CHAPTER 2

PUSH-OUT SPECIMEN CONFIGURATION AND TEST PROCEDURES

2.1 Introduction

The most common way used to evaluate shear stud strength and behavior is the push-out test. Push-out tests have been used as early as the 1960s and were used to develop Eqn. 1.8, which predicts the strength of studs in solid slabs. However, Grant et al (1977) used composite beam tests instead of push-out tests to develop Eqn. 1.11, which predicts the strength of studs in steel deck. The flexural strength of the beam was determined from the tests and the stud strength was back-calculated using the model developed by Slutter and Driscoll (1965). Back-calculating the stud strength from the beam strength, however, makes it difficult to evaluate the parametric influence on the shear stud strength. Push-out tests can be used to make this evaluation if the deck and stud details of the push-out specimen match those of the composite beam. This chapter describes the push-out tests that were performed in this study.

2.2 Test Matrices

2.2.1 Solid Slab Push-Out Tests

A total of 24 solid slab push-out specimens were tested to gain a better understanding of the basic shear stud strength without the influence of cold-formed steel deck. The test parameters are shown in Table 2.1. Twelve of these tests were performed to investigate the effect of the flange thickness to which the stud was welded. This was

Table 2.1 Solid Slab Test Matrix

Series	Tests	t_f (in.)	Nominal f'_c (psi)	Stud Position$^+$	Deck Height (in.)	Deck Gauge	Normal Load (%)**
1	1,2,3	0.52	3500	C	None	--	10
2	4,5,6	0.52	3500	F	None	--	10
3	7,8,9	0.38	3500	F	None	--	10
4	10,11,12	0.715	3500	F	None	--	10
5*	13,14,15	0.52	4500	C	0 (flat)	22	10
6	16,17,18	0.52	4500	C	0 (flat)	22	10
7	19,20,21	0.52	4500	C	None	--	10
8	22,23,24	0.52	4500	C	None	--	0

NOTES:
* Steel flange greased
** As a percentage of the axial load
$^+$ C = stud welded centrally on the flange, directly above tee web
$^+$ F = stud welded midway between tee web and tip of flange
t_f = flange thickness of tee
f'_c = concrete compressive strength
3/4 in. x 4 in. studs with nominal F_u= 65 ksi used for all tests
5 3/4 in. slab thickness and normal weight concrete used for all tests

accomplished by using different steel sections. In six other tests, the steel/concrete interface was changed by placing a piece of flat sheet metal between the steel beam and concrete slab. In the remaining six tests, the normal load applied to the specimens was varied.

Constants were stud diameter, stud length, stud tensile strength, number of stud connectors per slab, and steel reinforcement. Each series discussed consisted of three tests. The purpose of these tests is described below.

2.2.1.1 Effect of Flange Thickness (Series 1-4)

The first parameter evaluated was the effect on shear stud strength of the thickness of the flange to which the stud is welded. A large number of push-out tests performed at VT have used WT6x17.5 sections, with a nominal flange thickness of 0.52 in. Twelve tests were performed to verify that thinner or thicker flanges would cause no change in stud strength. The desired mode of failure was stud shearing; thus, the diameter-to-flange thickness ratio was kept below 2.7, as recommended by Goble (1968). A stud diameter of 3/4 in. was used for all tests, and the nominal concrete strength was constant.

2.2.1.2 Effect of the Steel/Concrete Interface (Series 5-6)

The second parameter investigated was the effect on stud strength of the steel/concrete interface. These tests were used to determine if the stud strength was reduced by placing a piece of flat sheet metal between the steel beam and concrete. It was thought that eliminating the bond and reducing the friction between the steel and concrete would reduce the apparent stud strength. If the stud strength decreased when flat sheet metal was used, then one could conclude that using cold-formed deck in composite slabs automatically reduces the stud strength from the solid slab stud strength, regardless of the profile of the deck. The strength of a stud where friction is not developed is probably a better representation of the reliable stud strength, given that friction cannot be relied upon for additional strength. If the effect of friction exists, it does not increase the *actual* strength of a stud, it increases the *apparent* strength of the stud.

These tests used studs with a diameter of 3/4 in. The nominal concrete strength was constant. Flat sheet metal was used in all specimens; three of the specimens were greased between the sheet metal and steel, and the other three were not.

2.2.1.3 Effect of Applying Normal Load (Series 7-8)

The third parameter investigated was the effect on stud strength of applying a normal load to the test specimen. Solid slab specimens tested previously at Virginia Tech did not have normal load applied, but specimens with formed metal deck did. To further investigate the effect of friction at the steel/concrete interface, six identical push-out specimens were tested. A normal load of 10% of the axial load was applied to three of these specimens, and no normal load was applied to the other three specimens. The 10% normal load is used to simulate load on a composite beam and to prevent the push-out specimen from "peeling apart". If applying a normal load causes a difference in strength, this is evidence that either friction is being developed or the state of stresses in the stud is being changed.

2.2.2 Composite Slab Push-Out Tests

A total of 93 composite slab push-out tests, summarized in Table 2.2, were performed as part of this study. The purpose of these tests is described below.

Table 2.2 Composite Slab Test Matrix

Series	Tests	Stud Diameter (in.)	Stud Position	Nominal f'c (psi)	Stud Height (in.)	Deck Height (in.)	Deck Gauge	Slab Depth (in.)	Normal Load (%)**
1	D1,D2,D3	0.5	S	3500	4	2	20	6	10
2	D4,D5,D6	0.5	2S	3500	4	2	20	6	10
3	D7,D8,D9	0.5	W	3500	4	2	20	6	10
4	D10,D11,D12	0.625	S	3500	4	2	20	6	10
5	D13,D14,D15	0.625	W	3500	3.5	2	20	6	10
6	D16,D17,D18	0.625	2S	3500	4	2	20	6	10
7	D19,D20,D21	0.5	S	6000	4	2	20	6	10
8	D22,D23,D24	0.5	2S	6000	4	2	20	6	10
9	D25,D26,D27	0.5	W	6000	4	2	20	6	10
10	D28,D29,D30	0.75	S	6000	4	2	20	6	10
11	D31,D32,D33	0.75	2S	6000	4	2	20	6	10
12	D34,D35,D36	0.75	W	6000	4	2	20	6	10
13	D37,D38,D39	0.625	S	6000	4	2	20	6	10
14	D40,D41,D42	0.625	2S	6000	4	2	20	6	10
15	D43,D44,D45	0.625	W	6000	4	2	20	6	10
16	D46,D47,D48	0.375	S	3500	4	2	20	6	10
17	D49,D50,D51	0.875	S	3500	4	2	20	6	10
18	D52,D53,D54	0.375	W	3500	4	2	20	6	10
19	D55,D56,D57	0.875	W	3500	4	2	20	6	10
20	D58,D59,D60	0.375	S	3500	5	3	20	6	10
21	D61,D62,D63	0.875	S	3500	5	3	20	6	10
22	D64,D65,D66	0.375	W	3500	5	3	20	6	10
23	D67,D68,D69	0.875	W	3500	5	3	20	6	10
24	D70,D71,D72	0.75	M	3500	6	4.5	16	6.75	10
25	D73,D74,D75	0.75	M	3500	7.75	6	16	8.75	10
26	D76,D77,D78	0.75	S	3500	4	2	20	5.75	5
27	D79,D80,D81	0.75	S	3500	4	2	20	5.75	20
28	D82,D83,D84	0.75	W	3500	4	2	20	6	5
29	D85,D86,D87	0.75	W	3500	4	2	20	6	20
30	D88,D89,D90	0.75	S	3500	3.375*	2	20	6	10
31	D91,D92,D93	0.75	W	3500	3.375*	2	20	6	10

NOTES:

S = single stud in strong position
W = single stud in weak position
M = single stud in middle of rib
2S = pair of studs in strong position

* Head of stud cut off & stud shank greased
** As a percentage of the axial load
f'_c = concrete compressive strength
Normal weight concrete used for all tests

2.2.2.1 Effect of Stud Diameter, Concrete Strength, and Deck Height

In Tests D1-D27 and D37-D69, smaller and larger diameter studs than previously tested at VT were used. In Tests D19-D45, stronger concrete than previously tested was used. In Tests D70-D75, deeper deck was used. The placement of the stud in the deck rib was varied among the tests.

2.2.2.2 Effect of Friction at the Deck/Beam Interface

Tests D76-D87 varied the amount of normal load placed on the specimens so that friction could be investigated. It is believed that increasing the amount of normal load applied to the specimen increases the friction between the deck and steel beam, which increases the *apparent* stud strength, discussed in Section 2.2.1.2. The placement of the stud in the deck rib was varied among these tests.

2.2.2.3 Effect of Tension in the Stud Shank

For Tests D88-D93, the heads of the studs were cut off and the stud shanks were greased in an attempt to decrease the tensile forces in the studs. If the stud is placed in a combination of shear and tension, as many researchers believe, the strength of the stud should be less than the stud strength in pure shear (which is approximately 60% of its tensile strength). The placement of the stud in the deck rib was varied among these tests.

2.3 Test Specimen Configuration and Construction

2.3.1 General

Both solid slab and composite slab specimens were tested in this study. The specimen configuration and construction is similar to that presented by Sublett et al (1992) and Lyons et al (1994), all of whom performed testing at the Virginia Polytechnic Institute and State University Structures and Materials Research Laboratory.

2.3.2 Solid Slab Specimens

All solid slab push-out specimens were constructed using wooden forms. Each specimen consisted of two concrete slabs, each of which was connected to a 44 in. long structural tee by welded headed shear studs. Slabs were 36 in. by 36 in., and consisted of a 5 3/4 in. thick normal weight concrete slab on a WT section. Series 1 and 5-8 used WT6x17.5; the studs were welded over the web of the steel section. Series 2 used WT6x17.5, Series 3 used WT6x13, and Series 4 used WT8x28.5; studs were welded off-center for these tests. The stud size used for all solid slab tests was 3/4 in. x 4 in. Two studs, spaced at 18 in., were in each specimen half. Steel reinforcement was the same for all tests: two layers of four #3 bars were placed on the bottom of the slab, and two layers were placed on the top. Bar chairs were used to support the top layers, and 2 in. long pieces of rebar were used to support the bottom layers. When sheet metal was used, holes were precut in the metal so that the studs could be welded directly to the steel beam. Lithium grease was applied between the sheet metal and steel flange when grease was specified. All slabs were cast horizontally. After the concrete was placed in the forms, it was vibrated with a mechanical vibrator, screeded with a wooden 2x4, floated, and broomed.

The specimens were covered and moist-cured for seven days, at which time the forms were removed. Concrete test cylinders were cast along with the specimens and cured similarly. The push-out specimen halves were then bolted through the webs to form a solid slab push-out specimen, which is shown in Figs. 2.1a and 2.1b. The specimens were tested around 28 days after being cast.

2.3.3 Composite Slab Specimens

Composite slab push-out specimens were constructed similarly to the solid slab specimens. Slabs were 36 in. by 36 in. with the thickness of the normal weight concrete slab and the deck size varied. Details of the deck used in this study are shown in Fig. 2.2. The structural tee used for all composite slab specimens was a 44 in. long WT6x17.5. The stud diameter and height, stud position, and concrete strength were varied. Steel reinforcement for all composite slab tests was 6x6-W1.4xW1.4 welded wire fabric.

A wooden form was used to ensure that the bottom of the slab would be perpendicular to the longitudinal axis of the beam and that the distance from the bottom of the slab to the bottom of the tee would be kept constant for all specimens. This ensured that the specimens would be vertical and that loading would be evenly applied to the two slabs. Each specimen was constructed using a 36 in. by 36 in. piece of steel deck and pour stop the depth of the slab to form the edges. The structural tee was placed in the form, after which the steel deck was placed on top of the beam with the ribs of the deck

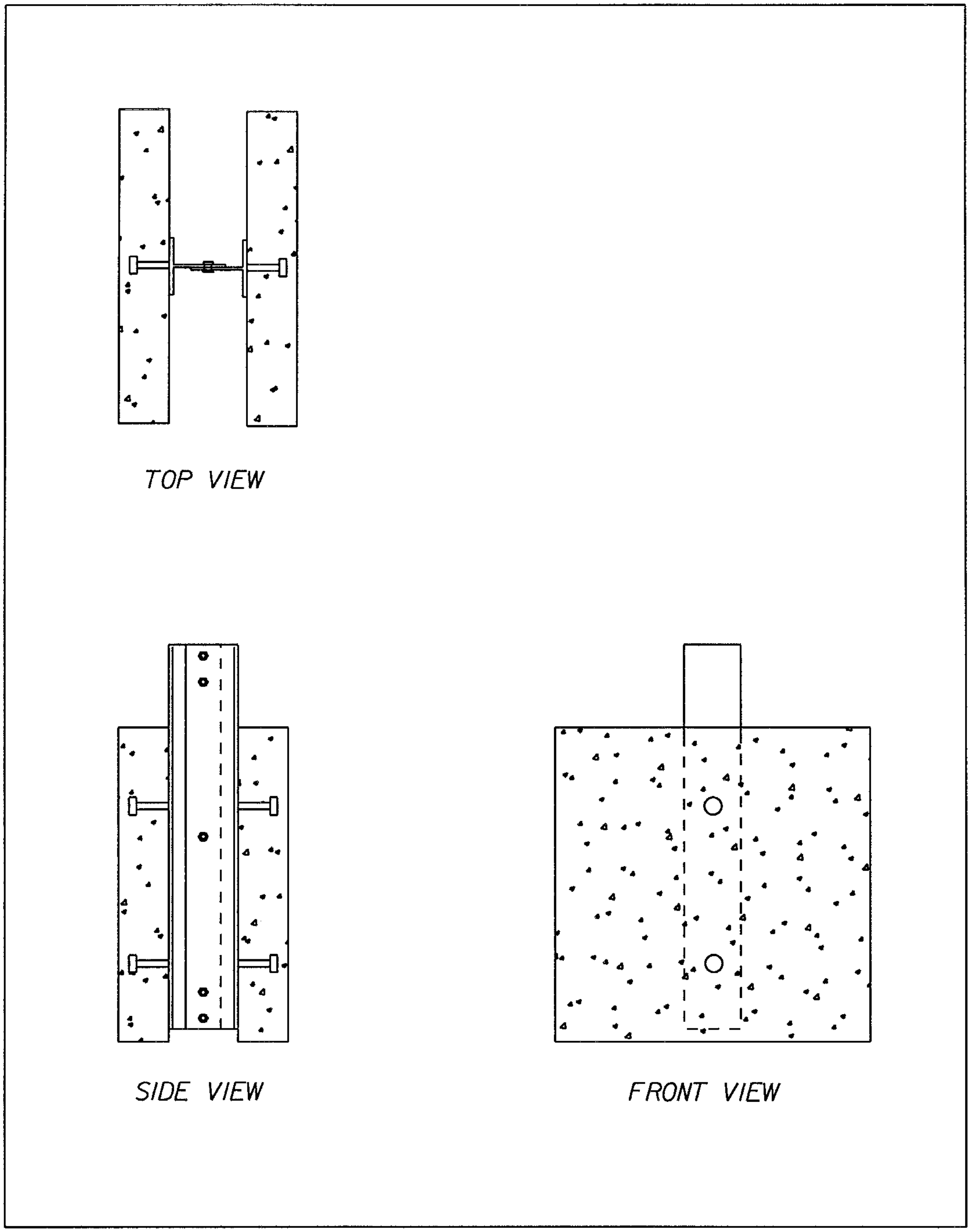

Fig. 2.1a Solid Slab Push-Out Specimen with Studs Welded Centrally on Flange (Reinforcing steel not shown)

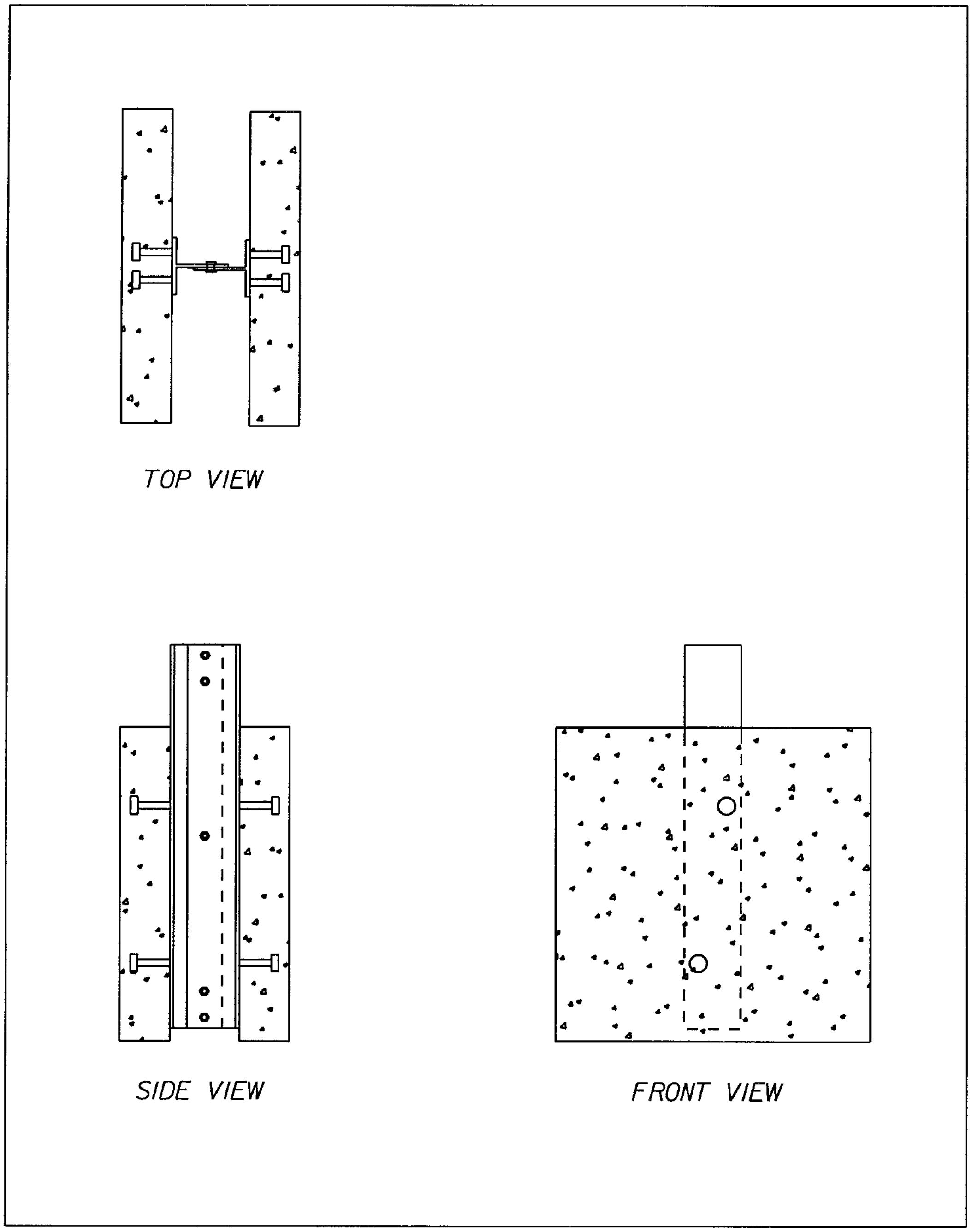

Fig. 2.1b Solid Slab Push-Out Specimen with Studs Welded Off-Center on Flange (Reinforcing steel not shown)

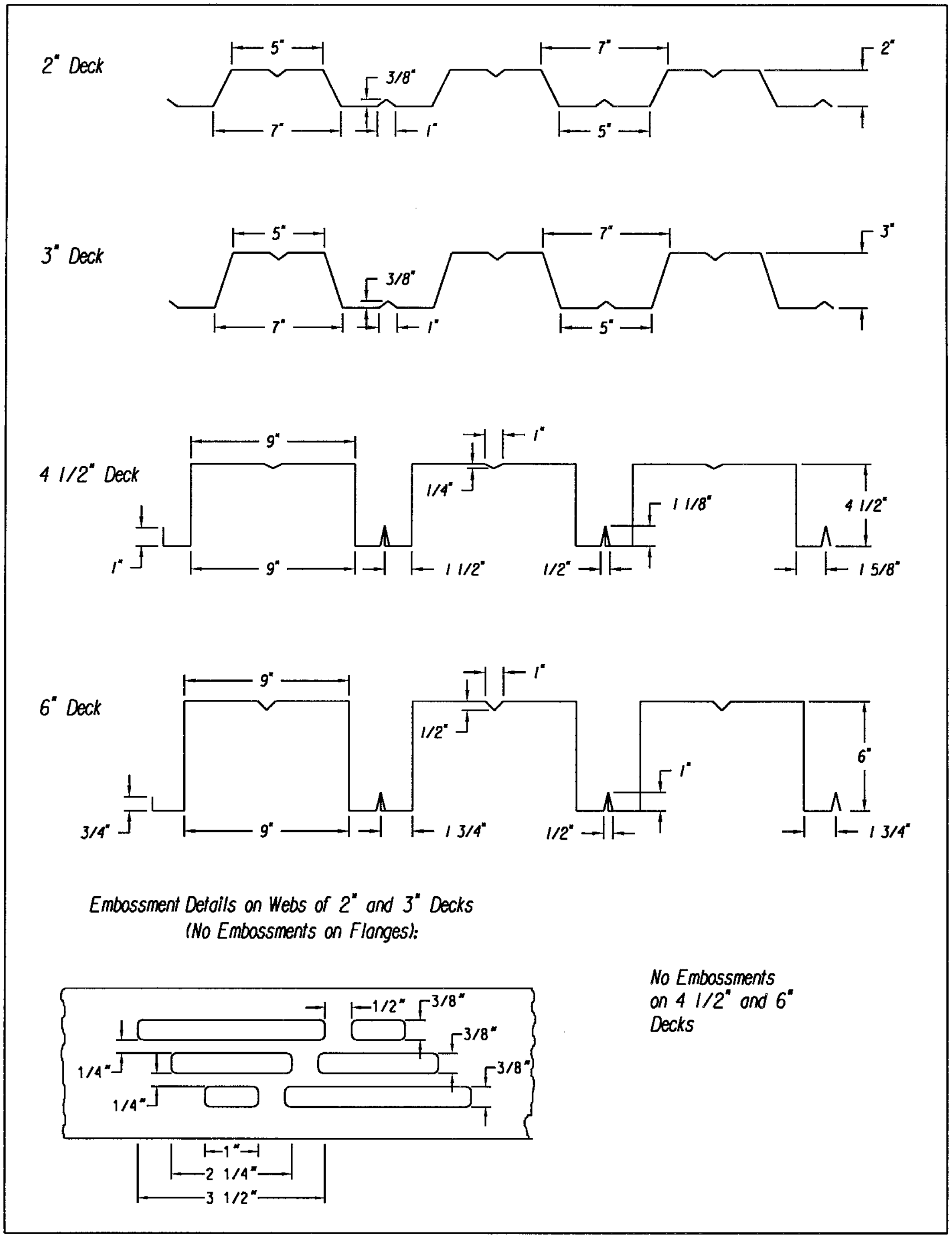

Fig. 2.2 Deck Details

perpendicular to the beam. The studs were then welded through the deck to the flange of the tee. The deck and tee were removed from the wooden form and placed on concrete blocks. The welded wire fabric was placed on top of the metal deck. Several slabs were then cast horizontally, using the same batch of concrete. After the concrete was placed in the forms, it was vibrated with a mechanical vibrator, screeded with a wooden 2x4, floated, and broomed. The specimens were covered and moist-cured for seven days, after which time the pour stop was removed. Concrete test cylinders were cast along with the specimens and cured similarly. The push-out specimen halves were then bolted through the webs to form a composite slab push-out specimen.

Figs. 2.3a – 2.3d illustrate composite slab specimens with different stud positions. The specimens were tested around 28 days after being cast.

2.4 Loading Method and Instrumentation

After the specimens had cured for about 28 days, they were placed in a test setup similar to the one presented by Sublett et al (1992) and Lyons et al (1994). The bottom edge of each concrete slab was placed on a 40 in. x 10 in. x 1 in. elastomeric bearing pad. Each slab was braced by two angles that were attached to the columns of the load frame to ensure that the specimen remained vertical throughout testing. A 11 in. x 7 in. x 1 in. plate was positioned on the webs of the tees at the fillets to distribute the load from the 200 kip capacity hydraulic ram equally to the specimen halves. The ram transferred the load to a load frame, which was bolted to the reaction floor. A typical test set-up is shown in Fig. 1.2.

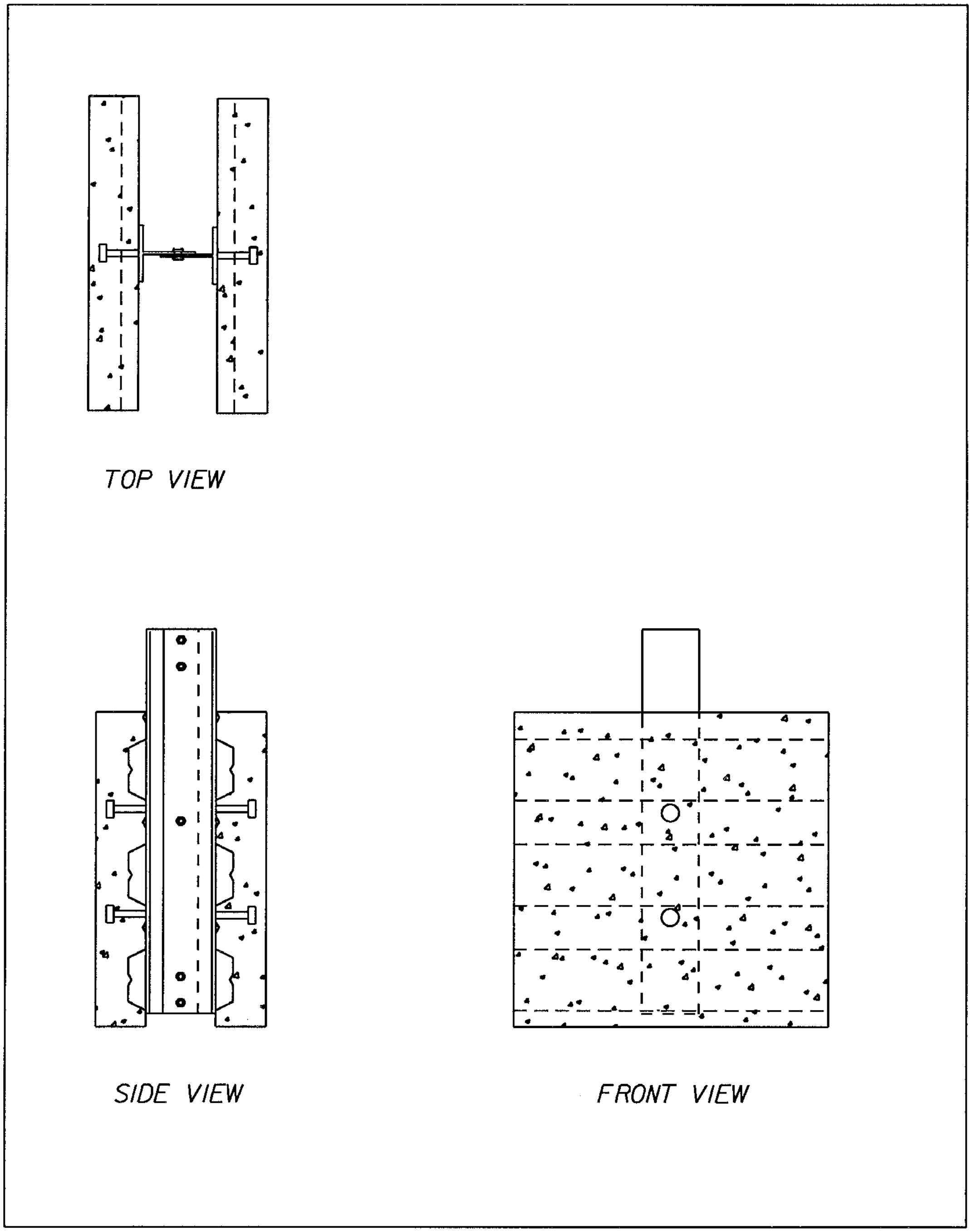

Fig. 2.3a Composite Slab Push-Out Specimen with Studs in the "Strong" Position (Welded Wire Fabric not shown)

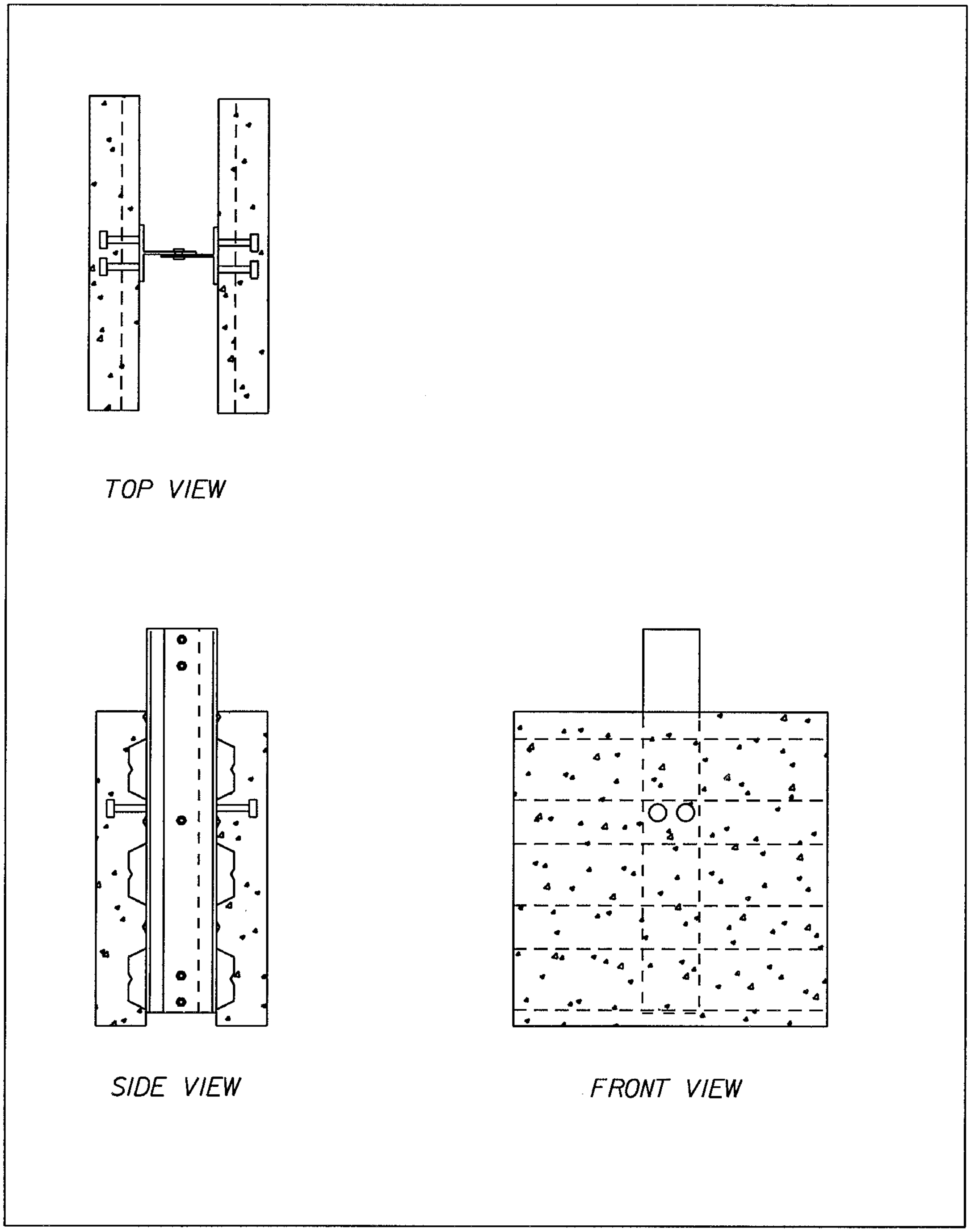

Fig. 2.3b Composite Slab Push-Out Specimen with Studs in the "2Strong" Position (Welded Wire Fabric not shown)

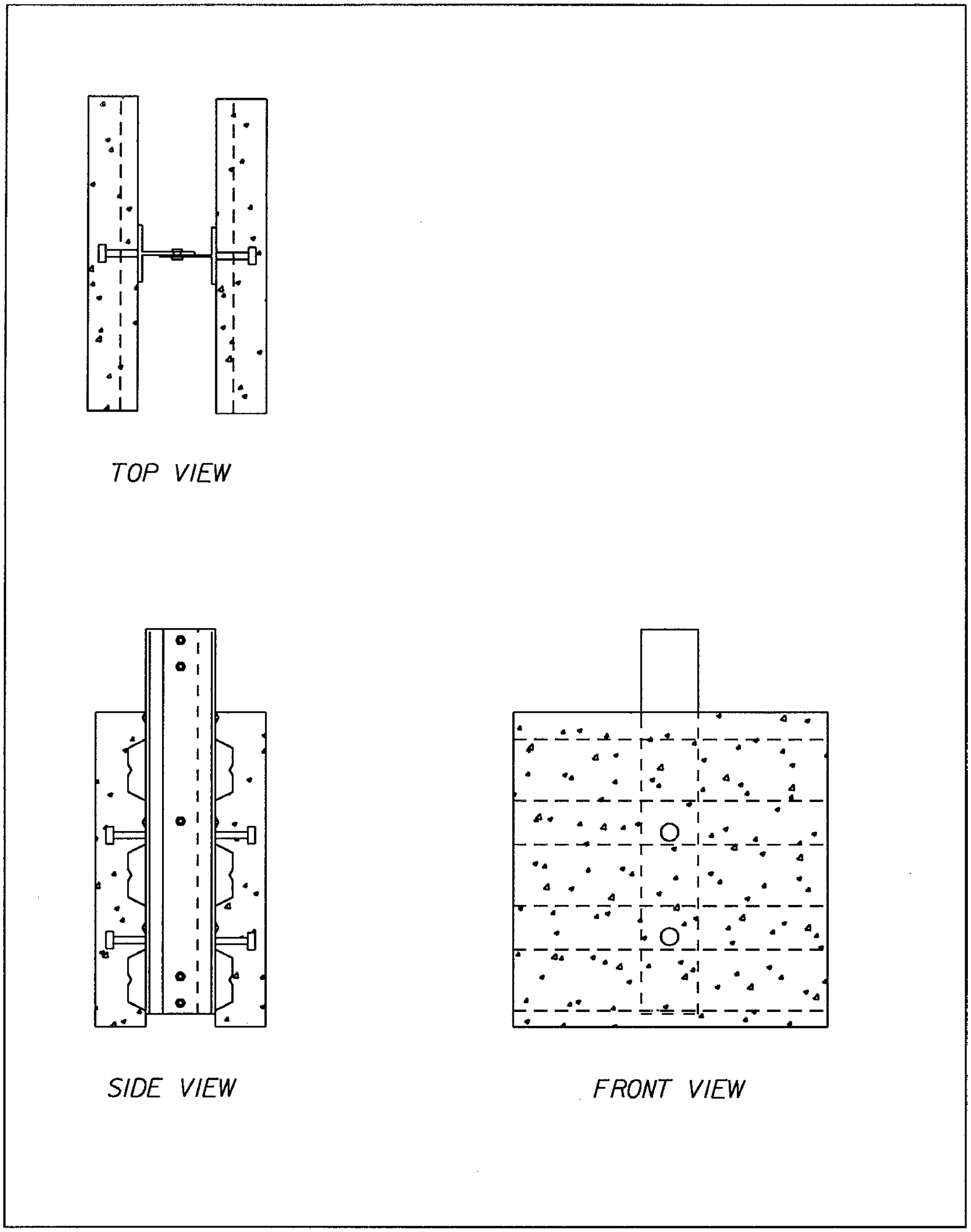

Fig. 2.3c Composite Slab Push-Out Specimen with Studs in the "Weak" Position (Welded Wire Fabric not shown)

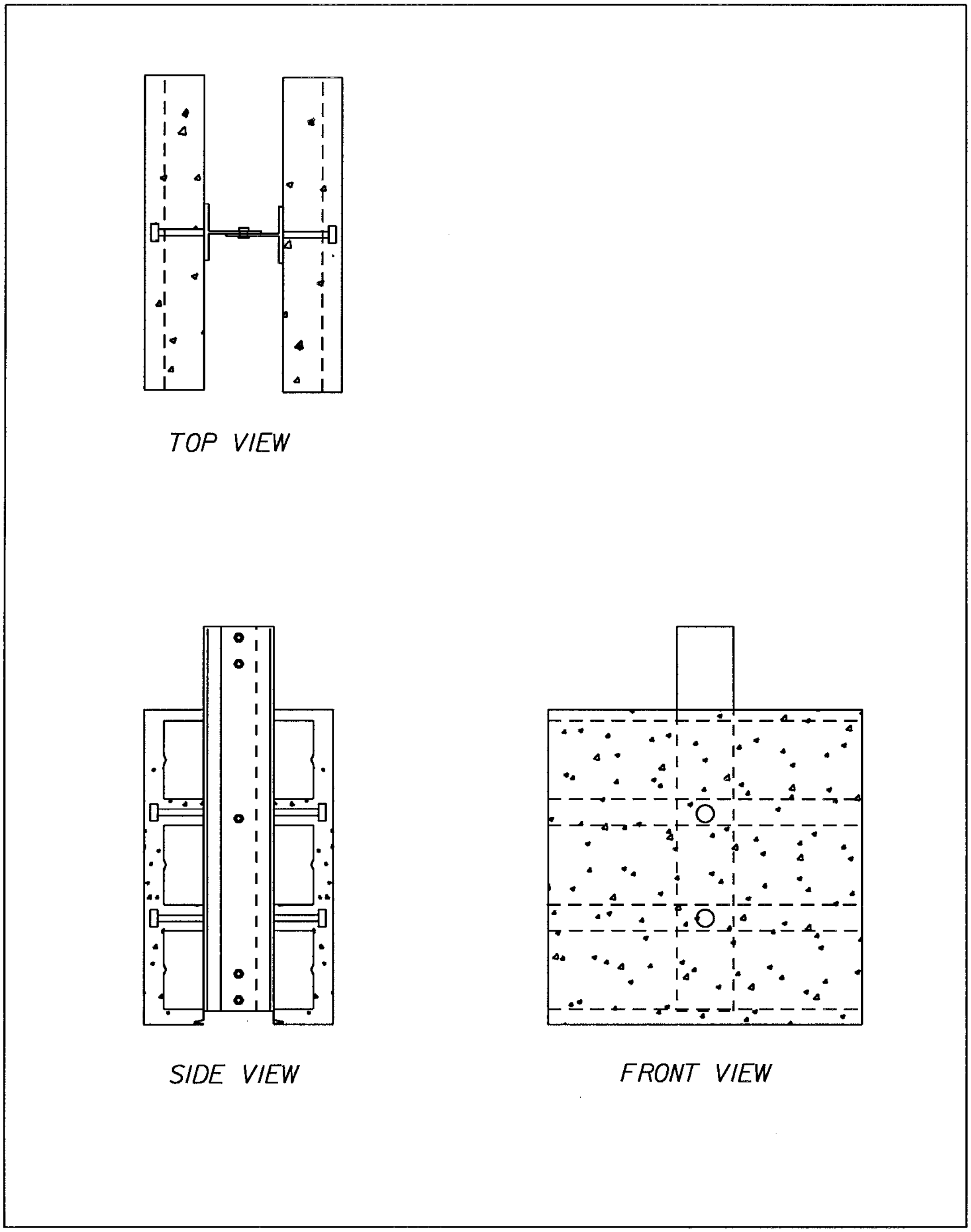

Fig. 2.3d Composite Slab Push-Out Specimen with Studs in the "Middle" Position (Welded Wire Fabric not shown)

An apparatus was used to apply normal load to some of the solid slab specimens and to all of the composite slab specimens. This apparatus consisted of a yoke device placed around the perimeter of the specimen. The load was generated by a hydraulic ram and was transmitted to the slab surfaces by beams, which were placed on the slab surfaces parallel to the beam axis. This normal load, as explained by Lyons et al (1994), prevented the metal deck from "peeling away" from the beam flange. As he stated, "loading normal to a composite floor is what causes bending and consequently shear forces across the steel-concrete interface."

The specimen was instrumented with two load cells and four linear potentiometers for the solid slab and composite slab tests. A 500 kip capacity load cell, placed between the ram and the beams of the load frame, was used to measure the axial load applied to the specimen. A 50 kip capacity load cell, placed between the hand-operated ram and yoke device, measured the normal load applied to the specimen. Six-inch linear potentiometers, placed near the location of each shear stud, measured the slip, or movement of the tee flange relative to the concrete slab. These potentiometers were clamped with light angles; the angles were then clamped to the tee flanges. Holes were drilled in the concrete slabs at the locations where slip was to be measured. For specimens with metal deck, 1 in. holes were drilled in the deck at these locations before the concrete was cast. Plastic concrete anchors were placed in the holes in the concrete, and nails were placed in the anchors. The potentiometers were then wired to the nails. All measuring devices discussed above were calibrated before use.

2.5 Test Procedure

All push-out specimens were tested according to the following procedures. Specimens were continuously loaded (i.e., they were not unloaded and loaded again), unless problems occurred during testing. First, normal load, if used, was applied. The applied normal load was usually 10% (but in some cases 5% or 20%) of the applied axial (shear) load. The axial load was then applied in 5-kip increments until a load of approximately 80% of the expected capacity was reached. It is around this load that the load-slip curve becomes nonlinear. Then, slip control was used; load was applied until the slip increased a fixed increment.

Load and slip measurements were recorded with a computerized data acquisition system. They were taken approximately every four minutes. This is about the length of time it takes for the specimen to deform for a given load and for the readings to "settle". Less time was allowed if the measurements settled quickly. No more than 5 kips were added to the specimen each time it was loaded. This meant that it may have taken two to three minutes just to add the load for the specimen to slip the desired amount. In this case, more than four minutes was allowed between measurements. At any rate, the intent was to measure the load that the specimen could sustain for a given displacement. Observations of the specimen behavior were recorded throughout the tests. Specimens were loaded to failure, when they could no longer sustain load or when excessive displacements were observed.

Throughout testing, measurements were input in a spreadsheet to obtain a load-slip plot. These measurements were plotted against the predicted load-slip plot, which was obtained from the equation by Ollgaard et al (1971). The predicted ultimate load was obtained from the equations for shear stud strength from Ollgaard et al (1971) and Grant et al (1977).