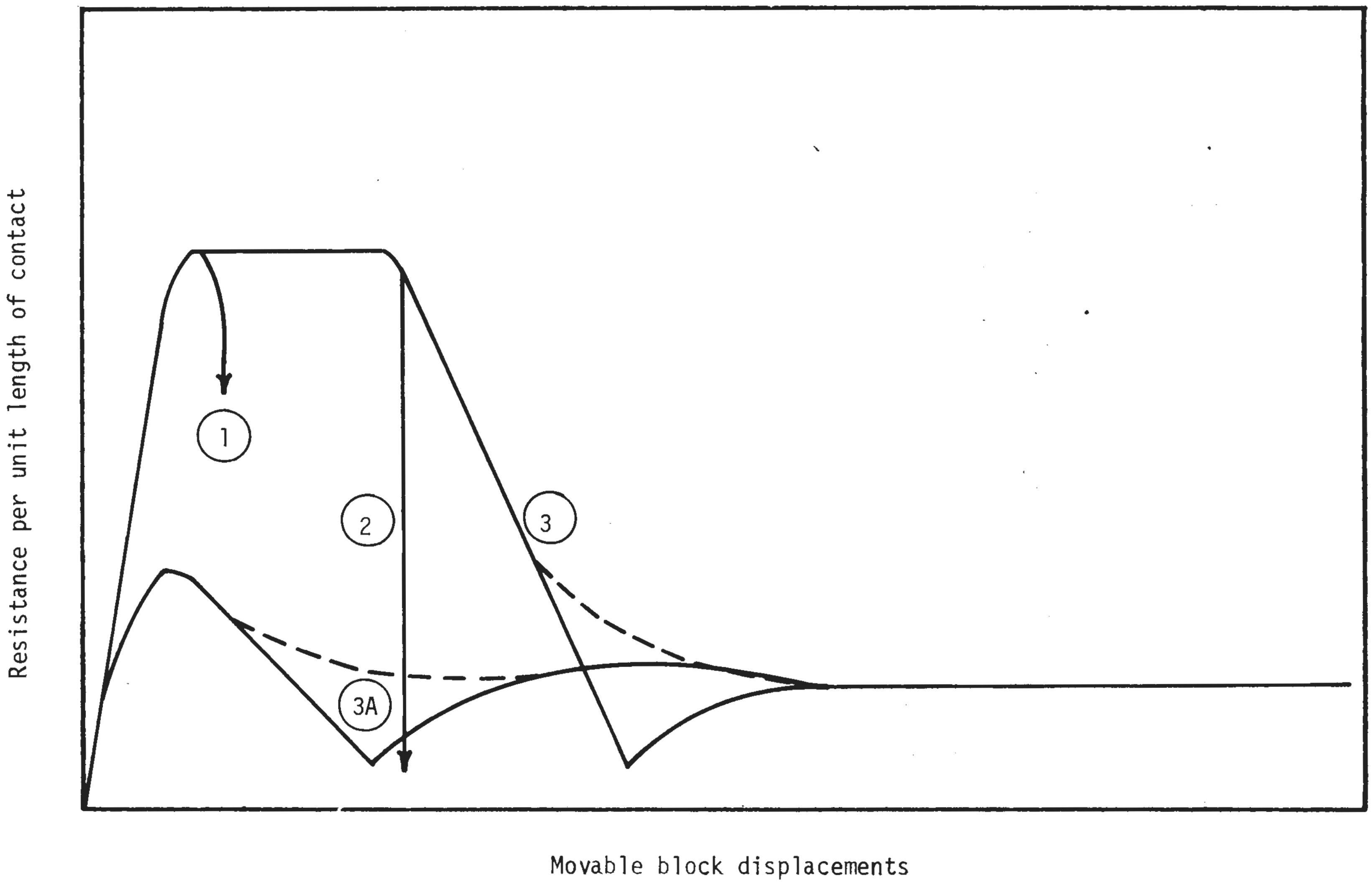


FIGURE 4.20 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

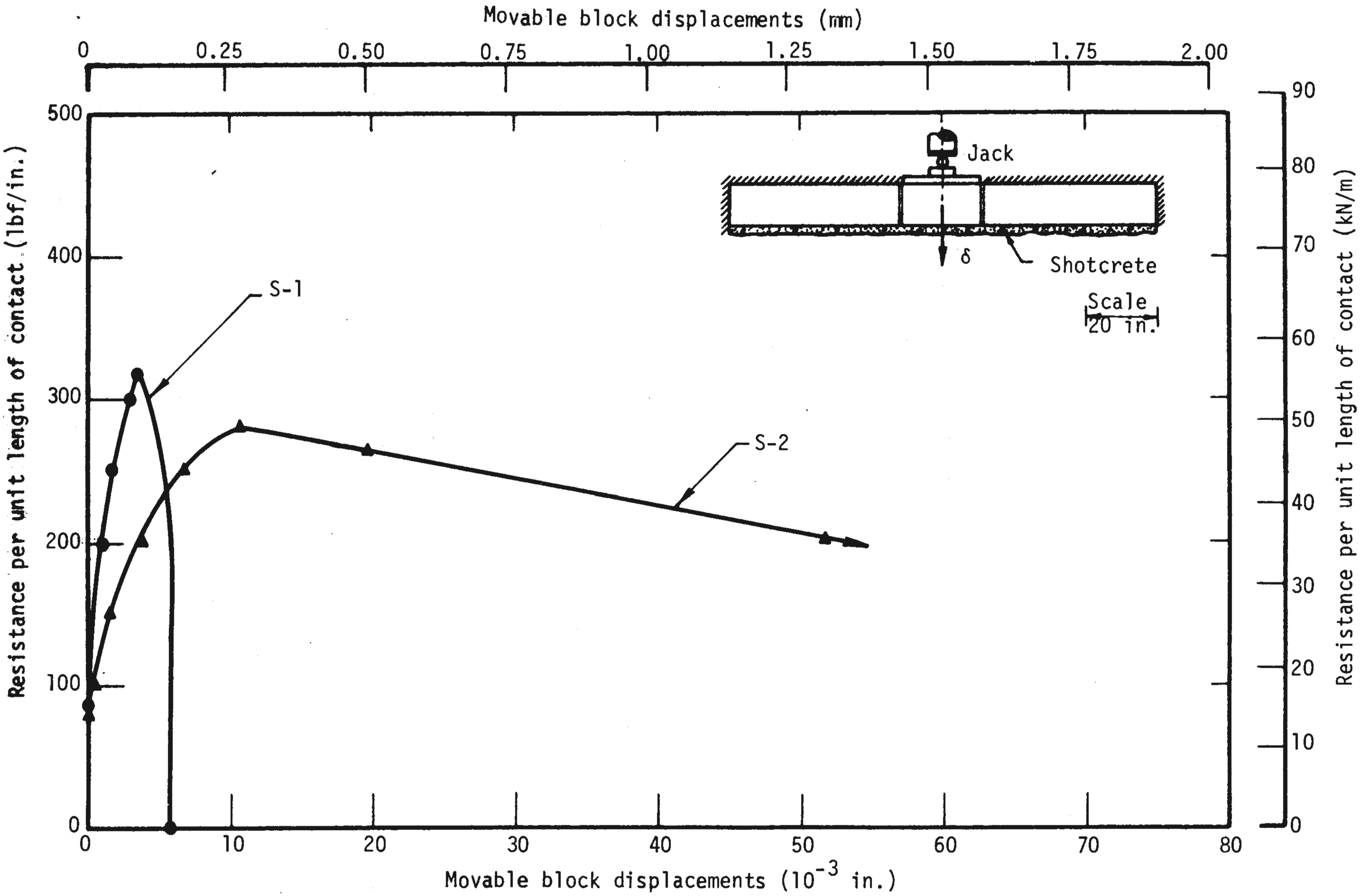


FIGURE 4.21 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

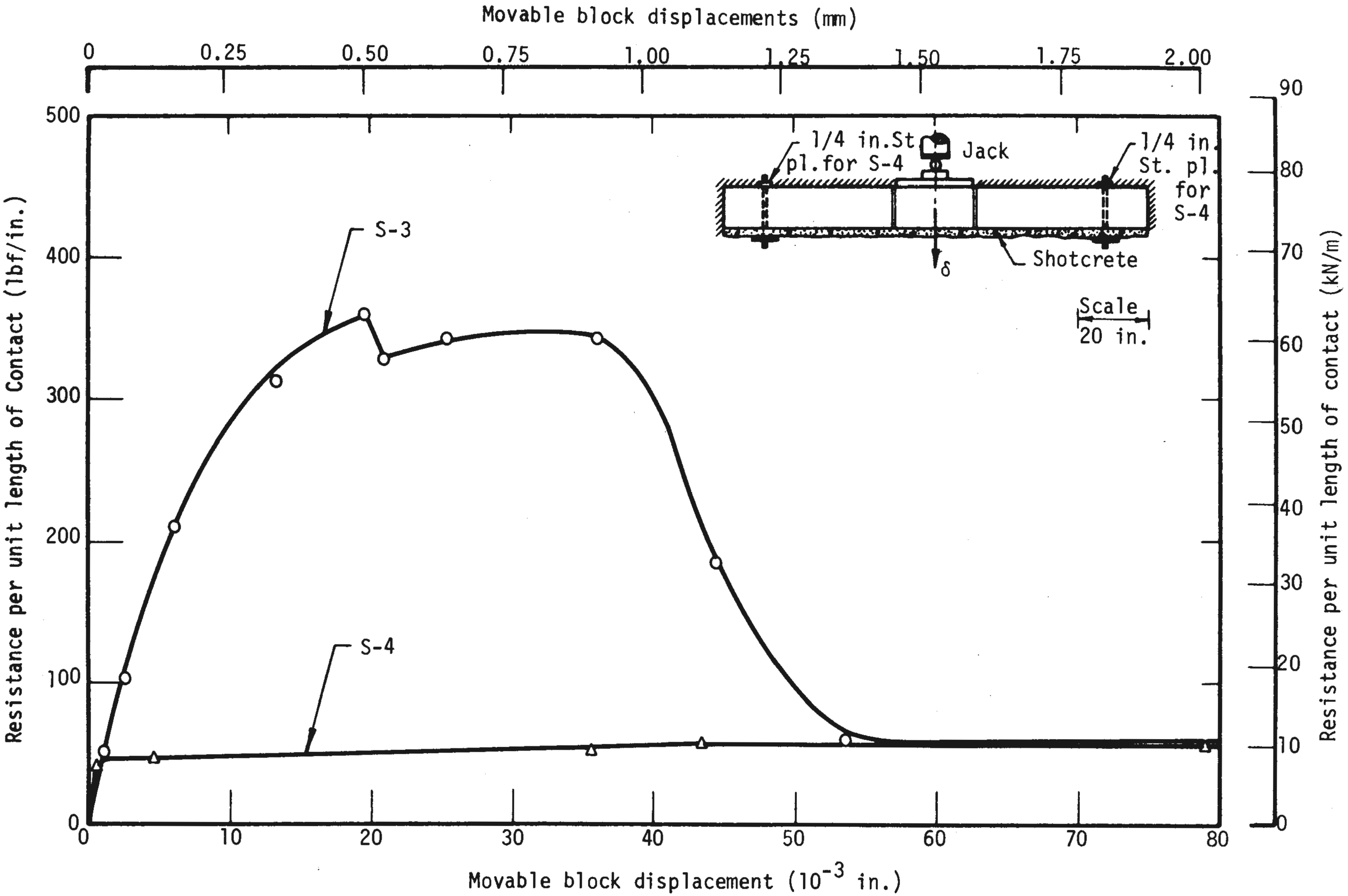


FIGURE 4.22 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

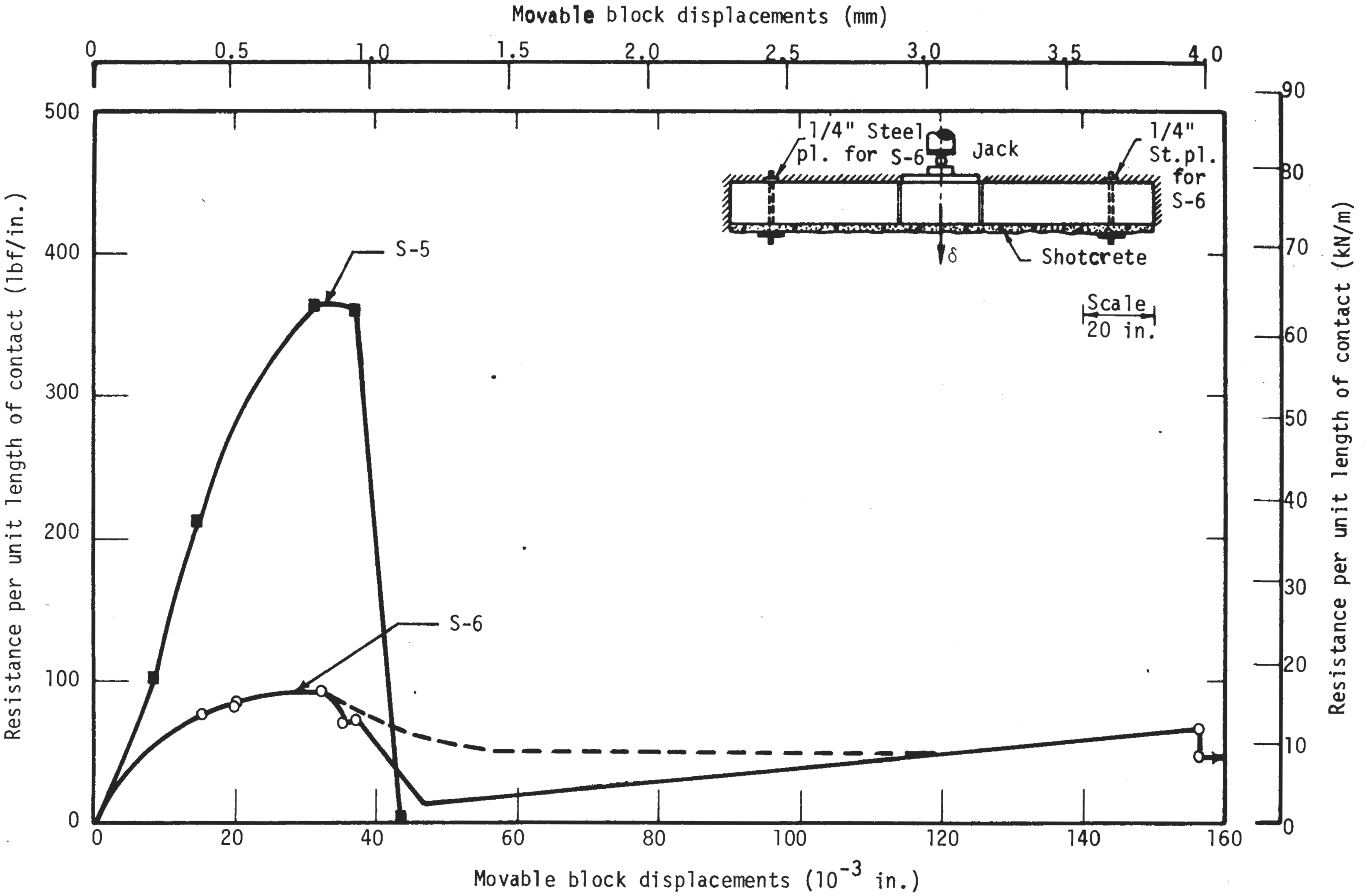


FIGURE 4.23 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

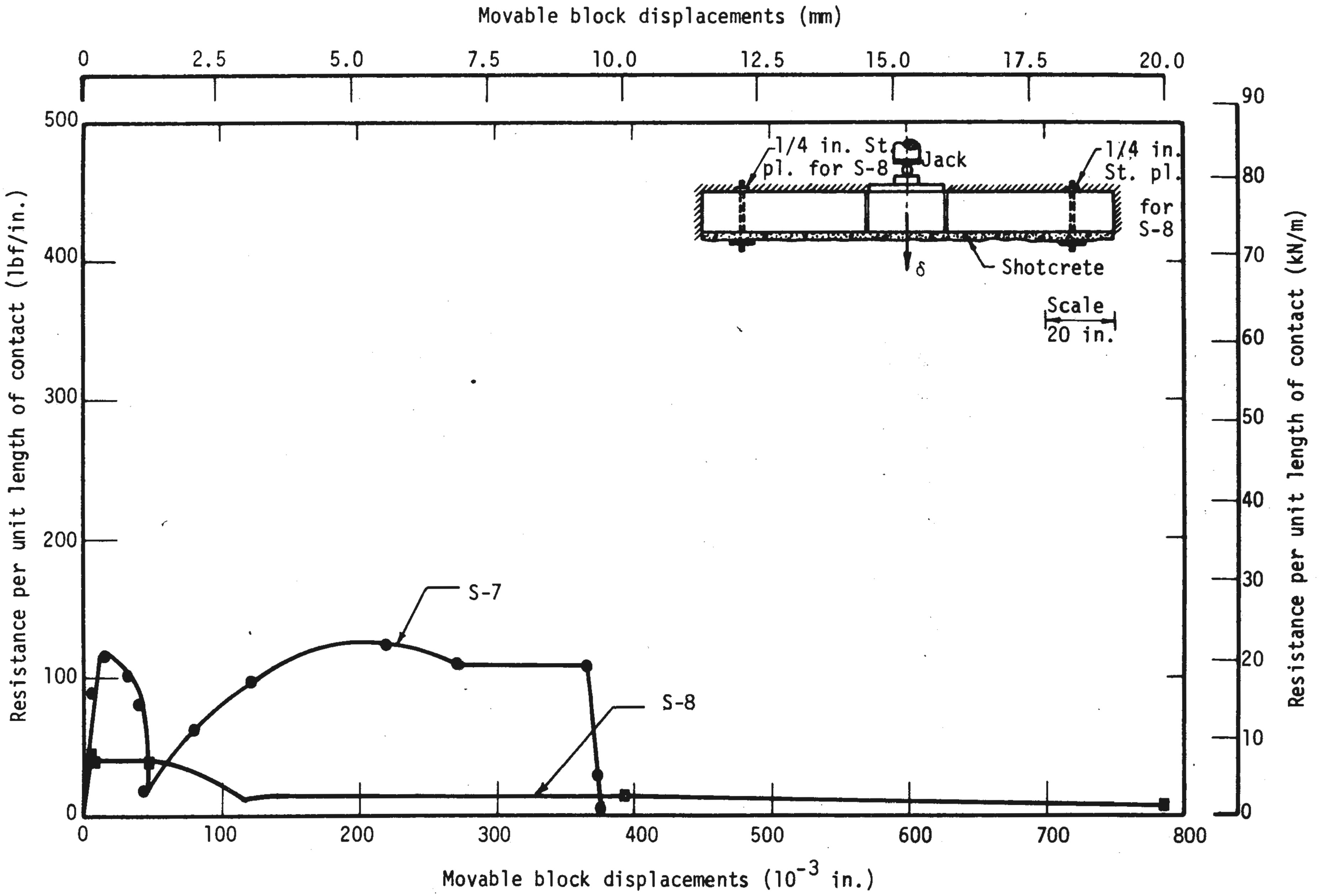


FIGURE 4.24 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

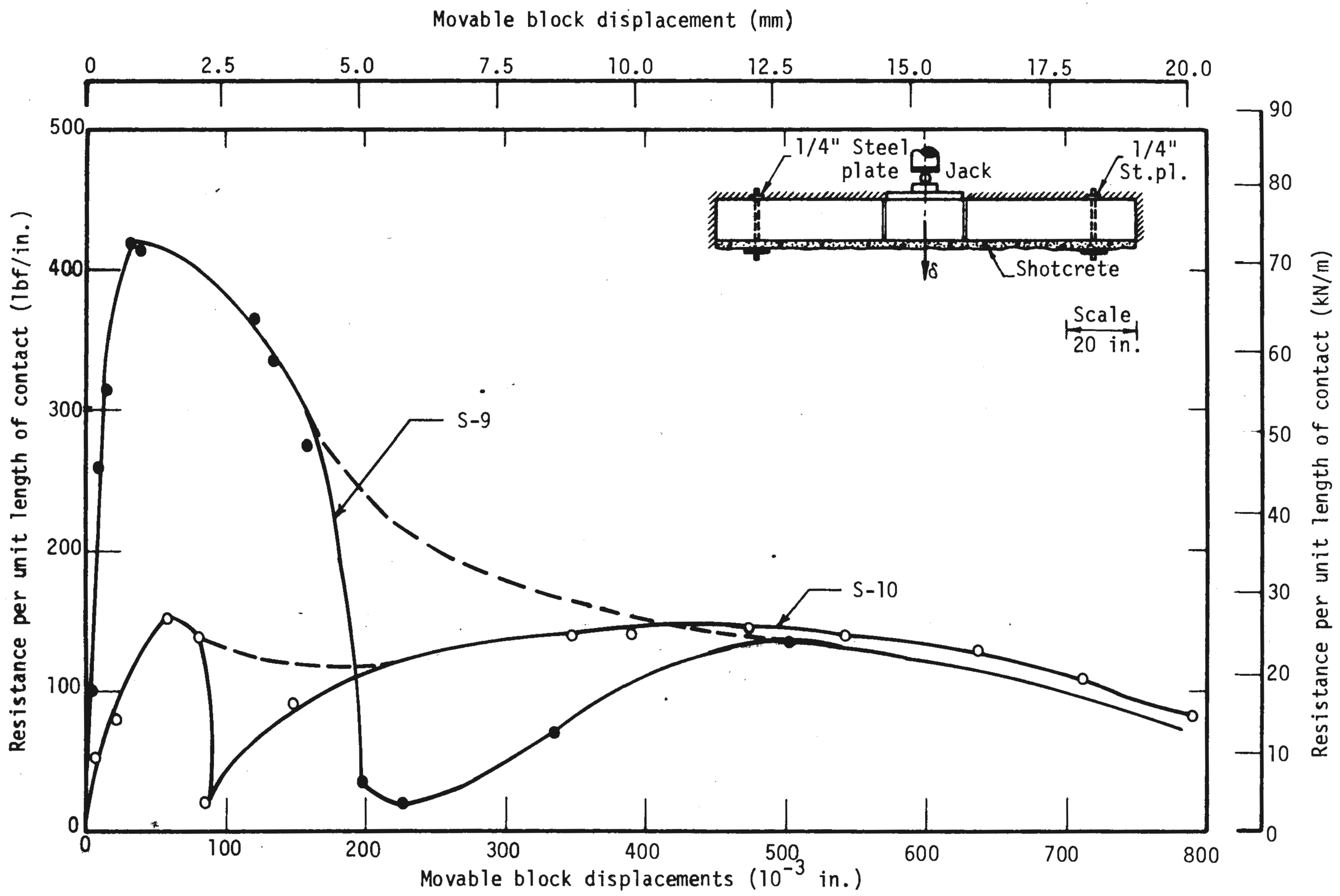


FIGURE 4.25 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

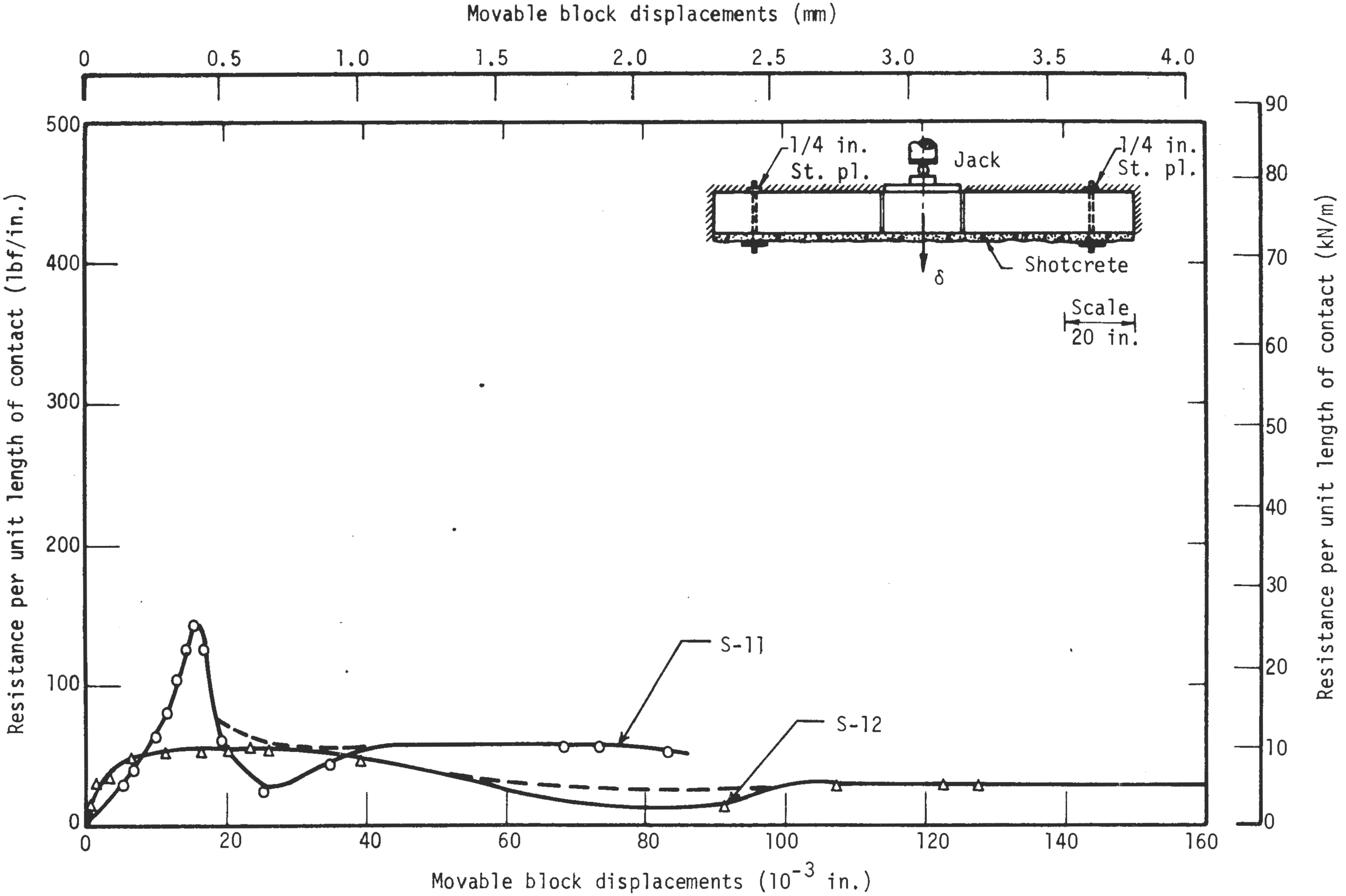


FIGURE 4.26 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

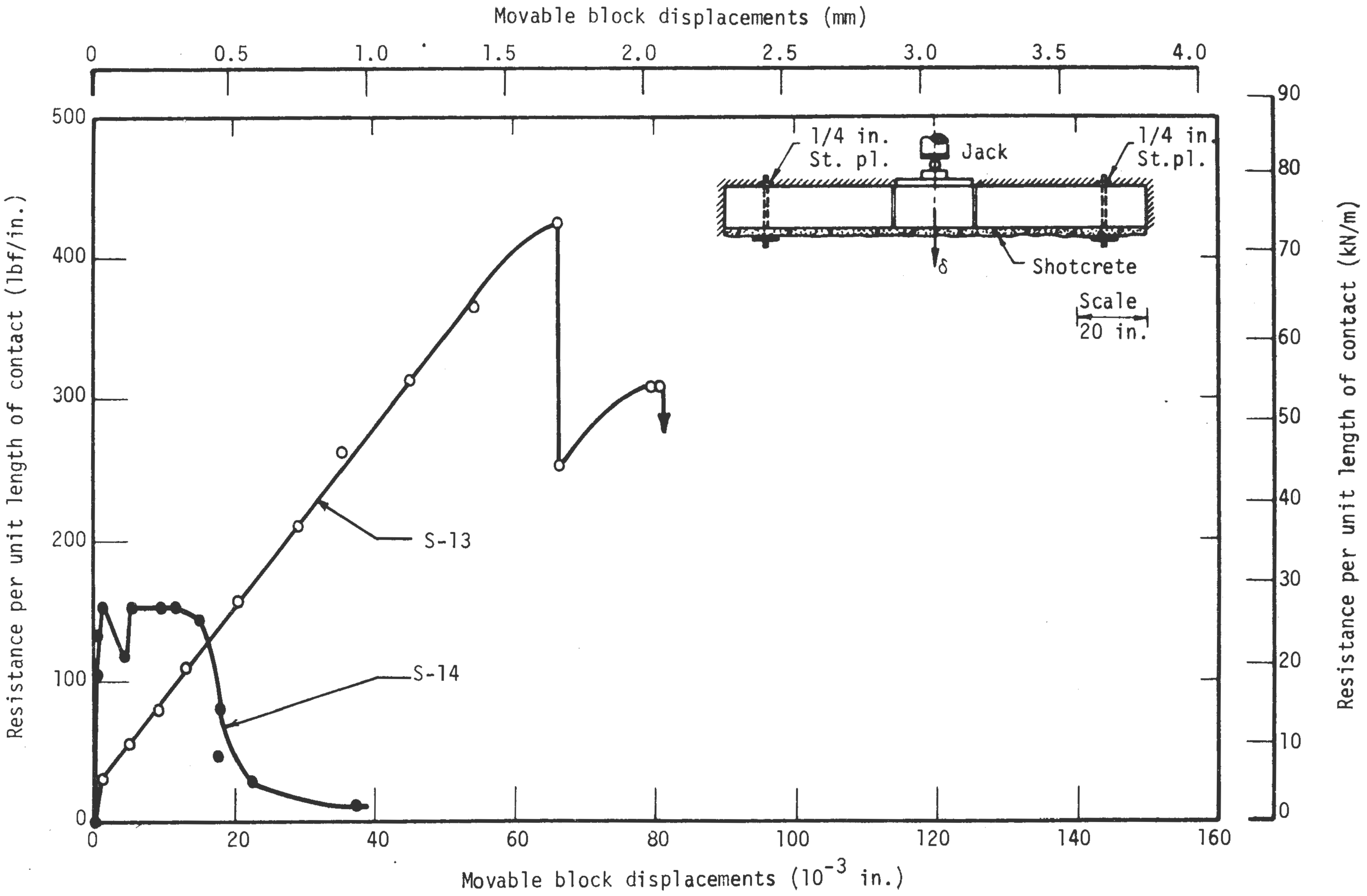


FIGURE 4.27 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

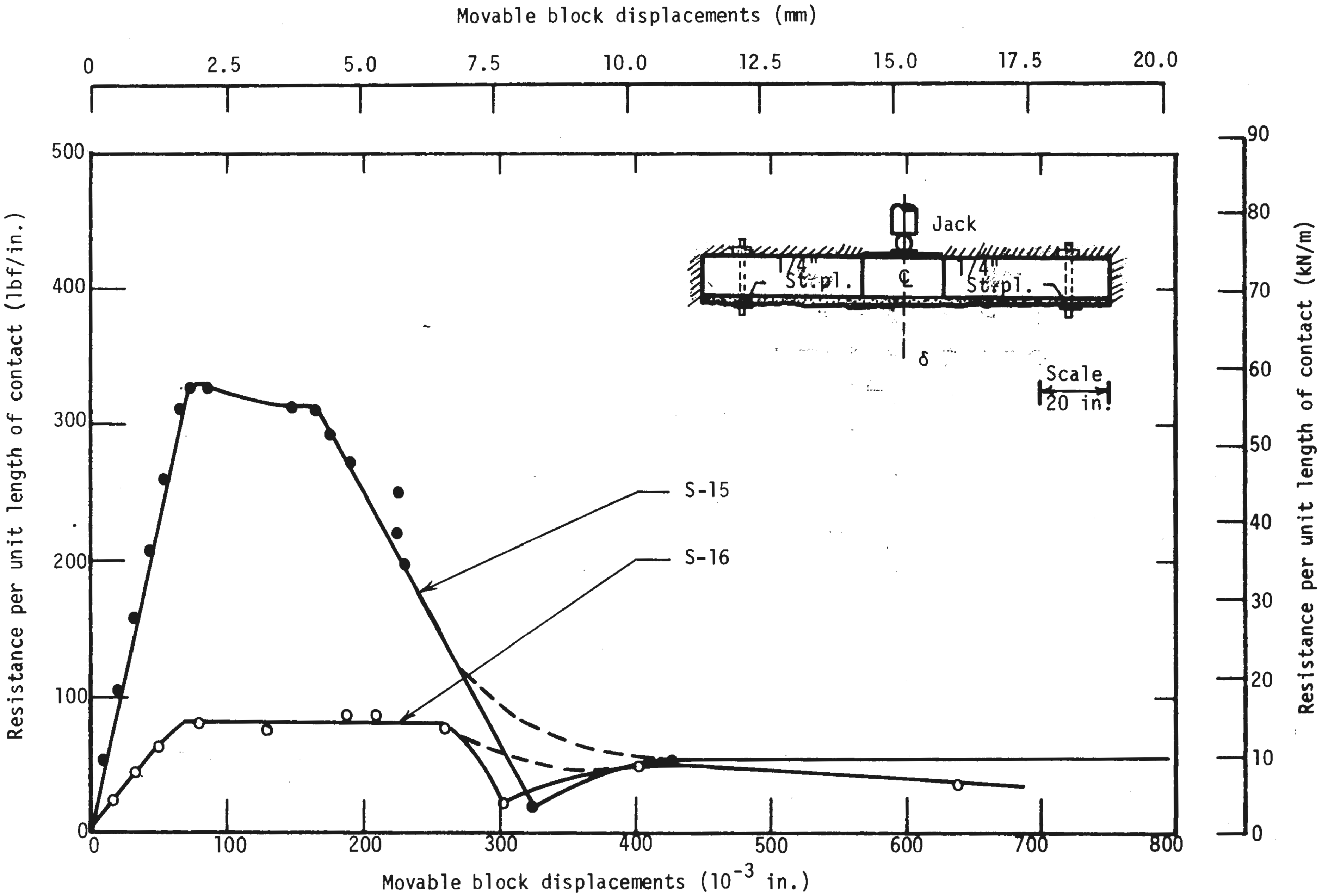


FIGURE 4.28 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

displacement obtained in each test are summarized in Table 4.4. Column 5 of the same table shows the value of the residual resistance after the adhesive failure reached its lateral boundary.

From the values given in Table 4.4, and the curves shown in Figs. 4.21 to 4.28, the following preliminary conclusions regarding the structural behavior of the shotcrete layers can be drawn.

1. The movable block displacement at which the maximum resistance of the shotcrete layers was developed varied between 0.01 to 0.16 in. (0.25 to 4.06 mm).
2. When failure occurred by separation of the shotcrete layer from the surface slab and no steel plates were present, the resistance remained at the maximum value as the separation gradually progressed outward. In these cases the movable block reached maximum displacements ranging between 0.04 in. (test No. S-5) and 0.3 in. (test No. S-3)(0.10 cm and 0.76 cm) without collapse of the shotcrete layer. This additional displacement of the movable block indicates certain ductility in the behavior of a thin shotcrete layer. This "ductility" depends on the adhesive strength along the total area of contact between the shotcrete layer and the surface slab and, more importantly, on the stiffness of the shotcrete layer.
3. Residual resistances ranging from 30 to 100 percent of the maximum layer resistance were observed depending on

the position of the boundaries, the shotcrete-slab bond and on the flexural strength of the layer. In these tests, the residual resistance was closest to the maximum resistance in layers having low bond strength and maximum thickness.

4. The presence of steel plates, simulating rock bolts or other tunnel boundaries, did not always have an influence on the structural behavior of the layers. In the cases where diagonal tension failures occurred, the failure surface did not extend more than 12 in. (30.5 cm) beyond the movable block, (curve type 1, test Nos. S-1, S-2, S-13 and S-14). Only steel plates located within 12 in. (30.5 cm) of the movable block would have had any effect on the structural behavior of the layer.

   In addition, steel plates located more than 30 in. (76.2 cm) from the movable block would not have had any influence in the residual resistance of the layer in test No. S-3. The minimum distance at which the lateral restraints begin to influence the residual resistance and displacement of the shotcrete layer depends on the nature of the adhesive strength in the vicinity of the movable block, the stiffness of the shotcrete layer, and, of course, any weak zones in the shotcrete layer created during or after shooting.

4.4.2 SHOTCRETE LAYER DISPLACEMENTS

Dial gages were placed against the front surface of the shotcrete layer and attached to a frame bolted to the floor to measure the relative forward displacements of the layer with respect to the floor. The displacements measured by these gages are shown in Figs. 4.29 to 4.43. These displacements were plotted in the same manner as those obtained in mortar tests. The upper portion of the figure shows a top view of the fixed walls and movable block, the shotcrete layer and the positions of the dial gages on the surface of the shotcrete. The displacements recorded by the dial gages at each load increment are plotted in displacement profiles. The resistance of the shotcrete layer at each increment is shown at the right side of the displacement profile.

The displacement profiles before initial failure are very similar for all tests in which adhesion failure occurred. Initially, equal increments of load resulted in equal increments of the forward displacement of the front surface of the shotcrete layer. The displacements were slightly greater along the vertical center line of the shotcrete layer and decreased toward the edges of the model. The shape of the displacement profiles, before failure, was produced by the stresses imposed on the layer at the contact with the movable block. Since the tensile stiffness at the contact between the shotcrete layer and the surface slabs is extremely high, the relative displacement was almost null.

In the cases where diagonal tension failures occurred, the displacement of the shotcrete surface increased linearly with increasing load.

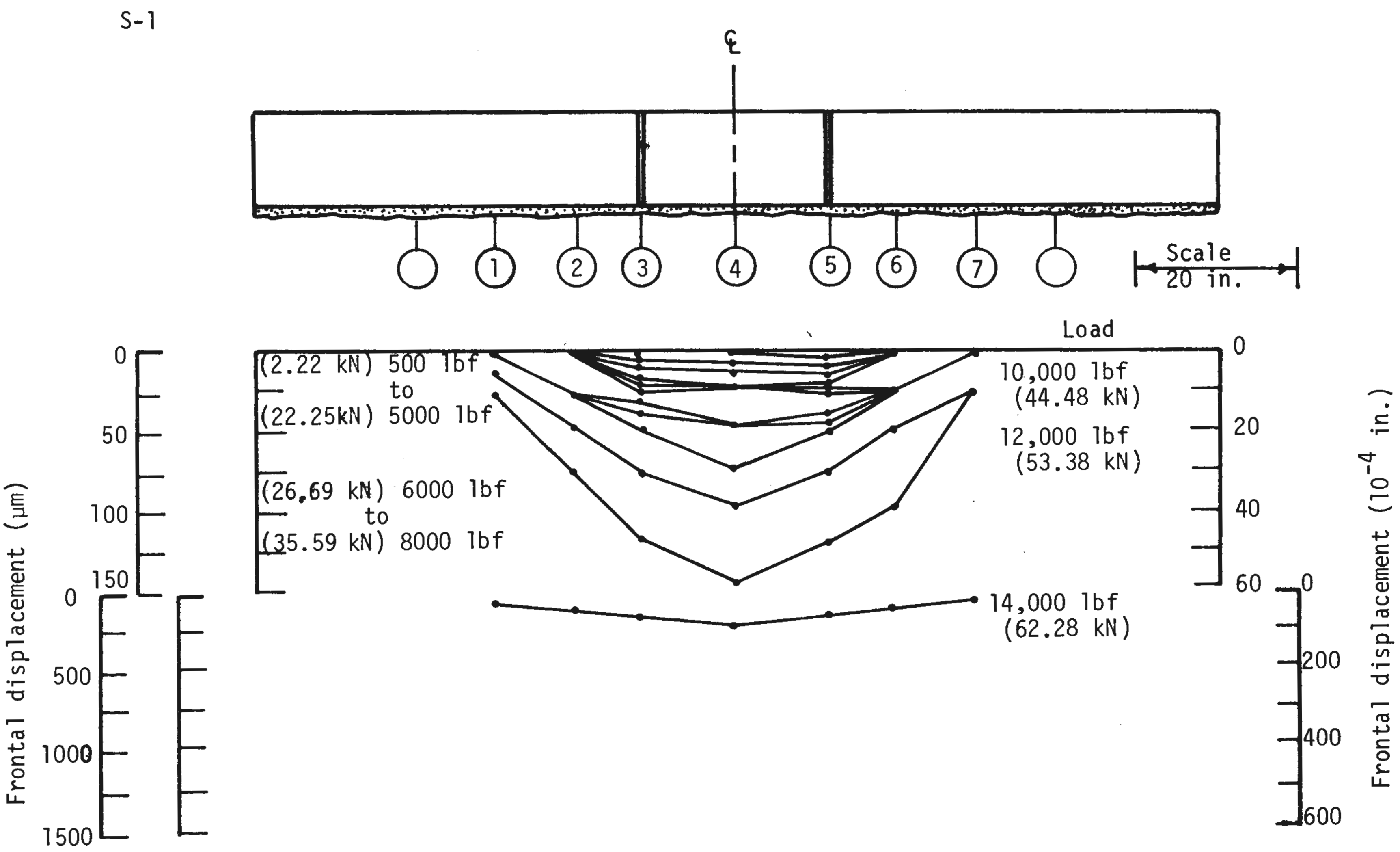


FIGURE 4.29 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

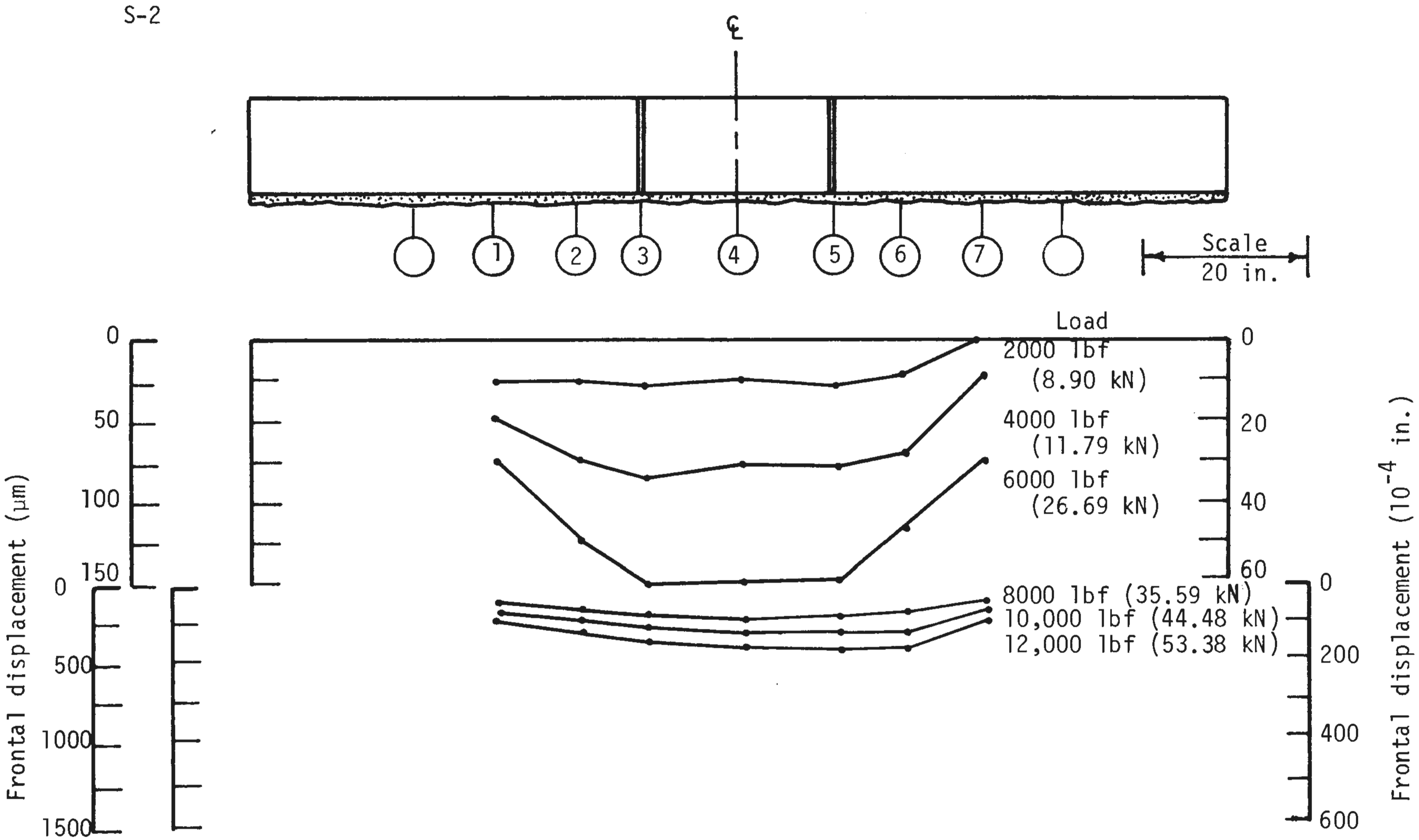


FIGURE 4.30 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

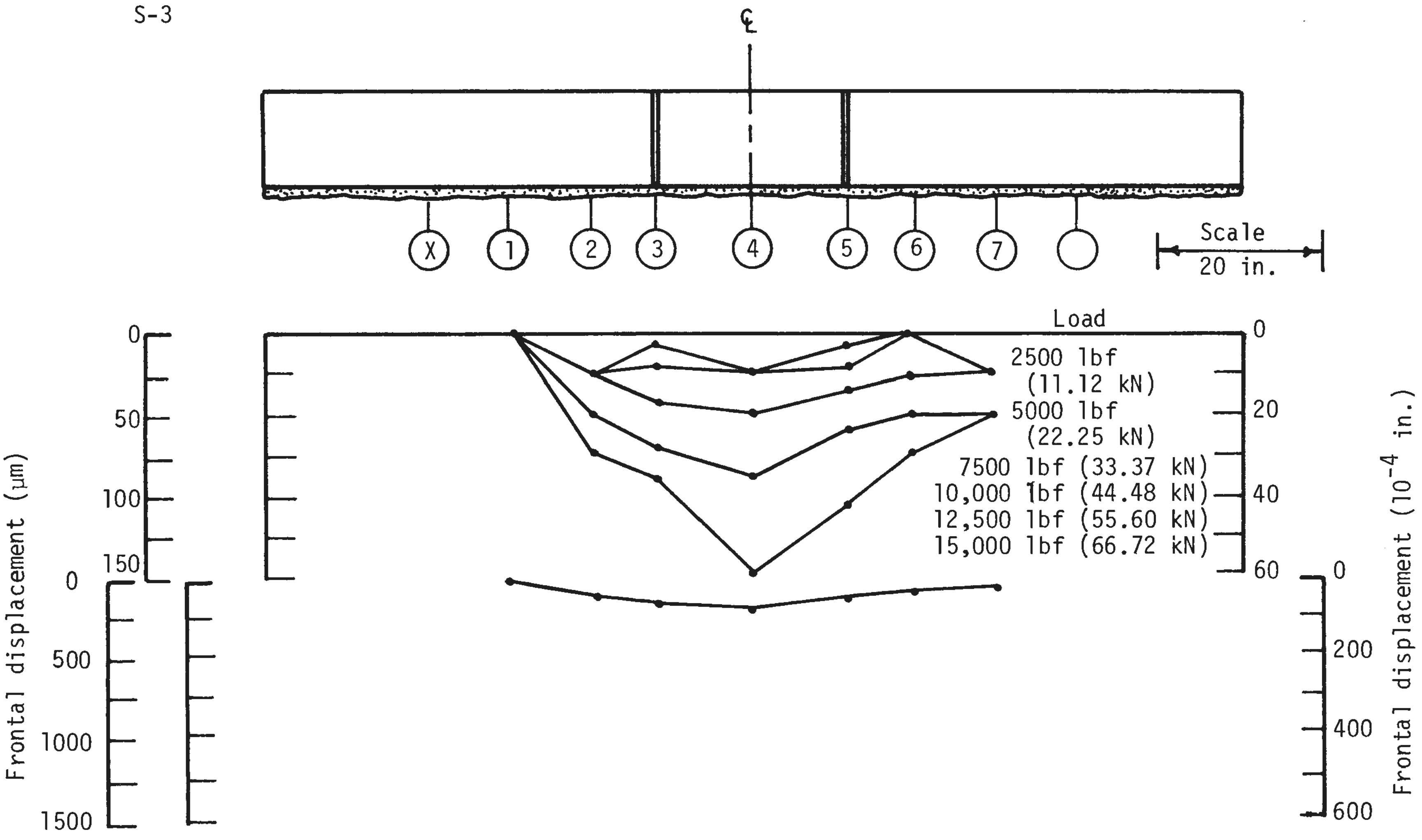


FIGURE 4.31 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

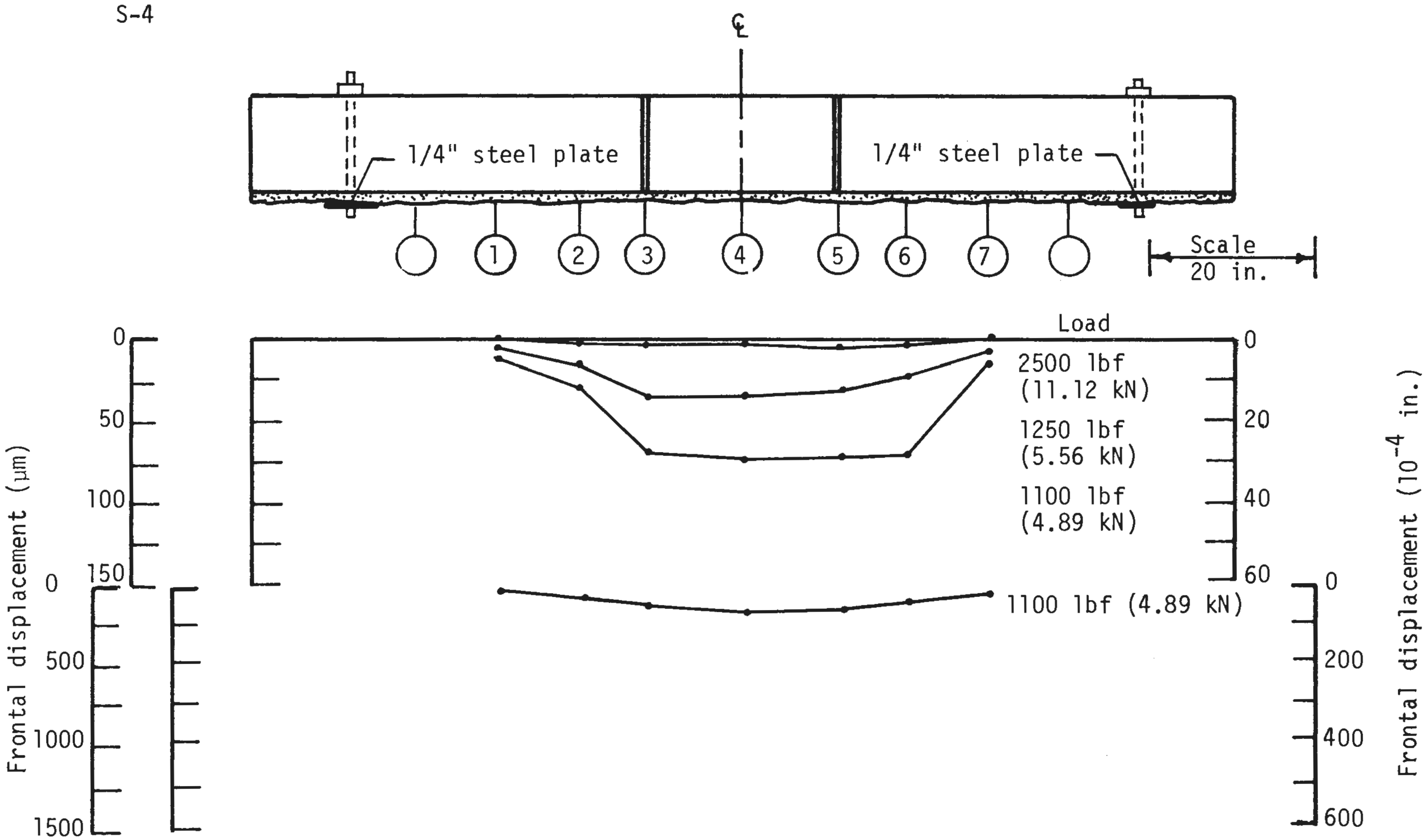


FIGURE 4.32 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

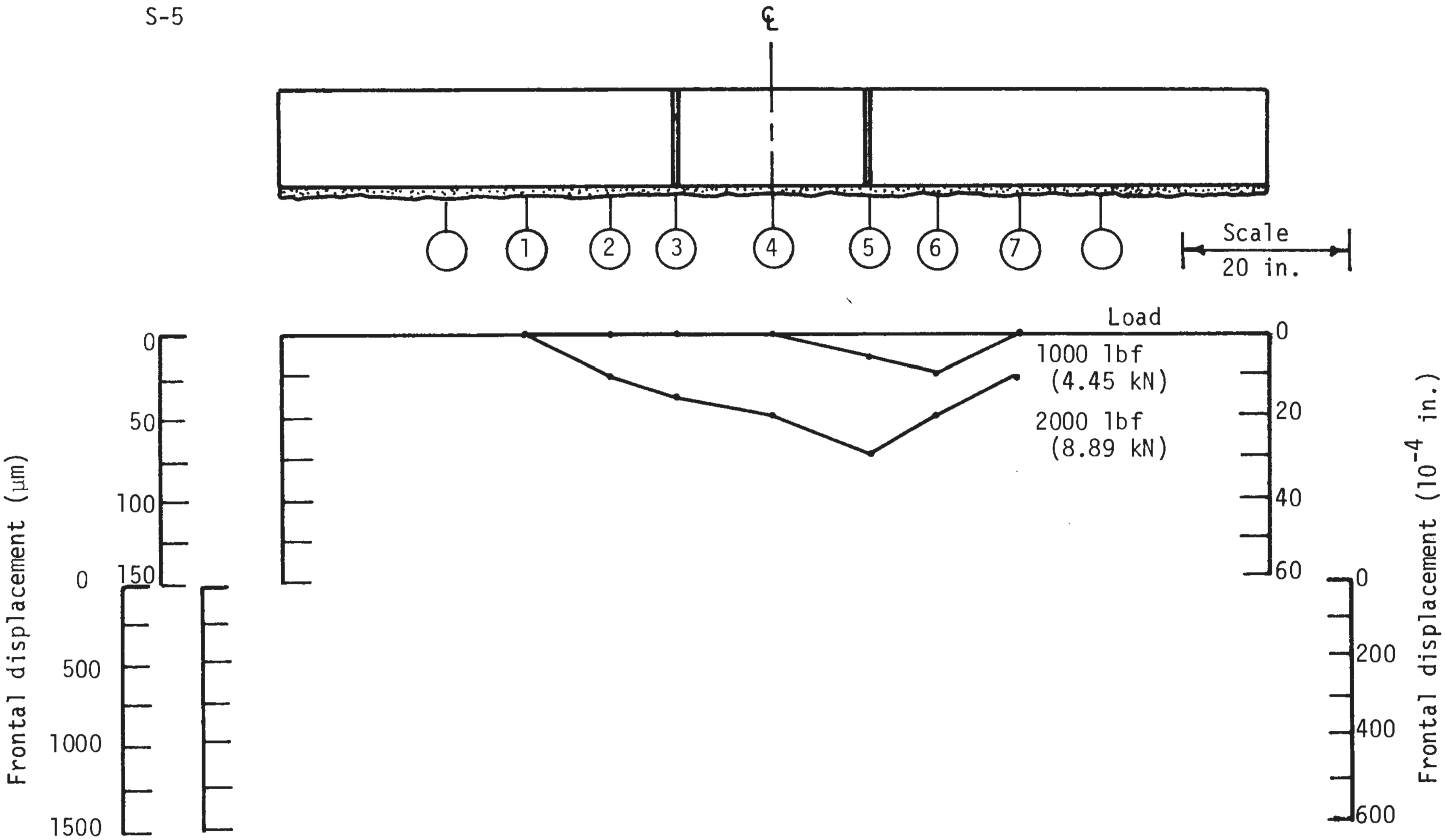


FIGURE 4.33 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

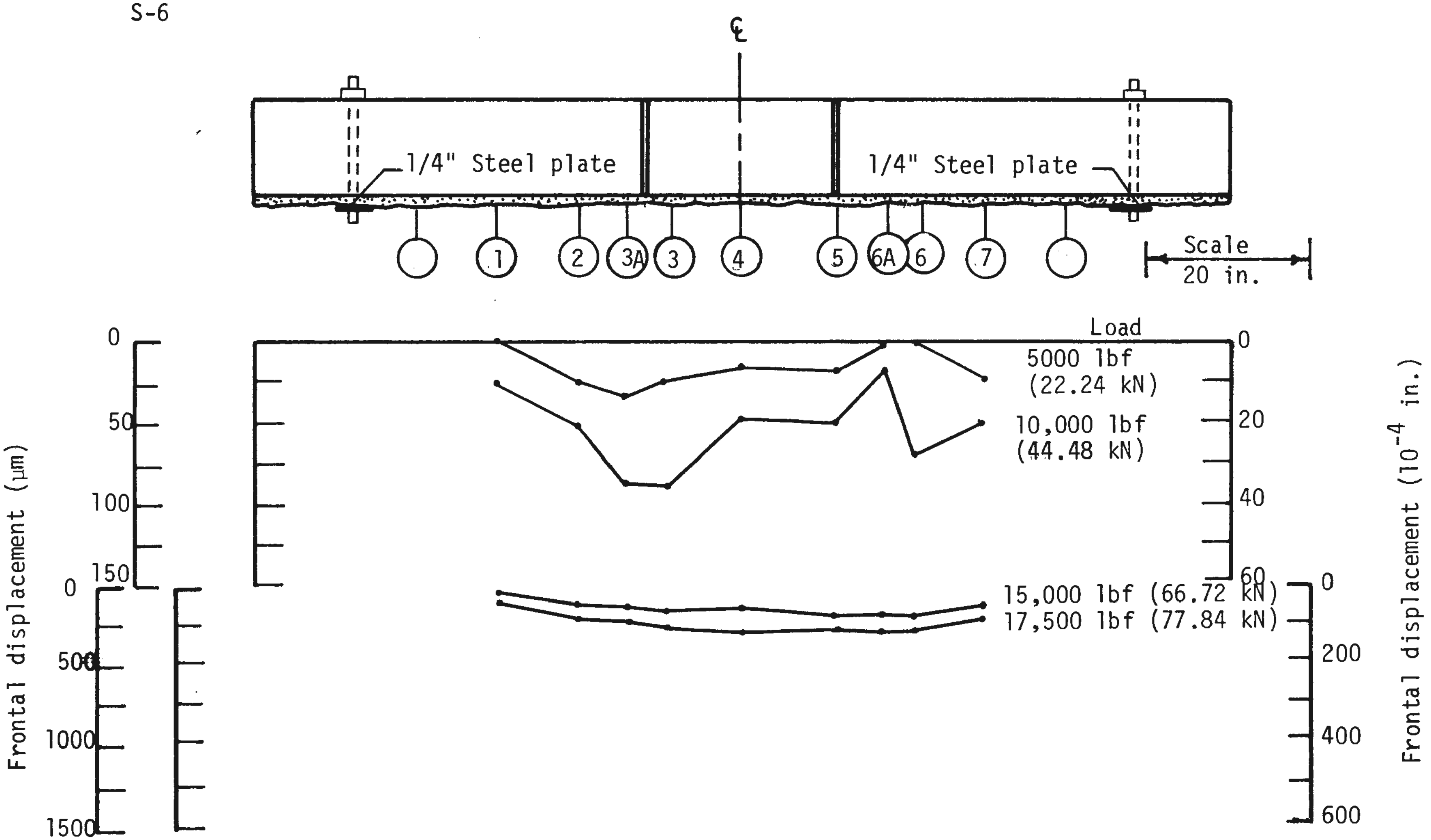


FIGURE 4.34 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

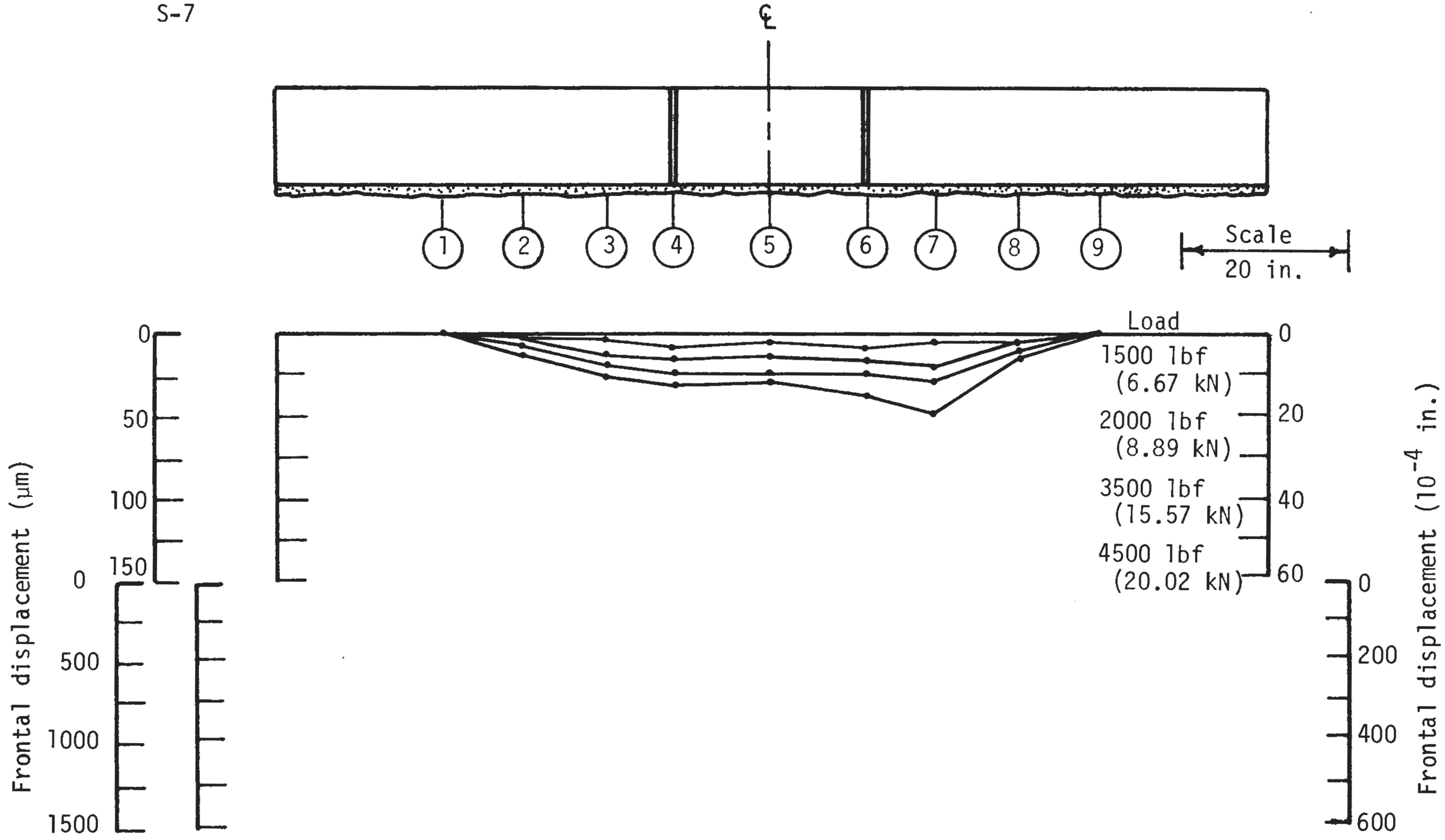


FIGURE 4.35 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

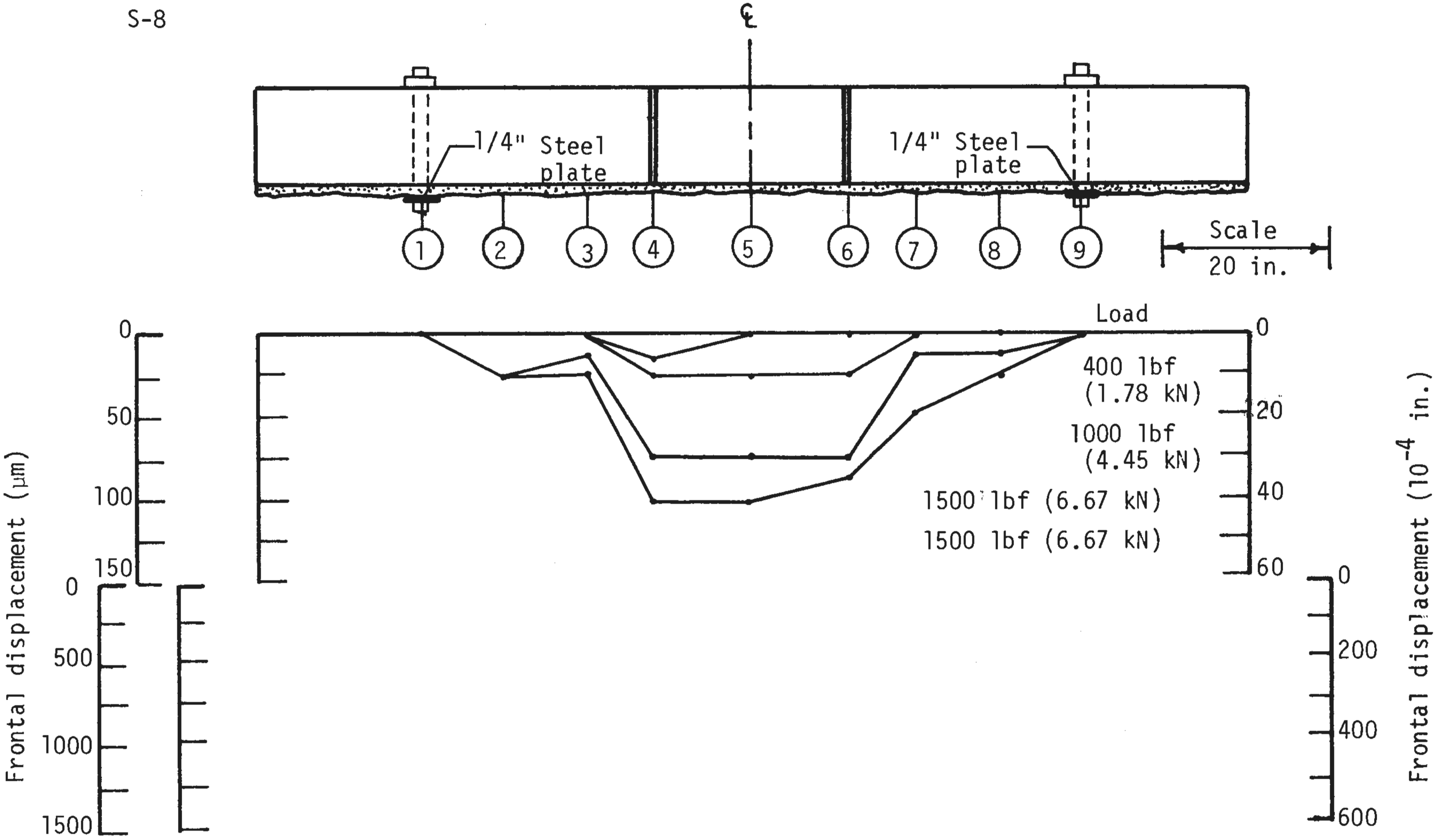


FIGURE 4.36 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

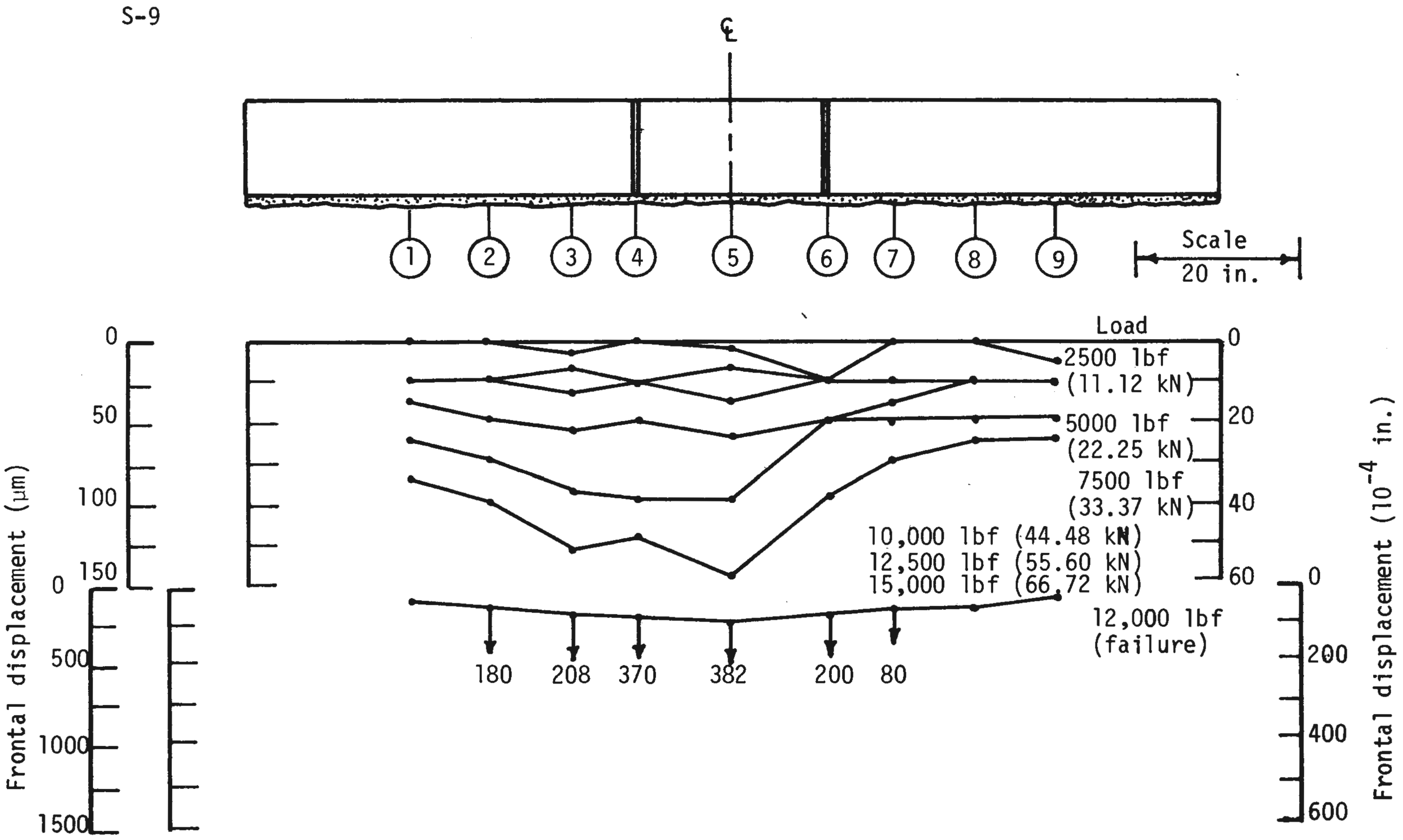


FIGURE 4.37 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

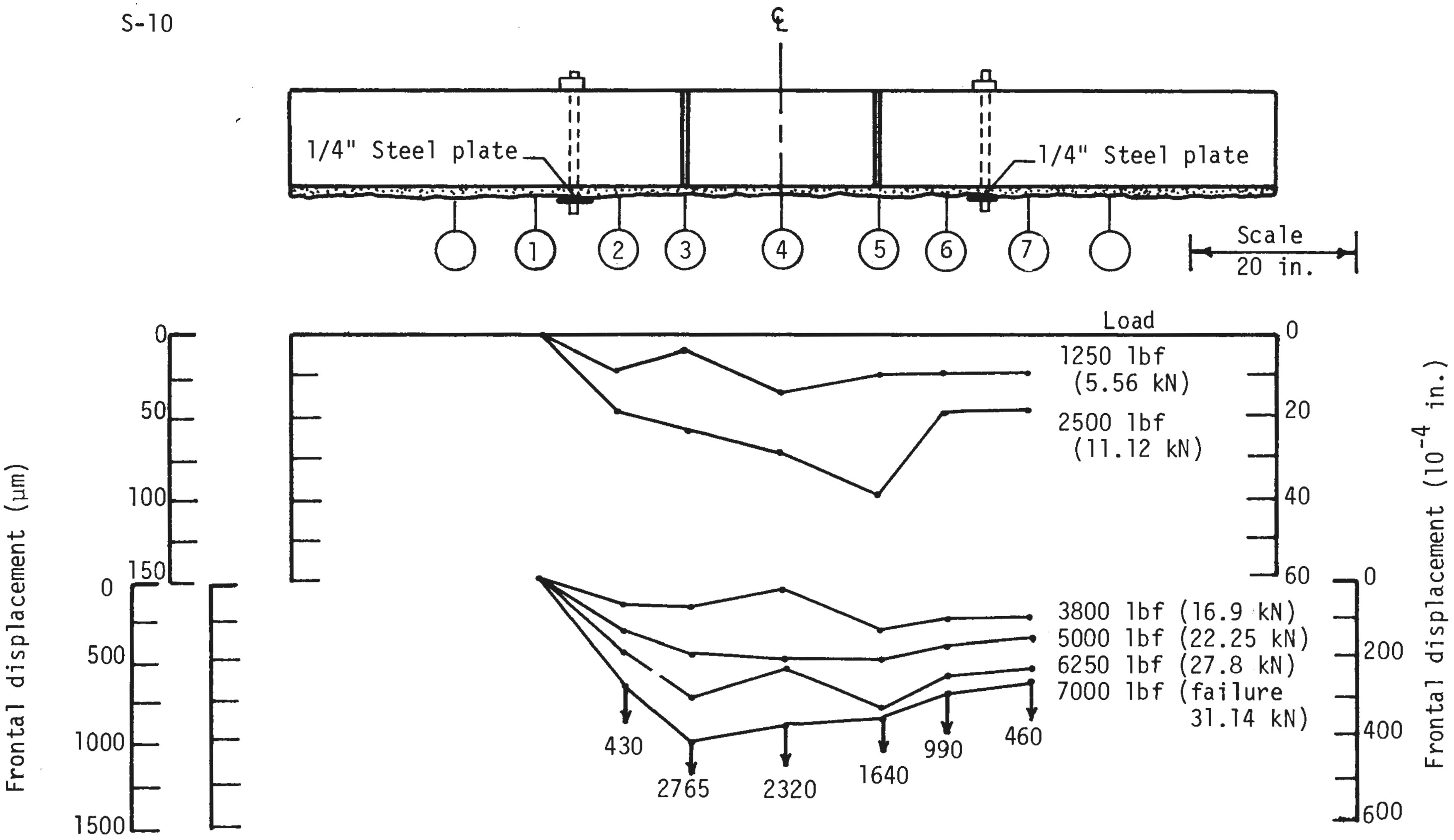


FIGURE 4.38 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

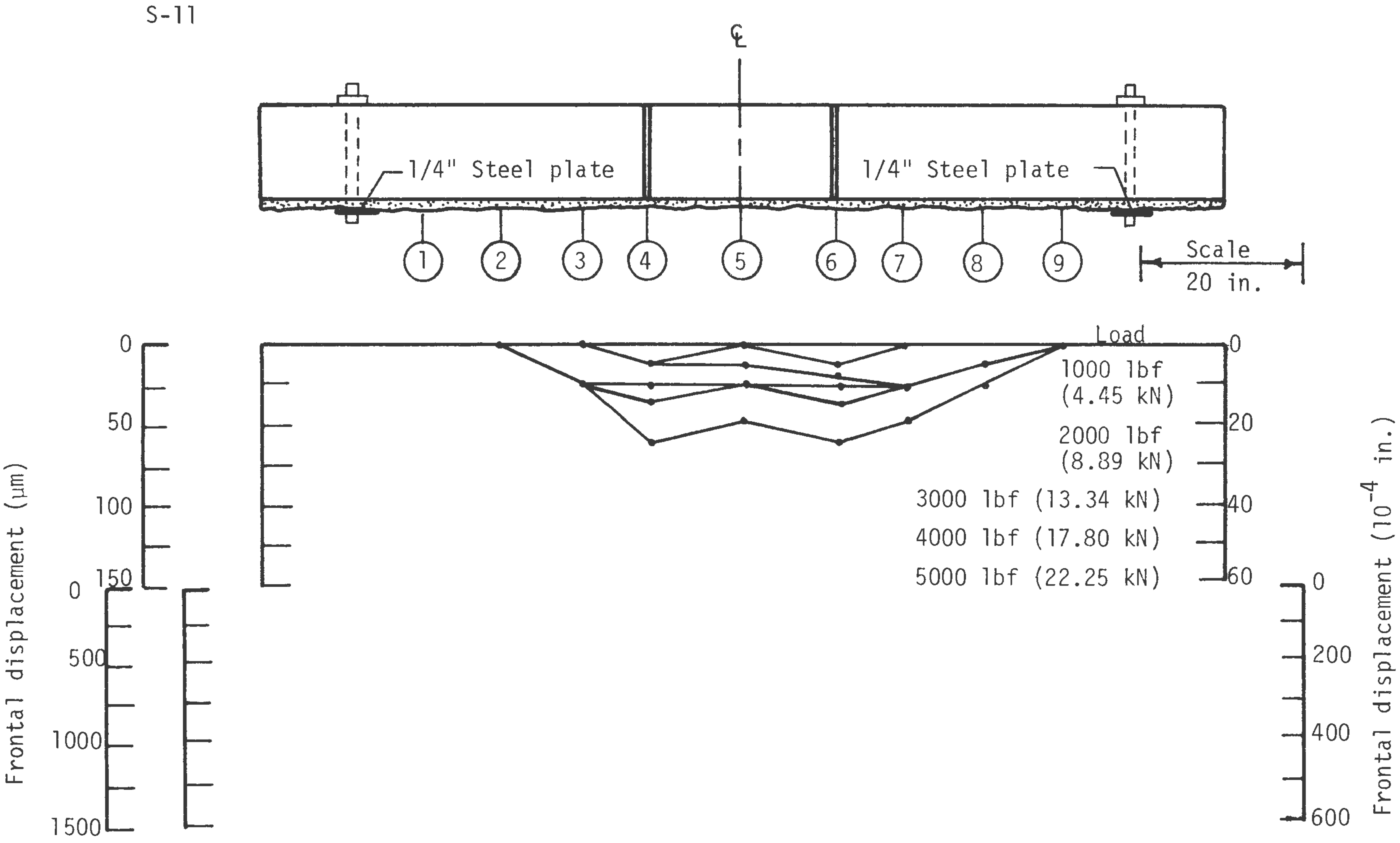


FIGURE 4.39 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

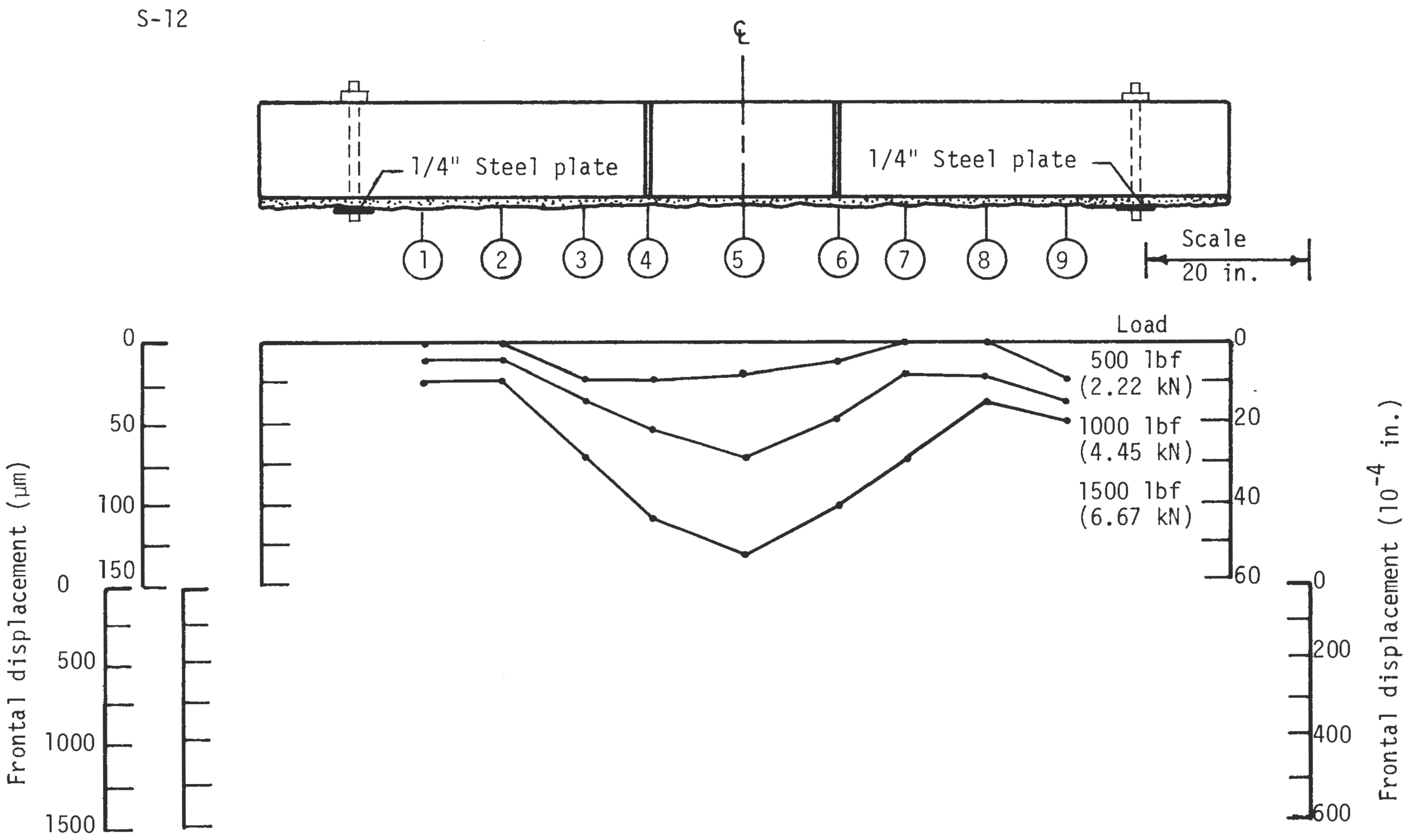


FIGURE 4.40 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

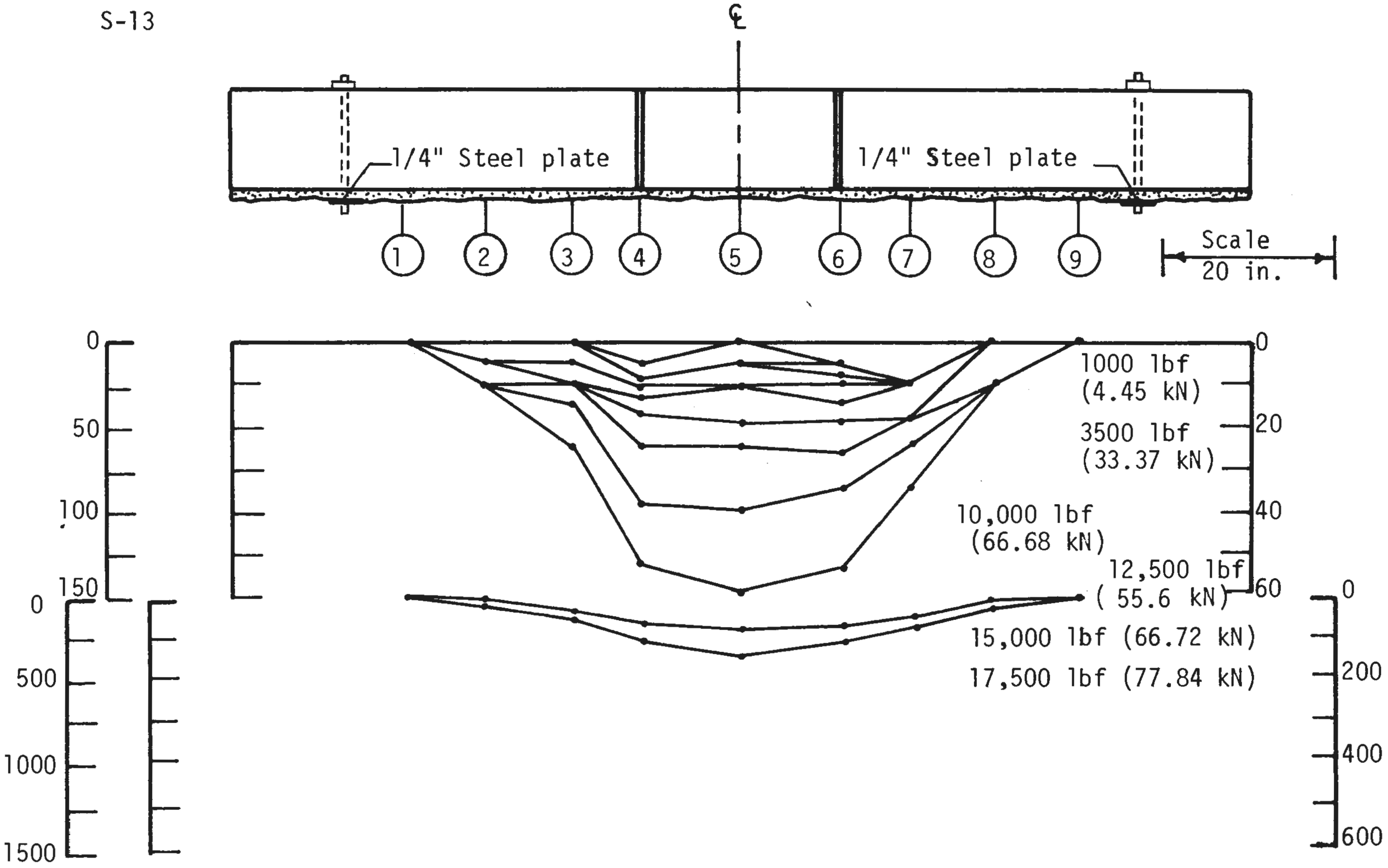


FIGURE 4.41 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

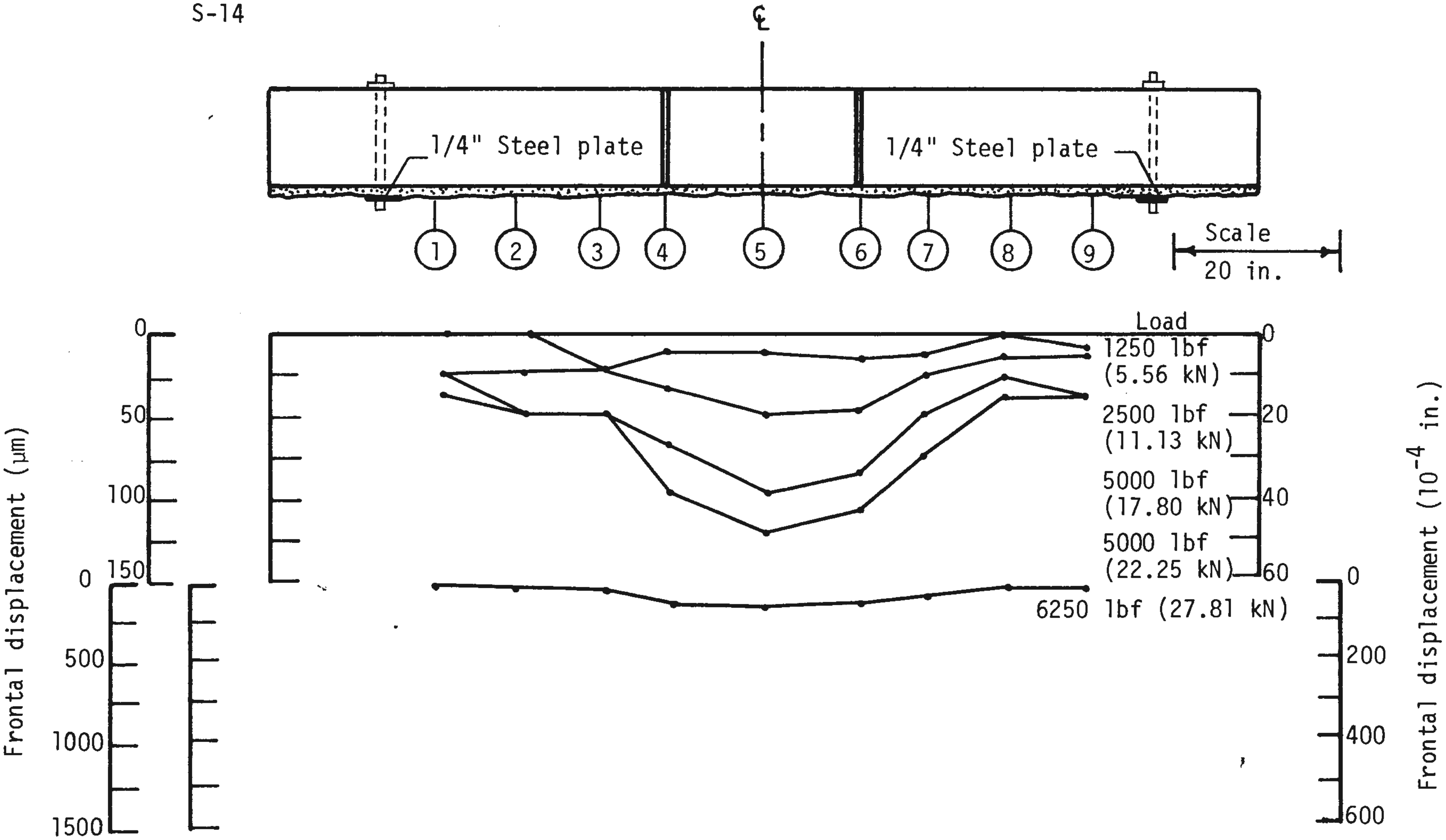


FIGURE 4.42 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

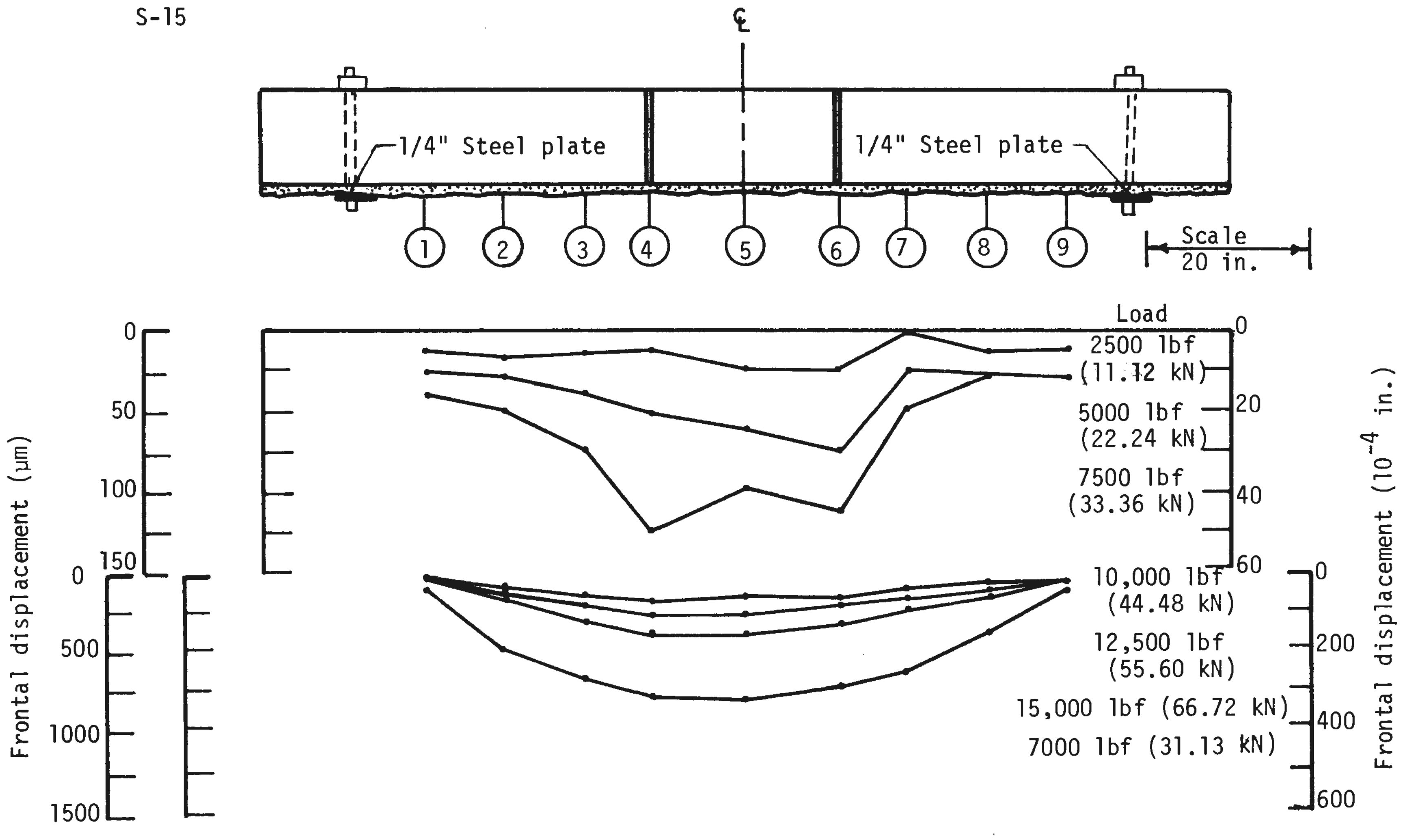


FIGURE 4.43 FRONT FACE DISPLACEMENT OF SHOTCRETE LAYER WITH RESPECT TO THE FLOOR

In these cases the adhesive force, F_0, was greater than F_1, the force required to induce a diagonal tension failure in the shotcrete layer. Separation of the shotcrete from the surface of the slabs occurred in two of these tests, Nos. S-1 and S-2, but was confined to a very narrow zone, 1-1/2 to 2 in. (3.81 to 5.08 cm) wide on the inside edge of the fixed wall. The initial loss of adhesion followed by the diagonal tension failure indicates that forces F_0 and F_1 were almost equal and both the adhesive strength and diagonal tension strength were fully mobilized.

When diagonal tension failures occurred,no additional resistance was offered by the shotcrete layers.

The second mode of failure, separation between the shotcrete layer and the concrete slabs, was present in all the other tests. The induced adhesive stress exceeded the adhesive strength between the shotcrete and the surface slabs before the level of stress in the layer reached the diagonal tension strength of the shotcrete. The separation of the shotcrete layer from the surface slab started at the movable block and progressed toward the boundaries of the layer. However, in the absence of steel plates the length of propagation of the failure surface was at least in part related to the thickness of the shotcrete. In test No. S-5, when the thickness of the shotcrete was 5.26 in. (13.4 cm), the failure propagated to the ends of the layer. In test No.S-3, 2.18in. (5.5 cm) thick. it progressed 15.5 in. (39.4 cm) to a point where the bending stresses in the inside face of the layer exceeded bending strength of the layer and a failure occurred. In test No.S-7, carried out on a 2.78in. (7 cm) thick layer cured only 7 hours, the adhesive failure propagated 48 in. (122 cm) on one side but only 24 in. (61 cm) on the other where a bending failure developed.

In the other tests, the shotcrete layer, after its separation from the surface slab, acted like a simply supported beam uniformly loaded in its center with end supports continuously moving apart to the limits imposed by the steel plates. Immediately after the adhesion failure propagated to the plates, the bending stresses produced by the ram exceeded the bending capacity of the layer and two vertical cracks appeared on the outside surface of the shotcrete along the contact between the movable and fixed blocks. The progressive separation of the shotcrete layer occurred so fast that the cracks appeared almost simultaneously with the adhesive failure.

In all tests, separation never occurred between the shotcrete layer and the surface slab covering the movable block.

4.4.3 LAYER RESISTANCE VS MOVABLE BLOCK DISPLACEMENT

The ram load and displacement were constantly monitored using an x-y plotter. The results were plotted in terms of unit resistance, i.e., the ram load divided by the vertical 48 in. (122 cm) of contact between the shotcrete layer and the fixed walls against the "net" displacement of the movable block.

Three basic types of curves corresponding to the three different structural behaviors were exhibited by the shotcrete layers (Fig. 4.20). In the load range before failure, all the curves showed a very stiff and linear relationship between the resistance of the layer and the relative displacement of the movable block. Once failure occurred, different structural behaviors of the shotcrete layer were observed as follows.

At load levels above 70 percent of the maximum layer resistance, a non-linear relationship developed in which rate of displacement increases faster than the rate of load.

The profile of displacements along the shotcrete layer out from the movable block depends mainly on the tensile stiffness between the shotcrete layer and the surface slab. It also depends on the stiffness of the shotcrete layer and to a lesser degree on the location of the lateral restraints. The post-failure displacements of some of the shotcrete layers occurred very rapidly and were not measured in tests represented by type 1 and 2 curves (Fig. 4.20). In tests represented by type 3 and 3A curves, displacements of the movable block were controlled so that the displacements of the shotcrete layer could be observed. In four of the tests (test Nos. S-4, S-8, S-9 and S-15) the shotcrete surface displacements were closely monitored thus allowing the deflective shape of the shotcrete layer and the propagation of the adhesive failure to be observed.

The deflected shapes of the failed shotcrete layers are very similar to those of the mortar layers and resemble the deflected shape of a simply supported beam (test No. S-4 - Fig. 4.32). In addition, the displacement obtained from dial gages placed against the center of the block were nearly the same as those obtained from the LVDT in the ram for the same load increments.

4.5 EVALUATION OF VARIABLES INFLUENCING THE STRUCTURAL BEHAVIOR OF THE LAYER

Each of the 16 shotcrete layer tests was carried out to evaluate the effect of a particular variable on the structural behavior of the layer. The variable to be compared in a given set of tests is summarized in Table 4.5. The influence of variables on the structural behavior will be discussed in the following section and will be described in terms of their effect on the observed modes of failure and the resistance and displacement of the movable block.

4.5.1 LATERAL BOUNDARIES

The effect of lateral boundaries on the behavior of the shotcrete layer can be seen by comparing test Nos. S-3, S-4, S-9 and S-10. Test Nos. S-3 and S-9 were carried out with shotcrete layers having approximately the same thickness and strength, however in test No. S-9 the lateral boundaries of the layer were located 4 ft (121.9 cm) apart, while in test No. S-3 steel plates were not used. In both tests, the same mode of failure involving separation of the shotcrete layer from the surface slab was observed. The maximum resistance of both shotcrete layers and the slope of the load-displacement curve were almost the same. After the peak load was reached in test No. S-3, the resistance dropped off rapidly after a small displacement (0.04 in.; 1.02 mm) of the movable block. In test No. S-9, however, the residual resistance decreased gradually (dashed line - Fig. 4.44) and finally reached zero after a relatively large (1.0 to 1.5 in.; 25.4 to 38.1 mm) displacement of the movable block. The ductility of the layer having lateral restraint was approximately 3 times that without restraining boundaries.

Figure 4.45 shows the resistance - displacement relationship for

TABLE 4.5

VARIABLES COMPARED IN THE SHOTCRETE LAYER TESTS

Test no.	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8	S-9	S-10	S-11	S-12	S-13	S-14	S-15	S-16
S-1	R															
S-2	T	T														
S-3																
S-4			A	T												
S-5	T	T	T													
S-6					A											
S-7			M													
S-8				M			A									
S-9			L													
S-10				L					A							
S-11					M											
S-12						M					A					
S-13	T	T	T						T							
S-14	T	T	T						T			T				
S-15			Re		Re				Re							
S-16				Re		Re				Re						

LEGEND:
R = Repeatability
T = Thickness value
A = Adhesion surface characteristics
M = Mortar strength
L = Lateral boundary conditions
Re = Reinforcement

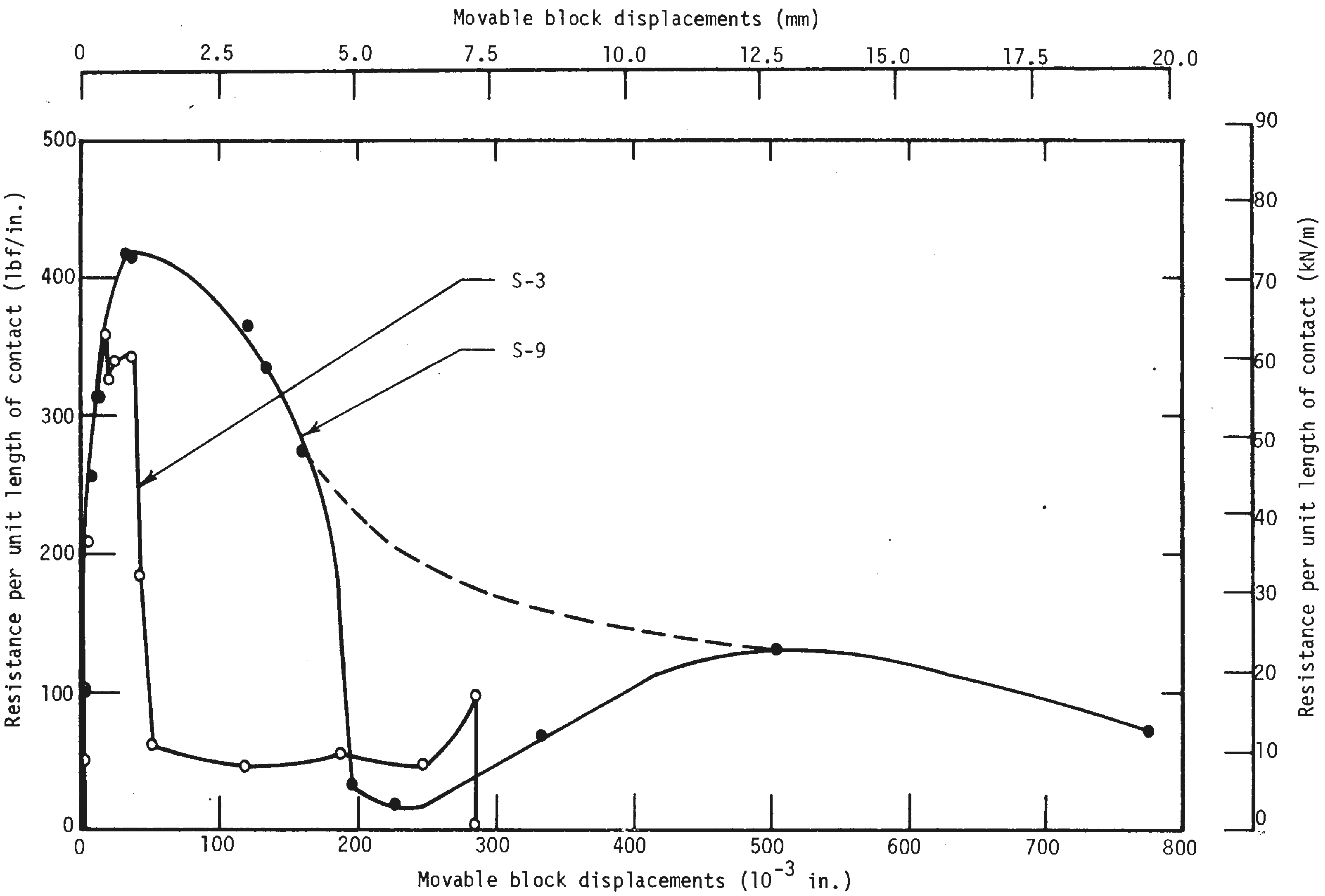


FIGURE 4.44 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

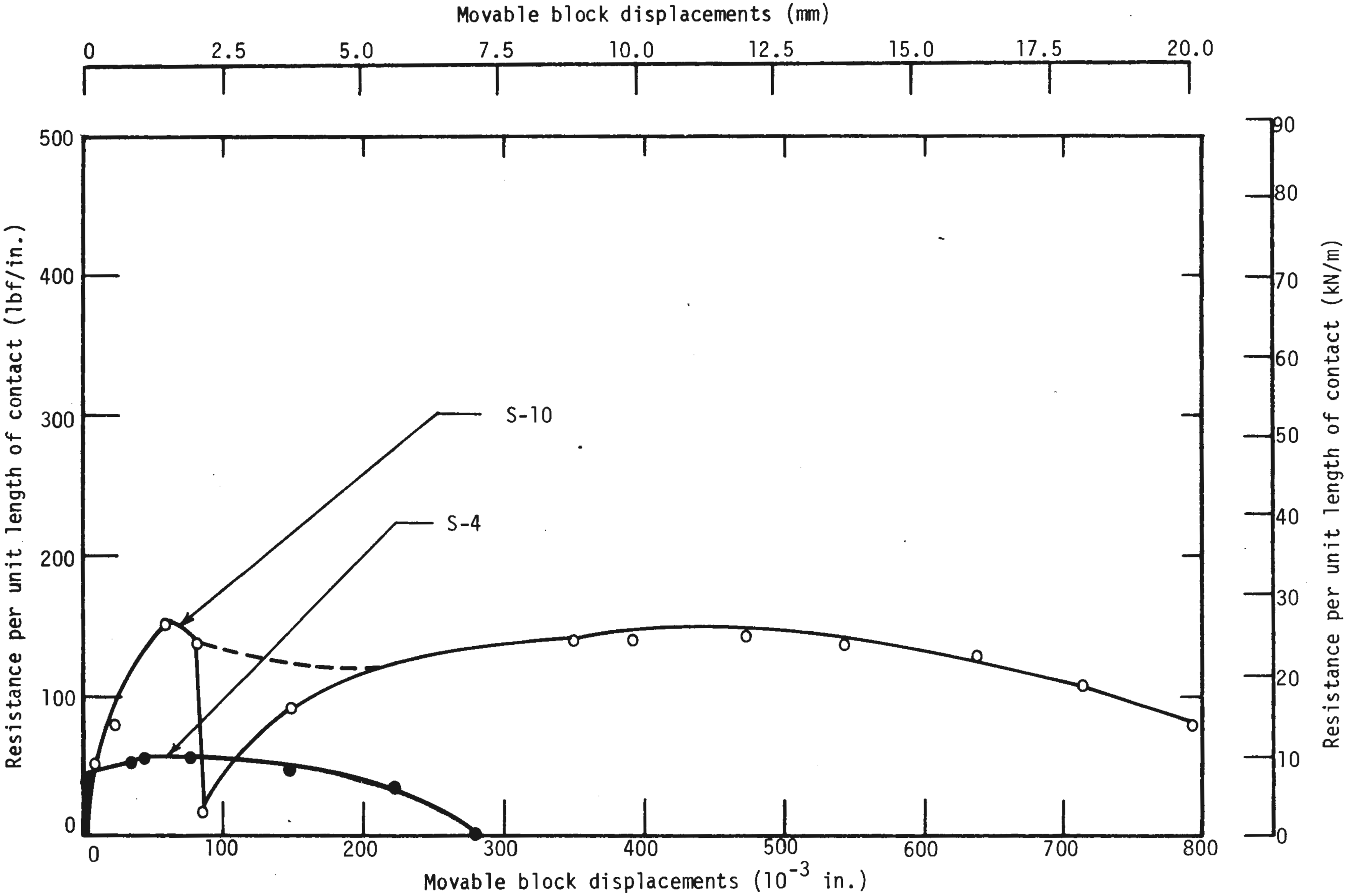


FIGURE 4.45 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

test Nos. S-4 and S-10 in which steel plates were spaced 8 ft (243.8 cm) and 4 ft (121.9 cm) apart, respectively. No difference was observed in the mode of failure of these 2 layers. The difference in the maximum resistance of the layers was probably caused by a greater adhesive strength along the contact between the layer and the surface slab in test No. S-10. The greatest difference in the structural behavior of the two layers can be seen in their residual resistances. Where the steel plates were spaced 8 ft apart (test No. S-4), the residual resistance of the layer did not exceed 50 lbs/in. (8.8 kN/m) and was reduced to zero for a displacement of 0.2 in. (5.1 mm). On the other hand, where the steel plates were located 4 ft apart (test No. S-10), the residual resistance of the layer reached 200 lbs/in. (35 kN/m) at 0.02 in. (0.51 mm) displacement and decreased to zero only after the movable block had displaced an additional 0.8 in. (20 mm). The difference in the residual resistance of the two layers was not only caused by the location of the end restraints but also was related to the greater thickness (1 in.) of the shotcrete layer in test No. S-10.

From the results of these tests, the following conclusions with respect to the structural behavior of the shotcrete layers were drawn:

1. The initial mode of failure and the maximum resistance of the shotcrete layers were not affected by the presence of steel plates within 1 ft (30 cm) of the movable block.
2. Observed variations in the maximum resistance of some layers were caused by differences in adhesive strength and not by the differences in the location of the lateral restraints of the layers.

3. Both the load carrying capacity and the displacement of the layer after adhesion failure were affected by the position of the steel plates.

4.5.2 THICKNESS OF THE LAYER

Variations in the mode of failure and in the maximum and residual resistances of the layers were produced by differences in shotcrete thickness. For shotcrete layers having thicknesses ranging between 1.1 in. and 1.9 in. (26.9 mm to 47.2 mm) and good shotcrete-slab bonds, diagonal tension failures occurred in the shotcrete layers (Fig. 4.46). The maximum resistance of the layer was directly related to the thickness of the shotcrete. In all of these tests the residual resistance of the layers rapidly decreased to zero.

The mode of failure changed primarily to separation of the shotcrete layer from the surface slab when the thickness of the shotcrete reached approximately 2.2 in. (5.53 cm) as seen in test No. S-3. The maximum resistance offered by the layer increased slightly as well as the displacements of the movable block relative to the tests in which diagonal tension failure occurred. Further increases in thickness, at least up to 5.26 in. (13.4 cm), did not affect the overall mode of failure nor the maximum resistance of the shotcrete layer.

For test Nos. S-4 and S-6, in which filament tape was used to reduce shotcrete-slab bonds, the shotcrete thickness had no effect on the failure mode or the maximum resistance of the layer. This would be expected since a diagonal failure could not develop in layers having loose bond unless restraints were placed close to the movable block.

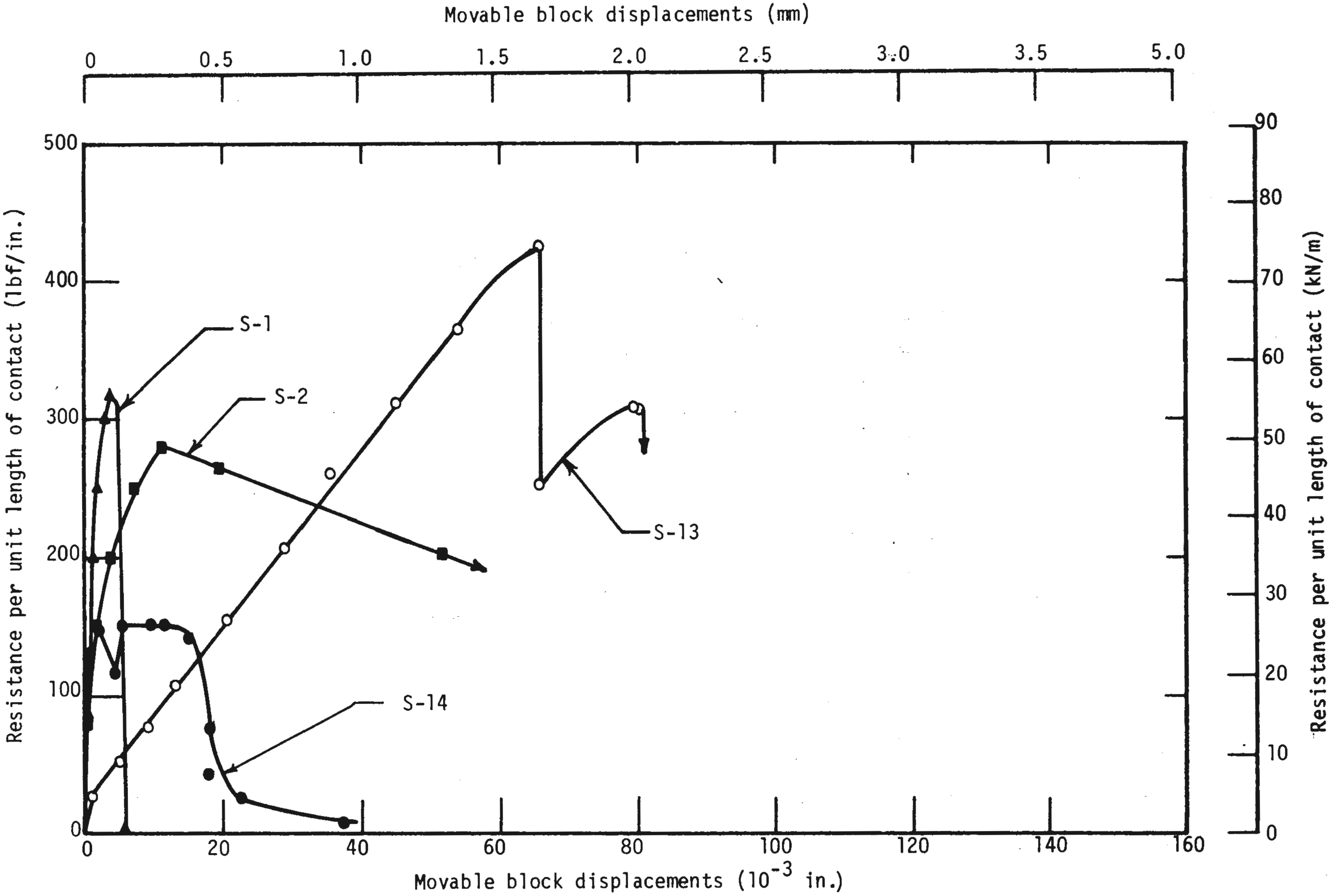


FIGURE 4.46 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

In tests where the shotcrete-slab bond was low and the thickness of the layer was high (test No. S-10) the maximum resistance of the layer was controlled by the bending capacity of the layer rather than by the adhesive strength. As the thickness increases, the bending stiffness of the layer increases and thus provides an increase in bending strength. In test No. S-10 the bending capacity was governed by both the thickness (3.1 in.) and the spacing of the steel plates (4 ft).

The following conclusions were drawn regarding the influence of the layer thickness in the structural behavior:

1. For a good shotcrete-slab bond (roughened surface and 7-day curing), the primary mode of failure changes from diagonal tension to adhesion as the thickness of the layer increases above 2 in. (5.1 cm). Once this thickness is reached, further increases do not alter the mode of failure.
2. For diagonal shear failures, the maximum resistance of the layer is directly proportional to layer thickness. For adhesive failure the thickness does not affect the maximum resistance unless the shotcrete-slab bond is poor and the layer has a greater bending capacity than adhesive strength. Where diagonal failure occurred the maximum resistance ranged from 150 lbs/in. (26 kN/m) for a 1-in. (2.5 cm) thick layer to 320 lbs/in. (56 kN/m) for a 2-in. (5.1 cm) layer.
3. The residual resistance of the shotcrete layer increased with increasing shotcrete thickness. A residual resistance of 30 lbs/in. (5 kN/m) was observed in test No. S-8

having a thickness of 3.0 in. (7.5 cm), while in test No. S-6 the resistance of the 4.7 in. (11.9 cm) layer was 50 lbs/in.

4.5.3 ADHESIVE SURFACE CHARACTERISTICS

Changes in the structural behavior of the layer resulting from differences in shotcrete-slab adhesion can be seen by comparing pairs of test Nos. S-3 & S-4, S-5 & S-6, and S-9 & S-10 performed at 7 days. The differences in adhesive strength for each pair of tests was obtained by using a roughened surface (representing good bond) and a surface covered with tape (poor bond). The same mode of failure, separation of the shotcrete layer from the surface slab, was observed in all the tests; however, the maximum resistance was strongly influenced by the adhesive strength developed between the shotcrete and the slab. The maximum resistance of layers having poor shotcrete-slab bond were approximately 20 percent of those in which the shotcrete was placed against roughened contacts (Figs. 4.22, 4.23 and 4.25). The higher resistance obtained in test No. S-10 relative to tests S-4 and S-6 was caused by localized penetration of shotcrete in the slots surrounding the movable block. Although maximum resistance was strongly affected, the residual resistance was not sensitive to surface adhesion when lateral restraints were present.

Similar results were obtained for the 7 hr tests (test Nos. S-7 & S-8 and S-11 & S-12). However, the maximum resistances of the layers having poor bond was 30 to 40 percent of the values obtained for the wire brushed surfaces. The residual resistance of the 7 hr tests were the same for both taped and untaped surfaces where the restraints were placed at the same location. Based on the test results, the influence of surface adhesion on the structural behavior of the shotcrete layers are summarized below:

1. For shotcrete layers greater than 2 in. (5 cm), the failure mode is not changed by bonding conditions of the surface. However, diagonal tension failures can develop when shotcrete thickness is less than 2 in. (5 cm) and shotcrete-slab bond is good. These failures cannot develop when bond is poor, independent of the thickness of the layer.
2. Poor contact bond can reduce the support capacity of the layer as much as 60-80% relative to layers having good shotcrete-slab bond. The greater reductions occurred in shotcrete layers having higher strengths (7 days).
3. The residual resistance of the layer was the same for both good and poor shotcrete bond strengths when lateral restraints were present at the same locations relative to the movable block.

SHOTCRETE STRENGTH

The variations in the adhesive strength caused by differences in the time of curing were studied by comparing results of test Nos. S-3 & S-7, S-5 & S-11,S-4 & S-8,S-6 & S-12. The strength of the shotcrete layers does not affect the mode of failure (separation of the shotcrete layers from the surface slabs),but bond. It had the greatest effect on the roughened surfaces while the taped surfaces were not as sensitive because the smoothness and impermeability of the tape tended to control the adhesive strength. When the bond is good, shotcrete 7 hours old has approximately 1/5 the support capacity of a comparable 7-day old layer. However, with poor bond only a slight increase in the capacity of the layer occurs (30-50 lbs/in.) between 7 hours and 7 days.

3. The residual resistance of the layer is directly proportional to the curing time. For the 7 hr test, the residual resistance of the layer was 1/4-1/5 of the value at 7 days.

4.5.4 USE OF REINFORCEMENT

The influence of steel fiber reinforcing in the shotcrete layers can be seen by comparing test Nos. S-4 and S-16. The layers in these tests are very similar except that in test No. S-16, steel fibers, 0.01 in. x 0.022 in. x 1 in. (0.025 cm x 0.056 cm x 2.54 cm), were added to the shotcrete before gunning. The presence of fiber produces no significant increases in the maximum resistance of the shotcrete layer (Fig. 4.48). However, both the residual resistance and ductility were greatly increased when fiber was present in the layer.

Residual resistance of the reinforced and nonreinforced shotcrete layers placed on roughened concrete cannot be compared due to different lateral

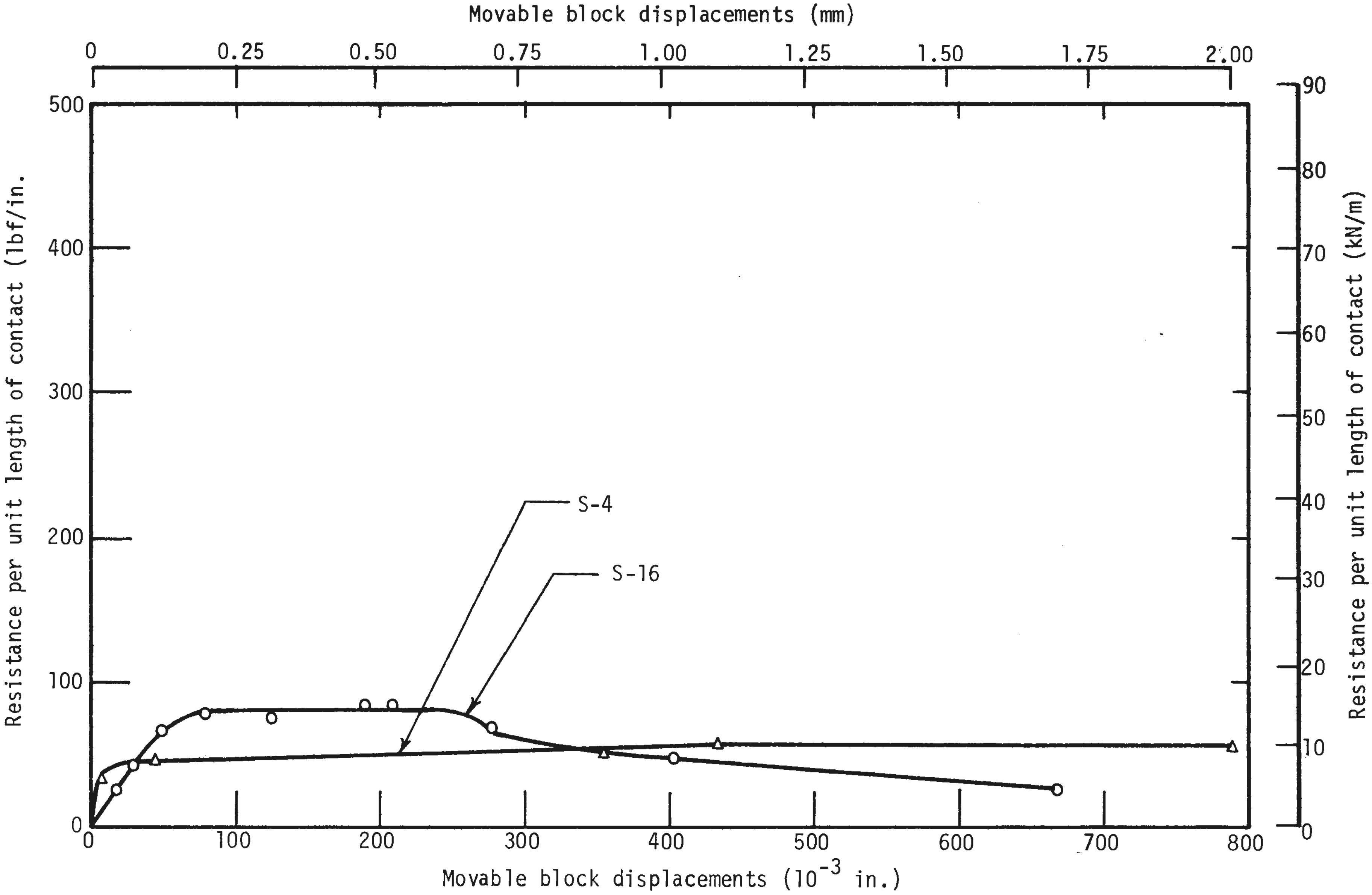


FIGURE 4.48 UNIT LENGTH RESISTANCE VS MOVABLE BLOCK DISPLACEMENTS

boundary conditions of the layers. However, differences in the adhesion surface conditions do not alter the residual resistance characteristics of the layer. From the above mentioned results it can be concluded that:

1. The use of fiber-reinforced shotcrete does not change the mode of failure nor increase the maximum resistance of the layer as compared with conventional shotcrete under similar conditions.
2. After adhesion failures occurred, the steel fibers increased the ductility of the layer and provided greater post-crack resistance.

4.5.5 REPEATABILITY OF THE TEST RESULTS

The repeatability of the test results was checked by performing two tests having essentially the same conditions (test Nos. S-1 and S-2). Even though a relatively small difference existed in the thickness of the layers, ±0.1 in. (±.25 cm), the same structural behavior was observed and the maximum resistance of the layers was very similar. In both cases the residual resistance decreased rapidly to zero after the adhesion failure. It can be concluded then, that the shooting and testing conditions can be controlled accurately enough to reliably reproduce test results.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 MAXIMUM RESISTANCE OF THE LAYER

In the tests where failure primarily involved separation of the shotcrete layer from the slab (adhesion failure), the maximum resistance was directly proportional to the adhesive strength along the shotcrete-slab contact and was almost independent of shotcrete thickness. The dashed band in Fig. 5.1 shows the linear relationship between the maximum layer resistance and its adhesive strength. In these cases the maximum resistance was equal to F_0, the resultant force of the adhesive strength developed between the shotcrete and the surface slabs. The relatively high resistance of the layer in test No. 9 was caused by the presence of shotcrete in the slots surrounding the movable block.

In the tests in which diagonal tension failures occurred, the maximum resistance was directly proportional to the thickness of the layer and to the shotcrete strength. The measured resistances coincided very closely with calculated values of F_1, which is the shear force required to induce a diagonal tension failure in the layer. Values of F_1 were calculated assuming the diagonal tension strength of the shotcrete equal to $2\sqrt{f'_c}$ (where f'_c is the compressive strength of the shotcrete) and are shown by the horizontal dashed lines in Fig. 5.1. In tests involving adhesion failures, the calculated values of F_1 were always greater than the actual maximum resistance of the layers. On the other hand, the calculated shear forces (F_1) were always less than or equal to the maximum resistance of layers

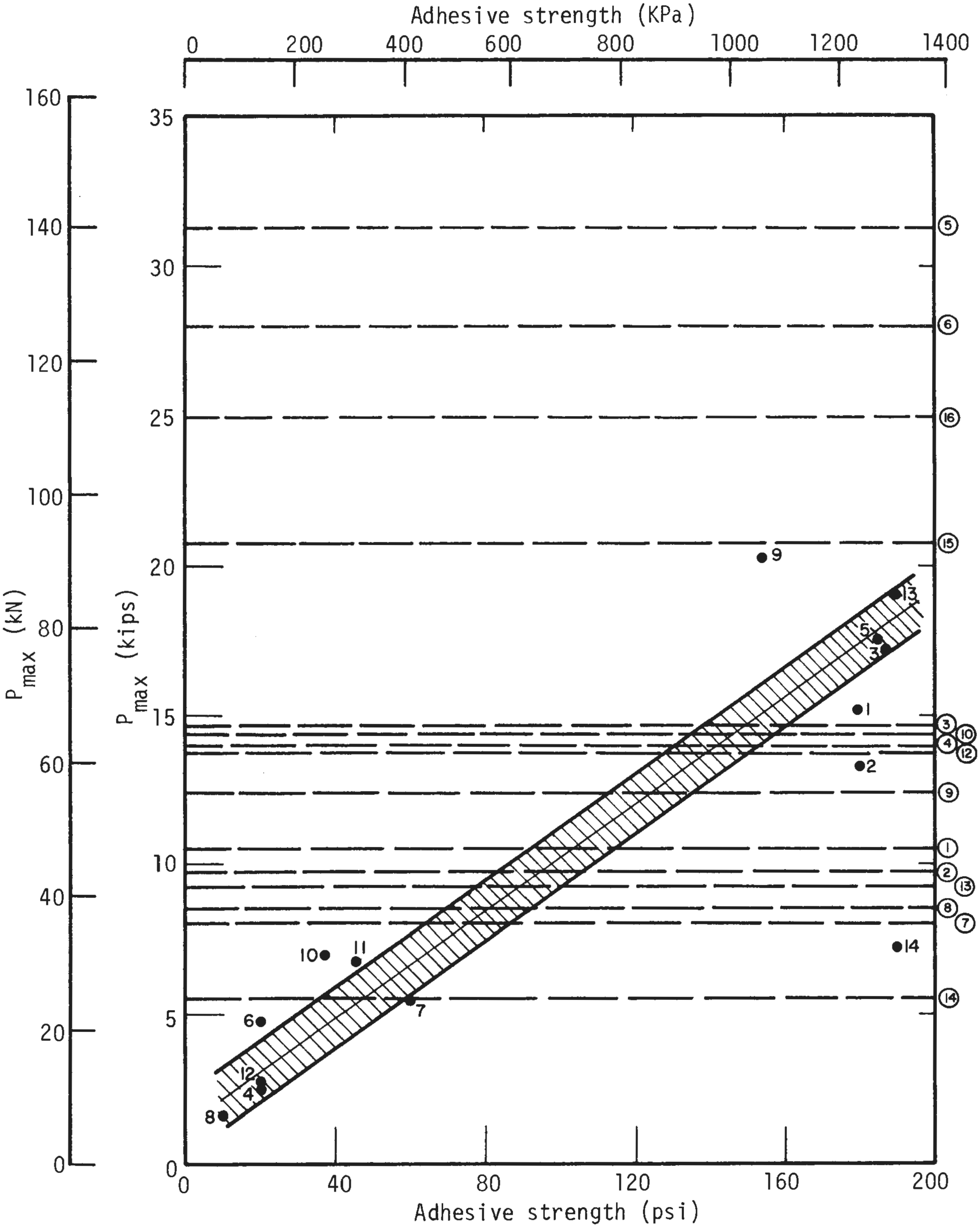


FIGURE 5.1 MAXIMUM RAM LOAD VS MEASURED ADHESIVE STRENGTH

in which diagonal tension failures occurred. In these cases the values of F_0 given by the dashed band were much greater than the actual maximum resistance offered by the layer.

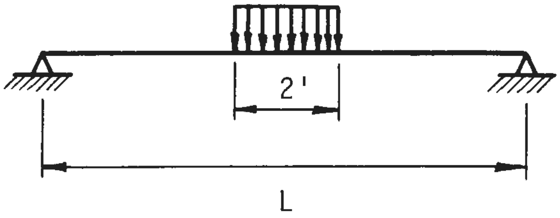
The structural behavior of the layers depends on the mode of failure which is controlled primarily by thickness and bond of the shotcrete. For any given layer when the diagonal tension strength is greater than the adhesive strength,a separation of the shotcrete layer occurs and the maximum resistance offered by that layer is given by the force F_0. On the other hand, when the diagonal tension strength is less than the adhesive strength, a diagonal tensile failure occurs and the maximum resistance offered by the layer is given by the value of F_1. This structural behavior corresponds exactly to the one proposed in the model of Chapter 3.

5.2 RESIDUAL RESISTANCE

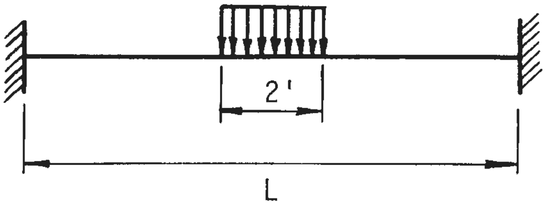
Visual observations together with the displacement measurements indicate that the shotcrete layers behave as simply supported beams uniformly loaded in their center sections after an adhesive failure develops.

The load carried by each shotcrete layer acting as a simply supported beam (Fig. 5.2) was calculated using the geometric characteristics of the layers, shotcrete strength and distance between the lateral restraints and the movable block. The values of the layer properties used in the calculations as well as the calculated and measured residual loads of each layer are summarized in Table 5.1.

Except for test Nos. 9 and 10, the measured and calculated residual loads assuming a simply supported beam are very similar although the



a) SIMPLY SUPPORTED BEAM



b) DOUBLE CANTILEVERED BEAM

FIGURE 5.2 BEAM MODELS USED IN RESIDUAL CAPACITY CALCULATIONS measured value is usually slightly higher than the calculated value. The difference between the calculated and measured residual resistance values was probably provided by the steel plates which served as a restraint against rotation at the extremes. It must be pointed out that the residual resistance values measured were much closer to the lower limit obtained assuming a simply supported beam than the upper limit calculated assuming development of a double cantilever beam (Fig. 5.2 (b) ; Table 5.1). Calculated residual resistance values assuming cantilever action at the beam supports were 5 to 10 times higher than the actual values of residual resistance. The double cantilever beam did not develop because of the flexibility of the steel plates and their supports. The closer the restraints were to the movable block, the more the layer tended to act as a cantilever beam. For test Nos. 9 and 10 in which the steel plates were located 1 ft (30.4 cm) from the movable block, the measured values of the residual load were 4 times higher than the value estimated for a simply supported beam. After large displacements (1 in.; 2.54 cm) of the movable blocks, the load decreased to 2200 lbs (9.79 kN); this was only twice the calculated value.

5.3 GENERAL CONCLUSIONS

Results of the tests carried out on the mortar and shotcrete layers confirm the validity of the model of behavior of thin linings on flat tunnel surfaces given in Section 3.3.

1. Two modes of failure were considered in the model: separation of the shotcrete layer from the surface slab and diagonal tension failure in the shotcrete layer. Both

modes were observed in the testing program; their occurrence depended on the relative value of forces F_0 and F_1.

2. The maximum resistance offered by the layer depends on the mode of failure and its magnitude is given by the smaller of the forces F_0 and F_1. When separation of the shotcrete layer occurs, the maximum resistance is directly proportional to the maximum adhesive strength per unit area of contact. For variations in the adhesive strength from 180 psi (1241.1 kPa) to 20 psi (137.90 kPa), maximum resistance per unit length of the movable block contact ranged from 400 lbs/in. (70.05 kN/m) to 50 lbs/in. (8.76 kN/m).

   If a triangular distribution of the adhesive strength between the shotcrete layer and the surface slab is assumed, the distribution of stress does not extend beyond a few inches (2 to 4 in.; 5 to 10 cm) away from the movable block. The load applied through the movable block is transmitted by the shotcrete layers along two narrow (2 to 4 in.; 5 to 10 cm - wide) bands parallel to the contact between the movable and the fixed walls. Test results indicate that variations in the surface adhesive conditions (wire brushed or taped surfaces), or in layer properties (thickness, strength) does not significantly change the width of these bands. Theoretical considerations, i.e., beam on elastic foundation theory, would predict that the area over which adhesive strength is distributed would remain constant since the stiffness in bond is much greater than the flexural stiffness of the beam.

3. The capacity of the shotcrete layer in diagonal tension depends on the thickness of the layer and in shotcrete strength while in adhesion it is governed by the surface characteristics and shotcrete strength (as affected by curing time).
4. After reaching its maximum resistance,the structural behavior of a conventional shotcrete layer depends mainly on the mode of failure, the adhesive surface conditions, the lateral boundaries of the layer, and the strength and stiffness of the shotcrete. When separation of the shotcrete starts, the adhesive failure propagates away from the movable block depending on the thickness of the layer and the slab surface characteristics. The length of propagation of an adhesive failure for wire-brushed surfaces varied from 48 in. (120 cm) for a 5.26 in. (13.5 cm) layer to 15.5 in. (39 cm) for a 2.18 in. (5.54 cm) - thick layer. When the adhesive strength is low, the failure propagated all the way out to the boundaries of the layer independent of layer thickness.

When steel plates were present, the adhesive failure was terminated at the plates and the shotcrete layer acted as a simply supported beam. The residual capacity of the layer varied with the spacing between plates and the thickness and strength of the shotcrete. When plates were located 4 ft (122 cm) apart the residual resistance of the layer was 110 lbs/in. (10.5 kN/m) while an 8 ft (244 cm) spacing produced a residual resistance in similar shotcrete layers of 60 lbs/in. (5.7 kN/m). The flexural strength and thickness both govern the load carrying capacity of a beam. In tests where the restraints were spaced 8 ft apart, an eight-fold change in strength produced a two-fold change in the residual resistance of the layers (60 lbs/in. to 30 lbs/in., respectively). The residual capacity of the layer varied with the spacing between the steel plates. When the plates were located 4 ft (120 cm) apart the residual resistance of the layer was 110 lbs/in. (19.3 kN/m) while an 8-ft spacing provided a residual resistance of 60 lbs/in. (12.5 kN/m).

5. No residual resistance was observed in shotcrete layers that failed initially in diagonal tension. Fiber reinforcement increases both the residual resistance and ductility of a shotcrete layer. The residual resistance of fiber-reinforced shotcrete remained constant for

displacements of the movable block of up to 0.8 in. (2 cm). These displacements were approximately 5 times greater than the residual displacements of similar non-reinforced layers. A rate of loading does not appear to have a significant effect on the maximum resistance of the layers. For changes of 2 lbs/sec to 5000 lbs/sec the layers showed a variation ±5 lbs/in. which is less than the variation between similar tests run at the same rate of loading.

RECOMMENDATIONS

1. The range of adhesion tested in this program is believed to be fairly representative of the range of values encountered in the field (Cecil, 1970 and Bortz and Singh, 1973). Values of the adhesive strength between shotcrete layers and typical rock surfaces from different rock types should be investigated to aid in predicting shotcrete-rock bonding conditions in the field.
2. Considerable differences in modes of failure and shotcrete resistances are expected for geometries other than a planar configuration of movable blocks and adjacent blocks. Such tests are to be carried out as a second stage of this investigation.
3. The support capability of fast-setting (reg-set) cement should be investigated.

4. A numerical model simulating the structural behavior of the layers should be used to conduct a parametric study of the main variables which affect layer resistance. The results obtained from the mortar and shotcrete tests would first be used to verify the numerical model. Once the model is verified, it can be used to establish the effect of the main variables having values different from those used in the tests on the resistance of thin shotcrete layers. Such a modeling could be done using a finite element technique where viability has already been substantiated (Jones, 1975).

REFERENCES

Cecil, S. O., "Correlations of Rock Bolt-Shotcrete Support and Rock Quality Parameters in Scandinavian Tunnels," Ph.D. Thesis, University of Illinois, Urbana, Illinois (1970).

Cording, E. J., "Measurement of Displacements in Tunnels," Proceedings, Second International Congress of the International Association of Engineering Geology, 2:VII-PC-3.1 - VII-PC-3.15, Sao Paulo, Brazil (1974).

Cording, E. J. and Mahar, J. W., "The Effect of Natural Geologic Discontinuities on Behavior of Rock in Tunnels," Proceedings, Rapid Excavation and Tunneling Conference, San Francisco, Vol. 1, pp. 107-138 (1974).

Cording, E. J., "Geologic Considerations in Shotcrete Design," Use of Shotcrete for Undergroudn Structural Support, ASCE and ACI SP-45, pp. 175-199 (1974).

Craig, L. Curtis and Brockman, L. R., "Survey of Tunnel Portal Construction at U.S. Army Corps of Engineers Projects," Symposium on Underground Rock Chambers, Phoenix, pp. 184-185 (1971).

Jones, R. A. and Mahar, J. W., "Instrumentation to Monitor Behavior of Shotcrete Support Systems," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 297-319 (1974).

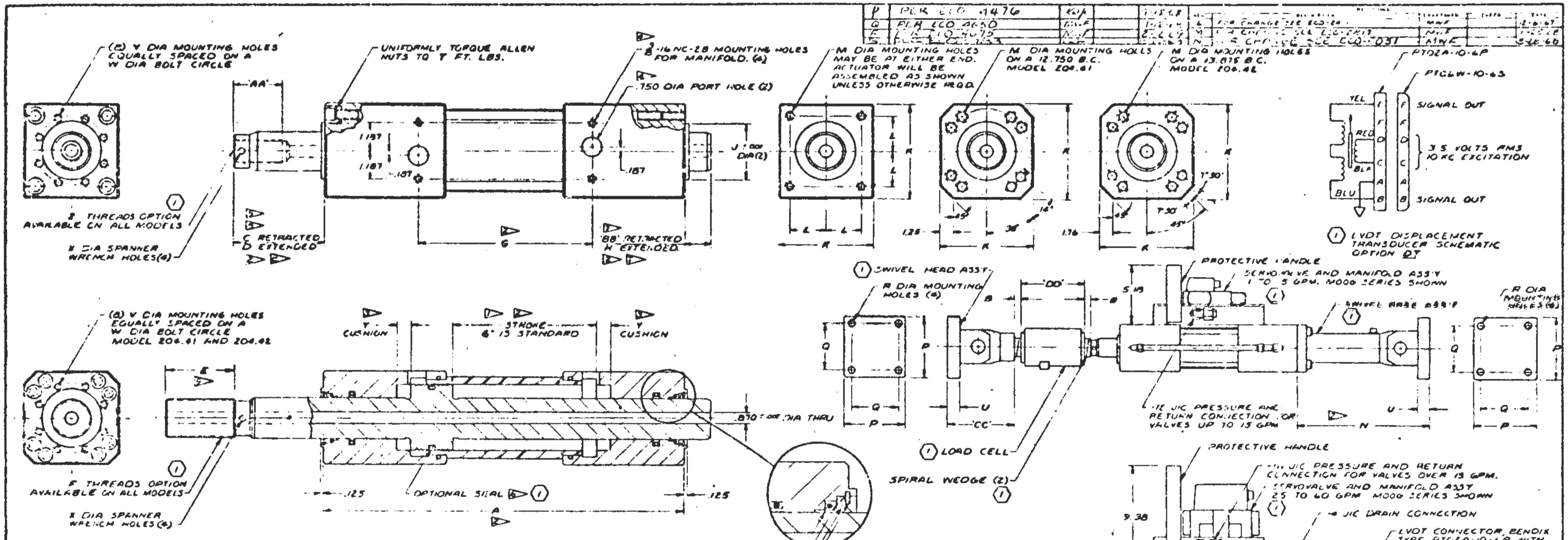
Parker, H. W., "Current Field Research Program on Shotcrete," Use of Shotcrete for Underground Structural Support, ASCE and ACI SP-45, pp. 330-350 (1974).

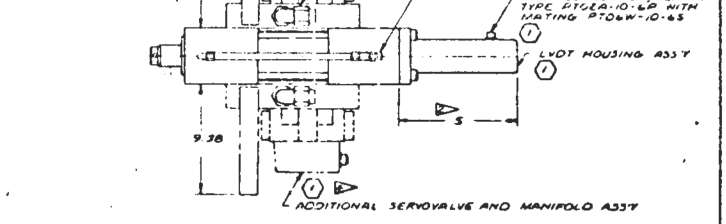
Peck, R. B., Hendron, A. J. and Mohraz, B., "State of the Art of Soft-Ground Tunneling," Proceedings, North American Rapid Excavation and Tunneling Conference, AIME, 1:259-286.

APPENDIX A

This appendix contains a plate in which the principal characteristics and dimensions of the different load-applying rams components are shown. Various cross-sectional areas along and across the ram axis, accompanied with explanatory descriptions, are also shown in this plate.

APPENDIX A





1▷ STANDARD STROKE LENGTH IS 6". OTHER LENGTH STROKES ARE OPTIONAL. MINIMUM OPTIONAL STROKE IS 2".

2▷ THESE DIMENSIONS ARE BASED ON ACTUATOR HAVING 6" STROKE. ADD 1.00" TO THESE DIMENSIONS FOR EACH 1.00" INCREASE IN STROKE. SUBTRACT 1.00" FOR EACH 1.00" DECREASE IN STROKE.

3▷ THE 204 ACTUATOR HAS Y LONG CUSHIONS ON EACH END. DIMENSIONS ARE GIVEN FOR NOMINAL OPERATING STROKE AND DO NOT INCLUDE Y CUSHIONS. TOTAL STATIC STROKE IS EQUAL TO THE NOMINAL STROKE PLUS 2(Y).

4▷ PORTING ON ONE SIDE OF ACTUATOR IS STANDARD. EXTRA PORTS ARE OPTIONAL OR AS REQUIRED BY ACCESSORIES.

5▷ ① EXTRA ROD LENGTH TO BE ADDED TO DIM. C AND DIM. D.

6▷ MODELS 204.12 AND 204.13 AND SERIES 204.2X AVAILABLE WITH PISTON SEAL. STANDARD ON SERIES 204.3X AND 204.4X.

7▷ DOES NOT INCLUDE PISTON RETRACTED INTO CUSHION. FOR MAXIMUM ADD H AND T. FOR MINIMUM SUBTRACT Y FROM 'BB'.

① INDICATES ITEMS THAT ARE OPTIONAL AND MUST BE SPECIFIED AT TIME OF ORDER.

8▷ DOES NOT INCLUDE PISTON RETRACTED INTO CUSHION FOR MAXIMUM ADD D AND Y. FOR MINIMUM SUBTRACT Y FROM C.

9▷ ADD DIMENSION 'E' TO 'C' FOR RETRACTED LENGTH, ADD DIMENSION 'E' TO 'D' FOR EXTENDED LENGTH. SEE NOTES 2▷ 3▷ 8▷ ALSO.

MODEL I.C.	NOMINAL RATING	ROD DIA.	AREA IN.²	A	B	C	D	E	F	G	H	J	K	L	M	N	P	Q	R	S	T	U	V	W	X	Y	Z	AA	BB	CC	DD
204.11	2.5 KIP	1.62	1.07	15.12	1.12	1.62	7.62	2.31	1½-12NF-2A	8.25	7.03	2.375	3.50	1.160	⅜-16NC-2B	16.29	5.50	4.50	.531	10.00	20	1.23	⅜-16NC-2B	2.800	.281	.65	1-14NF-2B	2.00	1.03	8.10	6.50
204.12	4 KIP	1.62	1.48	16.12	1.12	1.62	7.62	2.31	1½-12NF-2A	8.25	7.03	2.375	3.50	1.160	⅜-16NC-2B	16.29	5.50	4.50	.531	10.00	20	1.23	⅜-16NC-2B	2.800	.282	.65	1-14NF-2B	2.00	1.03	8.10	6.50
204.13	6 KIP	1.62	2.36	16.12	1.12	1.62	7.62	2.31	1½-12NF-2A	8.25	7.03	2.375	4.50	1.590	½-13NC-2B	16.29	5.50	4.50	.531	10.00	35	1.23	⅜-16NC-2B	2.800	.282	.65	1-14NF-2B	2.00	1.03	8.10	6.50
204.21	6 KIP	2.62	2.26	16.12	1.12	1.62	7.62	3.31	2½-12NF-2A	8.25	6.99	3.500	4.50	1.590	½-13NC-2B	16.29	5.50	4.50	.531	10.00	40	1.23	½-13NC-2B	4.100	.313	.65	1-14NF-2B	2.00	.99	8.10	6.50
204.22	9 KIP	2.62	3.54	16.12	1.12	1.62	7.62	3.31	2½-12NF-2A	8.25	6.99	3.500	4.50	1.687	½-13NC-2B	16.29	5.50	4.50	.531	10.00	50	1.23	½-13NC-2B	4.100	.313	.65	1-14NF-2B	2.00	.99	8.10	6.50
204.23	12 KIP	2.62	4.90	16.12	1.12	1.62	7.62	3.31	2½-12NF-2A	8.25	6.99	3.500	5.00	1.812	½-13NC-2B	16.29	5.50	4.50	.531	10.00	60	1.23	½-13NC-2B	4.100	.313	.65	1-14NF-2B	2.00	.99	8.10	6.50
204.24	20 KIP	2.62	7.15	16.12	1.12	1.43	7.43	3.24	2½-12NF-2A	8.25	6.86	3.500	5.50	1.960	½-13NC-2B	16.75	6.00	6.75	.531	10.00	65	2.25	½-13NC-2B	4.100	.313	.50	1-14NF-2B	2.00	.86	8.10	6.50
204.25	25 KIP	2.62	9.61	16.12	1.12	1.43	7.43	3.24	2½-12NF-2A	8.25	6.86	3.500	6.00	2.250	⅝-11NC-2B	18.75	6.00	6.75	.531	10.00	90	2.25	½-13NC-2B	4.100	.313	.50	1-14NF-2B	2.00	.86	11.75	10.00
204.26	35 KIP	2.62	12.30	16.12	1.12	1.43	7.43	3.24	2½-12NF-2A	8.25	6.86	3.500	6.50	2.280	⅝-11NC-2B	18.75	6.00	6.75	.531	10.00	120	2.25	½-13NC-2B	4.100	.313	.50	1-14NF-2B	2.00	.86	11.75	10.00
204.31	50 KIP	3.62	17.50	17.12	1.38	1.23	7.23	4.25	2½-12NF-2A	8.25	6.61	4.625	8.00	2.781	¾-10NC-2B	22.70	9.00	7.25	.781	10.00	160	2.44	⅝-11NC-2B	5.500	.375	.25	2-12NF-2B	3.00	.61	11.99	10.00
204.32	70 KIP	3.62	25.40	17.12	1.38	1.23	7.23	4.25	2½-12NF-2A	8.25	6.61	4.625	8.00	3.062	¾-10NC-2B	22.70	9.00	7.25	.781	10.00	240	2.44	⅝-11NC-2B	5.500	.406	.25	2-12NF-2B	3.00	.61	13.99	10.00
204.41	100 KIP	5.25	38.48	27.12	1.38	[illegible]	[illegible]	5.00	5-8NF-2A	8.25	6.61	6.500	11.75	NONE	⅞-14NF-2B	27.25	13.75	10.75	1.281	12.00	480	3.50	1-8NC-2B	10.375	.531	.25	2-12NF-2B	3.00	.61		10.00
204.42	150 KIP	5.25	53.00	27.12	1.38	[illegible]	[illegible]	5.00	5-8NF-2A	8.25	6.61	6.500	11.75	NONE	1-14NF-2B	27.25	13.75	10.75	1.281	12.00	760	3.50	1-8NC-2B	10.375	.531	.25	2-12NF-2B	3.00	.61		10.00

THIS DWG IS ALSO AVAILABLE IN 'D' SIZE

NONE

MODEL 204 ACTUATOR
ASSY AND DIMENSIONAL

D29581

SYSTEMS CORPORATION

SHEET 1 OF 1

APPENDIX B

The roughness of the concrete slabs was measured to compare the different surfaces used in the mortar and shotcrete tests and for future comparison with the roughness of actual rock surfaces.

A cold rolled steel surface was used as a standard to compare different slab surface conditions.

Surface roughness was measured with a device designed to measure the vertical relief along the surface of the slab minimizing damage to the irregularities and thereby reducing chances for erroneous results (Fig. B-1). This device consists of a base, a rotating arm and a contact needle. The base of the instrument rests on three legs placed on the surface of the sample. The length of each leg is adjustable so that the base can be leveled. The base support remains stationary while the arm, which contains the sensing element, rotates about the centoidal axis.

The rotating arm is attached to the base on one end and holds the contact needle on the other. The contact needle is located 10-1/2 in. (26.7 cm) from the axis of rotation. When measuring the roughness of a sample, the arm is rotated slowly and the needle is maintained in continuous contact with the surface. The needle is vertically displaced by the undulations on the surface of the sample. This vertical displacement causes a corresponding deformation in the cantilever arm. A strain gage mounted on the arm measures the strain induced on its top caused by the deflection of the needle. A linear relation exists between the deflection and the recorded strain.

The results of the roughness measurements are plotted directly on

FIGURE B-1 ROUGHNESS MEASURING DEVICE

an x-y chart recorder. The instrument is calibrated and appropriate scale factors obtained so that the actual rotational and vertical displacements can be determined. The horizontal scale factor is 1 in. equals 2.2 in. of arc distance and the vertical factor is 1 in. equals 0.0125 in. of vertical displacement.

Measured surface roughness of the cold rolled steel and typical rough and smooth slabs are shown in Figs. B-2, B-3 and B-4, respectively. Two main characteristics of the slab roughness were detected: 1) pits and 2) bumps. Pits are crevasses on the surface which have extremely small widths but are very deep. Bumps are surface discontinuities which have widths of considerable extent in comparison with pits. They usually have second order features on the roughness plots.

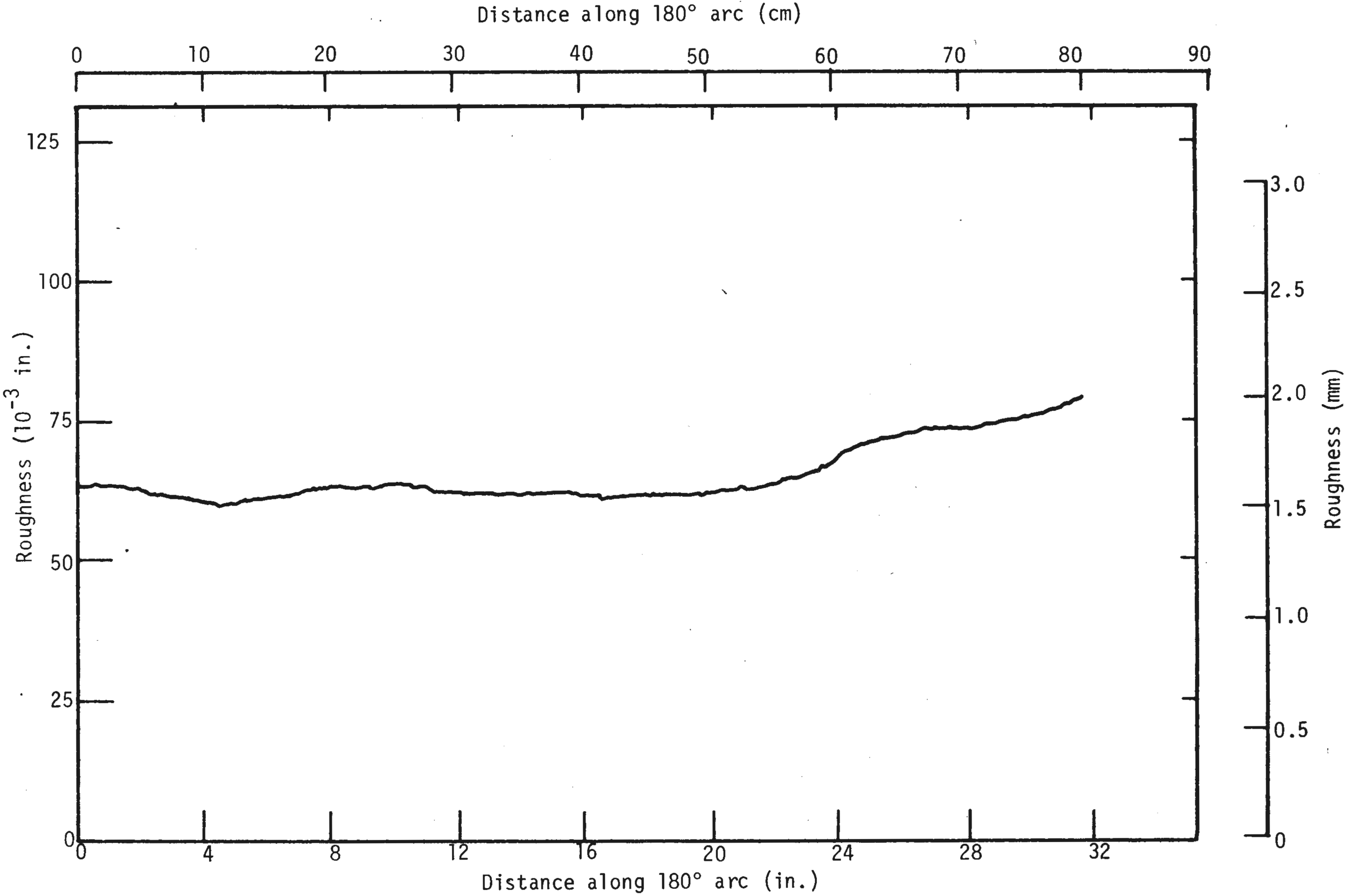


FIGURE B-2 Test 1 (11/4/74) Cold rolled steel (very smooth)

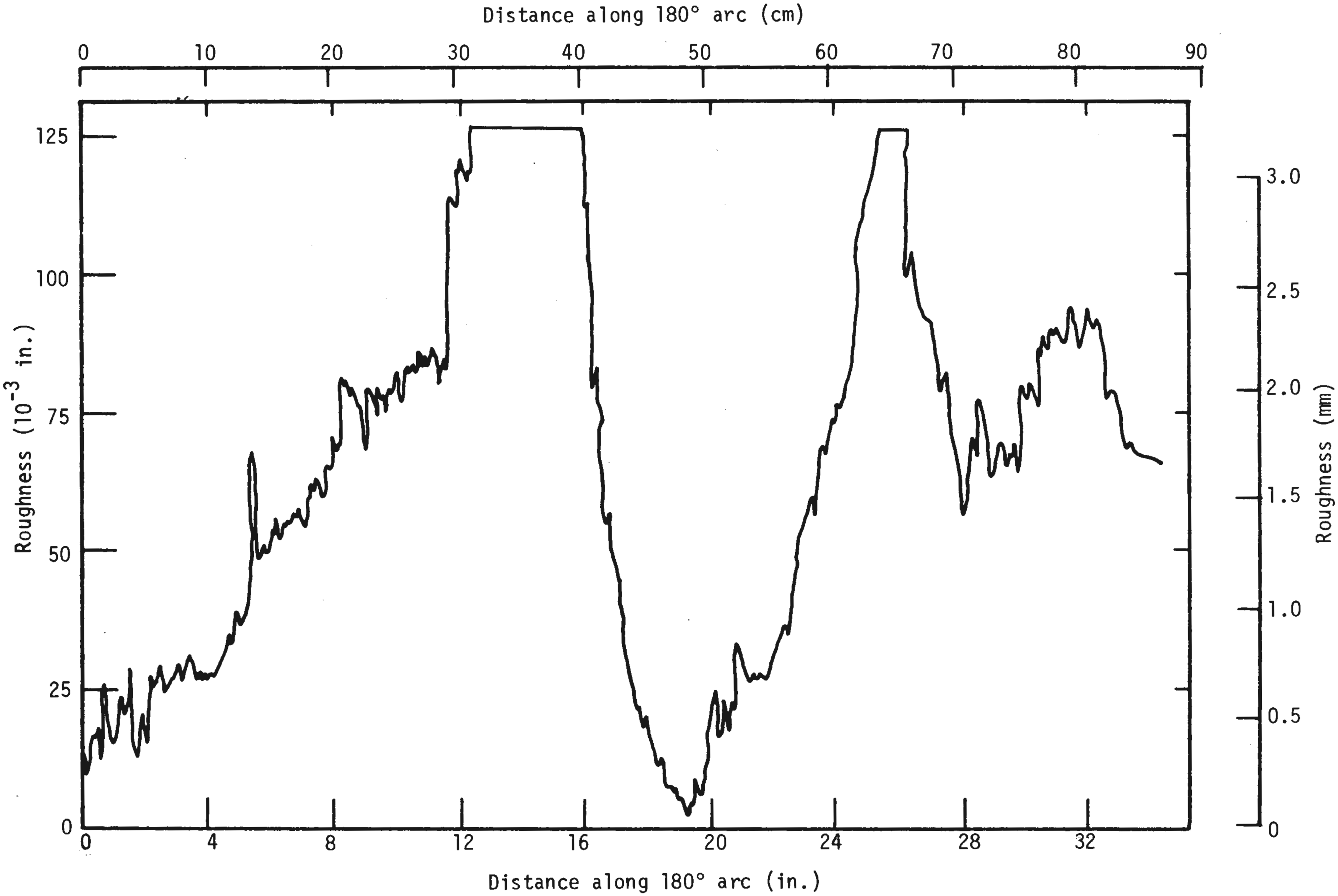


FIGURE B-3 Test 1 (11/12/74) Mid-north finjshed side

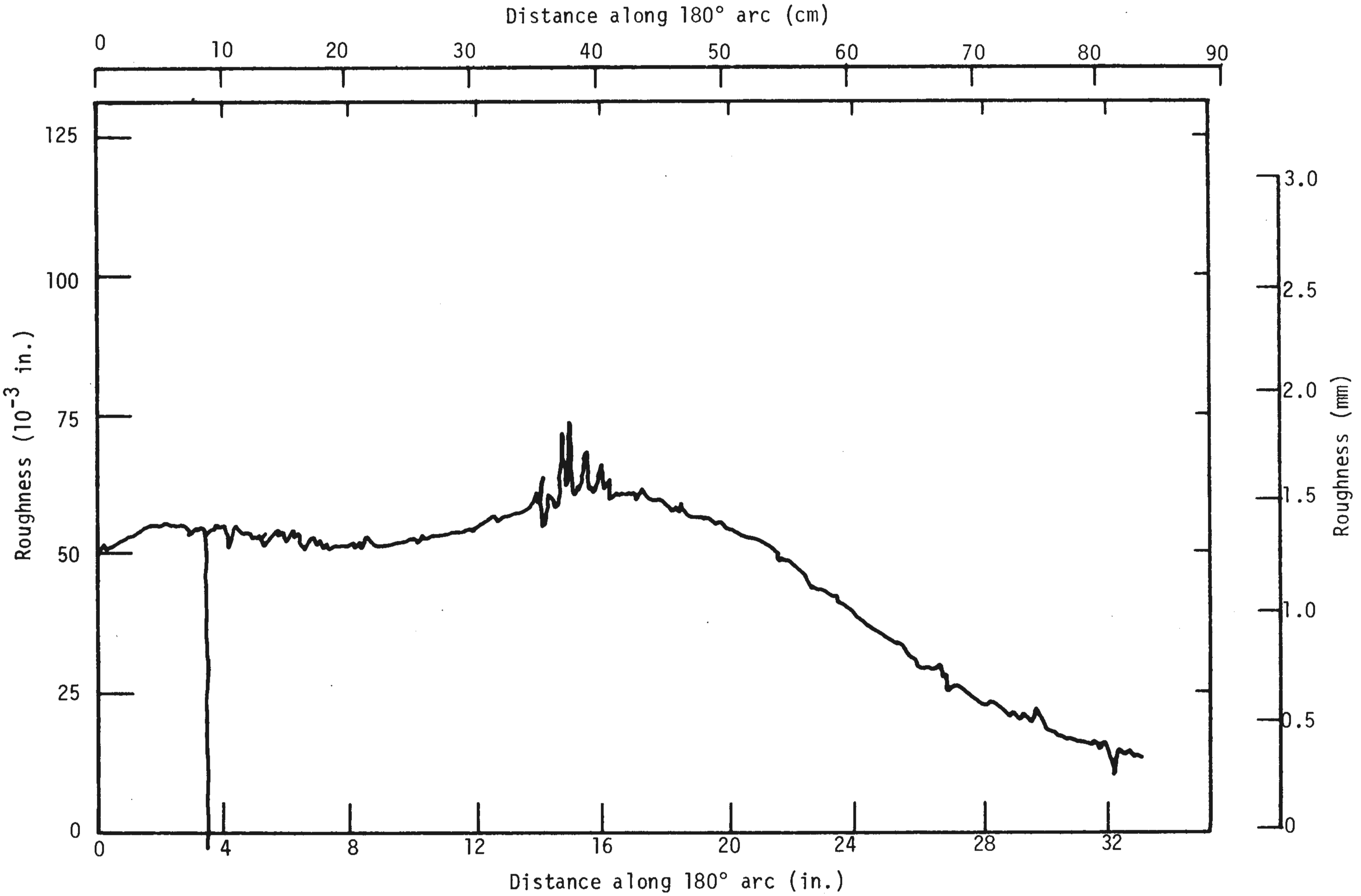


FIGURE B-4 Test 3 (11/11/74) South top form side

APPENDIX C

Tensile tests to measure the adhesive strength between the shotcrete and the surface slabs were carried out on samples cut from the model. The size of the samples and the sampling method have already been described in Section 4.3.3

EQUIPMENT USED IN THE TENSILE TESTS

The equipment used to perform the tensile tests is shown in Fig. C-1. The sample was attached to the MTS loading machine shown in the center of the picture. The tensile load was applied at a uniform rate and was electronically controlled using the console shown on the right side of the loading machine. Deformations were measured across the shotcrete-slab contact using MTS strain gages. The loads and corresponding displacements were continuously monitored on a chart recorder.

Figure C-2 shows a close-up of the sample in the loading position. Each side of the sample was connected to the loading machine by means of steel plates and a clamp which was welded to a double joint firmly held in the loading head of the machine. Each clamp was provided with a set of screws that exerted pressure on the steel plates in contact with the sample. This arrangement plus careful sample preparation produced a relatively uniform load with no noticeable eccentricity and did not allow slippage along the grippers. The strain gage used to measure axial deformation was placed so that its reference points, located 1/2 in. (1.25 cm) apart, bridged across the shotcrete-surface slab contact (Fig. C-2). Although some samples failed

FIGURE C-1 FRONT VIEW OF THE TESTING DEVICE AND MONITORING SYSTEM

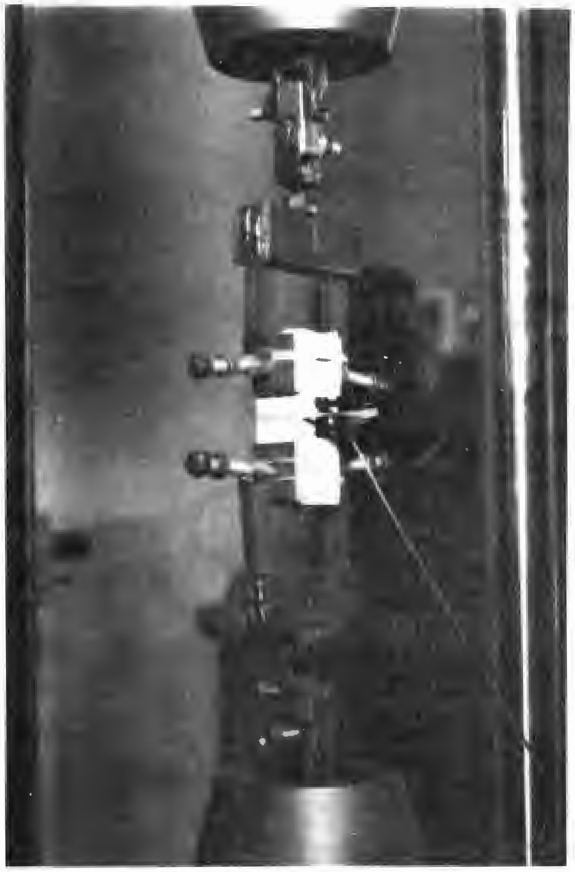


FIGURE C-2 SAMPLE ATTACHING SCHEME AND GAGE MEASURING STRAIN ACROSS THE CONTACT along weaknesses (laminations) in the shotcrete, most failures occurred along the shotcrete-slab contact (Fig. C-3).

FIGURE C-3 FAILED ADHESIVE TEST SAMPLE

TABLE C-2

SUMMARY OF ADHESION-TEST RESULTS

Test no.	Sample no.	Test hours	Hours between cutting & testing	Hours of curing	Adhesion value psi	Adhesion value (MPa)	Remarks
S-9 & S-10	T-1A*	144	0	144	144.7	(1.0)	Cured in crane bay
	T-2A*	144	0	144	164.4	(1.13)	Cured in crane bay
	T-3A*	144	0	144	142.6	(0.98)	Cured in crane bay
	T-4A*	144	0	144	160.0	(1.10)	Cured in crane bay
	T-5A*	144	0	144	158.8	(1.09)	Cured in crane bay
					Σ = 770.5		
					Avg = 154.0	(1.06)	

* Samples obtained from center section, tested on June 4, 1975

TABLE C-3

SUMMARY OF ADHESION-TEST RESULTS

Test no.	Sample no.	Test hours	Hours between cutting & testing	Hours of curing	Adhesion value psi	(MPa)	Remarks
S-7 & S-8	S-1	7	0	24	86.8	(0.60)	
	S-2	7	0	24	108.1	(0.75)	
	S-3	7	0	24	92.3	(0.64)	
	S-4	7	0	24	73.1	(0.50)	
	S-5	7	0	24	83.9	(0.58)	
	S-6	7	0	24	65.3	(0.45)	
	S-7	7	0	24	73.4	(0.51)	
	S-8	7	0	24	87.6	(0.60)	
	S-9	7	0	24	111.8	(0.77)	
	S-10	7	0	24	40.7	(0.28)	
					Σ = 823		
					Avg = 82	(0.57)	

TABLE C-4

SUMMARY OF ADHESION-TEST RESULTS

Test no.	Sample no.	Test hours	Hours between cutting & testing	Hours of curing	Adhesion value psi	(MPa)	Remarks
S-11 & S-12	B2	7		24	8.4	(0.06)	
	C2	7		24	81.2	(0.56)	
	D2	7		24	38.6	(0.27)	
	E2	7		24	15.4	(0.11)	
	F3	7		24	7.2	(0.05)	
				Excluding B2 & F3; Σ	= 135.2	(0.31)	
					Avg = 45		

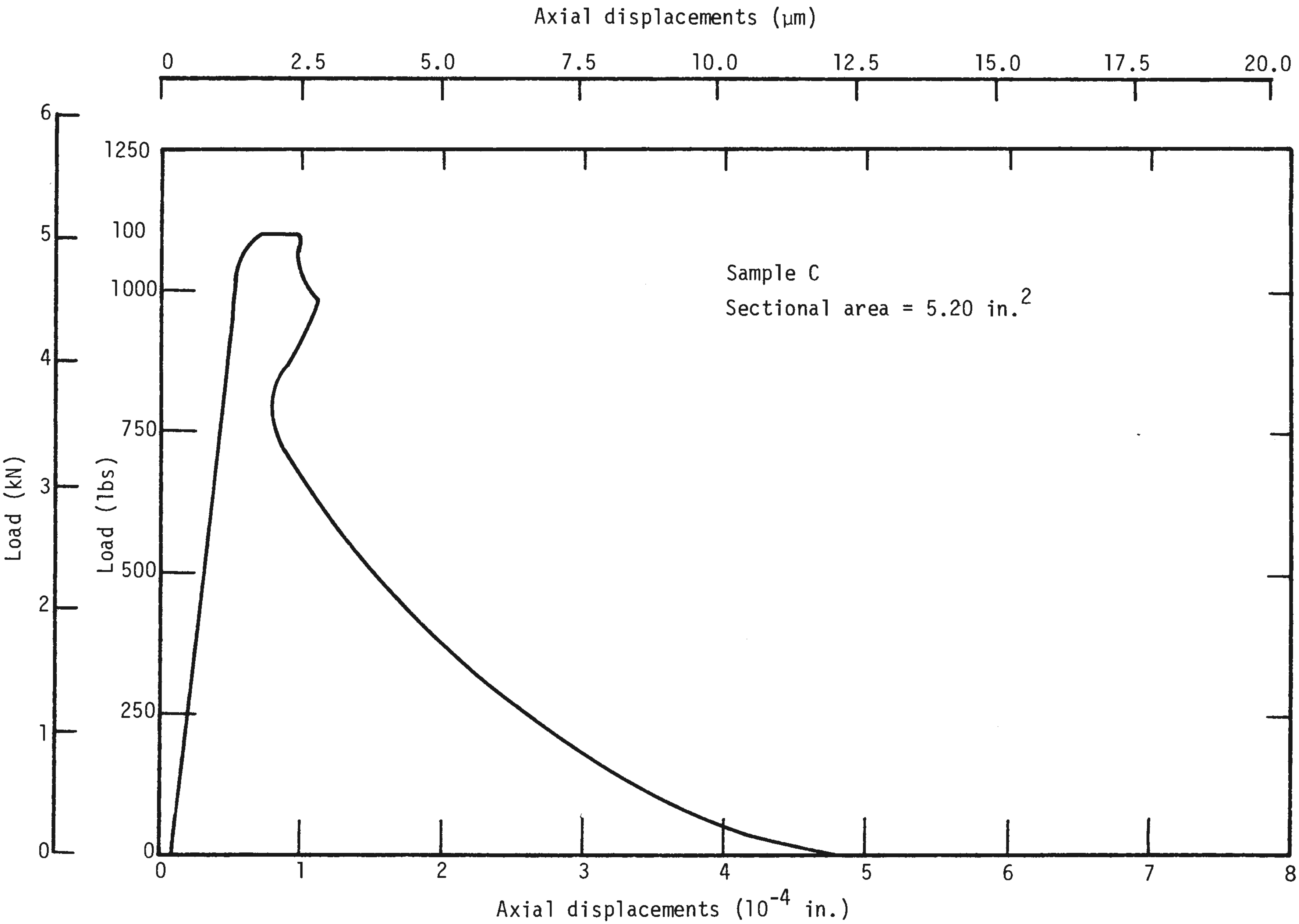


FIGURE C-4 LOAD VS CONTACT DISPLACEMENTS RELATIONSHIP OBTAINED FROM ADHESIVE TESTS

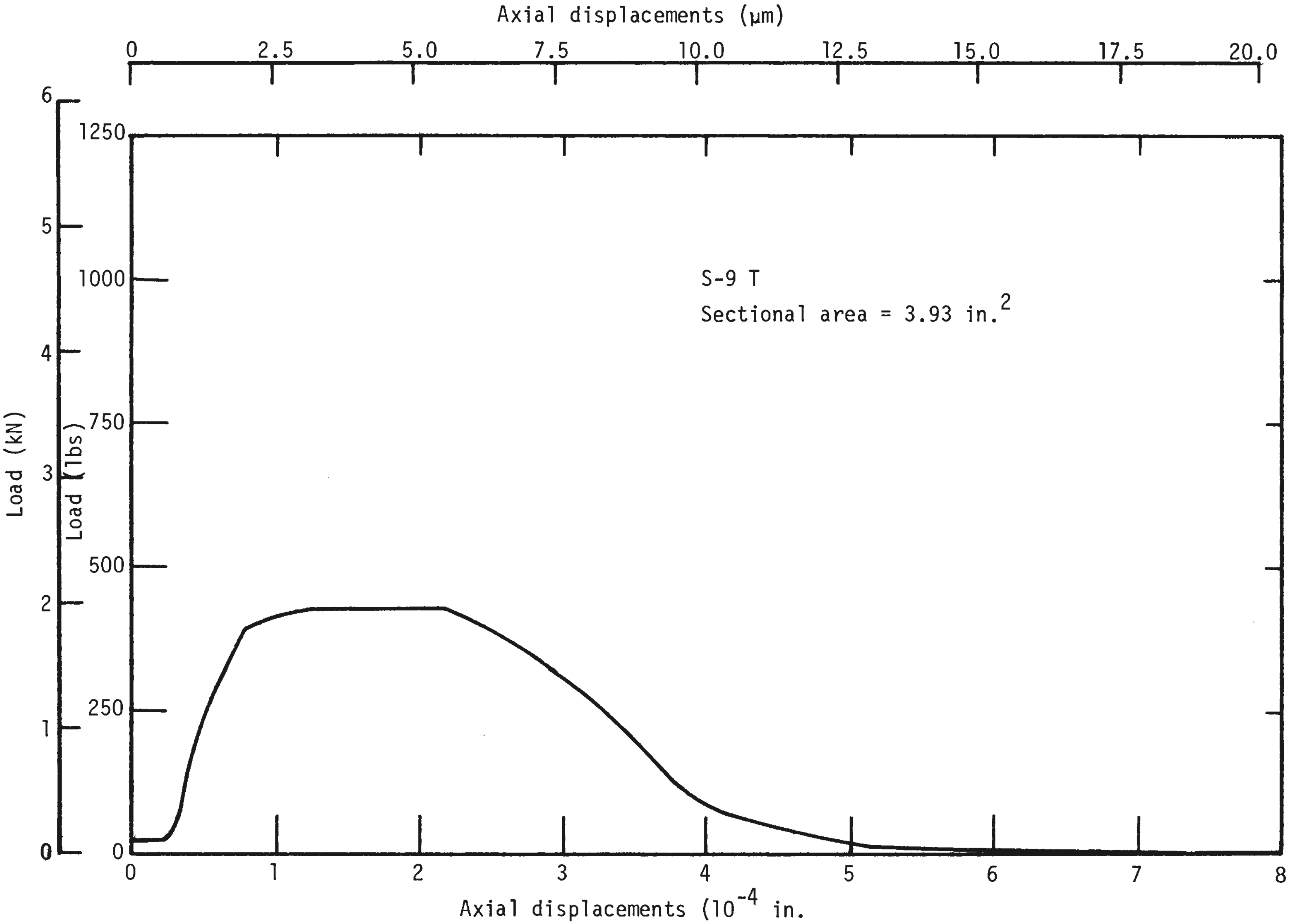


FIGURE C-5 LOAD VS CONTACT DISPLACEMENTS RELATIONSHIP OBTAINED FROM ADHESIVE TESTS

EFFECT OF SAMPLE SIZE

Tests were conducted to determine the effect of sample size on adhesion measurements. These test results indicate that a minimum cross-sectional area of 2 in. x 2 in. (5.1 cm x 5.1 cm) is necessary to avoid reductions in the adhesive strength created by the shrinkage of the shotcrete layer.

These shrinkage effects can be minimized if the samples are kept intact during curing and if they are prepared immediately prior to testing. Vibration caused by the saw can also disturb the shotcrete-slab bond contact and can diminish the adhesive strength. The disturbance created by the saw can be reduced by precutting the surface slab, binding the cut pieces together and spraying shotcrete on the slab mosaic. The samples are prepared by sawing the shotcrete along the precut sides of the slab sections. This technique works very well for obtaining samples with young shotcrete or having poor shotcrete-slab bond. The adhesive strength values shown in Tables C-1 to C-4 are probably lower than the actual adhesion developed in the model.

☆U.S. GOVERNMENT PRINTING OFFICE: 1976-211-173/486