COMPOSITE FLOOR DIAPHRAGM SLAB TESTS

by

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SUMMARY

The test facility described in this paper was designed and constructed for testing composite steel deck diaphragms. All slabs were constructed using corrugated, cold-formed steel decking as composite reinforcement for the concrete slabs. The results of the tests will eventually be used to formulate design recommendations for in-plane shear strength for steel deck reinforced slabs. These design recommendations are intended to supplement those proposed in Reference 2 for gravity-loaded steel deck slabs. This paper presents tentative design failure modes and associated test results. An illustration of a unique failure mode is given in the oral presentation.

INTRODUCTION

Concrete floor slabs reinforced with composite steel decking (see Fig. 1) have become increasingly popular in the past 12-20 years. This is because the deck not only provides formwork during the casting stages, but also serves as the tension reinforcement under positive bending. Other advantages, with a summary of background research conducted at Iowa State University, are given in Reference 1. This previous research conducted on steel deck composite slabs subjected to gravity loads led to the development of design recommendations (Ref. 2). The predominant mode of failure for slabs subjected only to gravity loads was that of shear-bond (Ref. 3,4), where the selected design equation was based upon a modification of Eq. (11-6) of the American Concrete Institute (ACI) Code (Ref. 5).

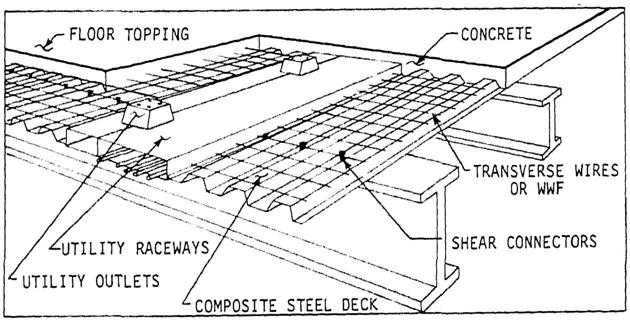

Fig. 1. Typical building floor construction utilizing cold-formed steel decking with composite support beams.

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For building floor slabs subjected also to lateral (in-plane) loads, the composite shear due to gravity combined with in-plane loads must be considered. Past research considered only the effects of gravity loads for the composite deck slab action. The additional effects of composite slab-to-support beam behavior, together with the concerns of lateral shear due to earthquakes, led to the work described in this paper to determine the in-plane shear strength and failure behavior. The work described was part of a project sponsored by the National Science Foundation on "Seismic Resistance of Composite Floor Diaphragms" (Ref. 6).

FAILURE MODES

Table 1 lists potential failure modes for composite steel deck diaphragms subjected to in-plane shear. This list is based on previous ISU research (Refs. 1-3) and some previous diaphragm research (Refs. 6-11) as well as on the test results from this project. The major parameters involved in these failure modes are shear connections (arc spot welds, studs), concrete qualities (strength, depth), diaphragm configuration (orientation, plan dimensions, and thickness), composite deck strength and stiffness, and loading history (cyclic and monotonic). To understand the relative importance of these parameters and to arrive at possible design criteria, the failure modes must be studied and understood. In general, these modes, as applied to the floor slab, are divided into three broad categories:

- overall composite diaphragm action,
- steel deck-to-concrete interface behavior; and
- diaphragm-to-edge member interface failure.

Table 1. Failure modes for composite diaphragms.

1. Composite Diaphragm:
   a. Shear strength
      1. Diagonal tension
      2. Parallel to deck corrugations
   b. Stability failure
   c. Localized failure

2. Deck/Concrete Interface:
   a. Interfacial shear parallel to the corrugations
   b. Interfacial shear perpendicular to the corrugations
      1. Pop up (overriding)
      2. Deck fold-over

3. Diaphragm/Edge Member Interface:
   a. Arc spot welds
      1. Shearing of weld
      2. Tearing and/or buckling of deck around weld
   b. Concrete rib
   c. Studs (or other shear connectors)
      1. Shearing of stud
      2. Shear failure of concrete around stud

Composite Diaphragm Failures

Composite diaphragm failures occur when, at the time of maximum load, the system acts as a composite unit. A diagonal tension failure (Failure Mode

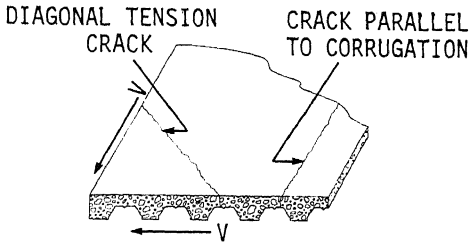

Fig. 2. Failure by shearing of the concrete in a) diagonal tension and b) cracks parallel to the corrugations (Failure Mode 1a-1 and 1a-2 in Table 1).

1a-1 in Table 1) is an example of this type of failure. This failure mode, which occurs when the concrete stress reaches its tensile limit, is characterized by diagonal cracks (at an angle of approximately 45°) across the slab (Fig. 2). After this crack forms, the steel deck begins to act as shear reinforcement, transferring the forces across the crack.

Another type of composite diaphragm failure is a direct shearing of the concrete along a line parallel to the deck corrugations (Failure Mode 1a-2) (see Fig. 2). If the concrete covering is thin, this failure will be most likely to occur over an up corrugation, with the ultimate strength depending on the shear strength of the concrete.

Two other failure modes, stability and localized (Failure Modes 1b and 1c), are also possible. A stability failure is typical for metal deck diaphragms with large width-(or span)-to-thickness ratios. However, in composite diaphragms, the concrete effectively prevents out-of-plane buckling due to in-plane loads for the practical span lengths. All of the tests for this research consisted of composite diaphragms of moderate span lengths with only in-plane loading, so the stability failure mode did not occur. Combined in-plane and vertical (gravity) loading may necessitate consideration of this failure mode. A localized failure typically occurs when there is a nonuniform shear distribution in the diaphragm and, consequently, a discrete region of high stress. This failure, which is restricted to a small area, is created by concentrated loads or reactions and/or flexible edge beams.

Deck/Concrete Interface

If the composite deck does not make use of shear connectors (e.g., studs), all of the diaphragm force must be transferred to the concrete by forces at the interface of the steel deck and the concrete, i.e., by interfacial shear forces. Failure by interfacial shear (Failure Mode 2) can occur either parallel or perpendicular to the deck corrugations. Interfacial shear failure parallel to the corrugations (Failure Mode 2a) is similar in character to the shear-bond failure experienced in vertically loaded specimens (Refs. 3,4).

When failure occurs in the direction perpendicular to the steel deck corrugations, the concrete bears against the inclined face of the cell. Two types of behavior may then occur. If the corrugations are stiff enough, the concrete may actually ride up and over them (Failure Mode 2b-1). If they are flexible, the concrete will flatten out the corrugations (Failure Mode 2b-2).

Which mode occurs depends on the stiffness of the deck corrugations and the relative interfacial shear strength in both the transverse and longitudinal directions.

Diaphragm/Edge Member Interface

Edge connections are frequently made with arc spot welds or studs. With the arc spot welds, the load is transferred through the steel deck. Failure at these points would be a direct shearing of the weld (Failure Mode 3a-1), or a buckling and/or tearing of the deck around the weld (Failure Mode 3a-2). With arc spot welds or short studs that do not extend above the up corrugation, a direct shearing of the concrete rib, resembling an unreinforced corbel, could occur (Failure Mode 3b).

With studs that extend above the up corrugation of the steel deck, the shear force is transferred directly onto the concrete above the deck profile. Failure of this form of connection may be a result of stud shear (Failure Mode 3c-1) or concrete failure around the stud (Failure Mode 3c-2). This second form is usually the result of inadequate concrete in the down corrugation and/or at the edges.

TEST FACILITY

To study the failure modes, strength, and many other behavioral characteristics of composite steel deck diaphragm slabs, a large test frame facility was constructed. Several types of test frame facilities were evaluated prior to the selection of the final configuration.

A cantilever diaphragm test frame with a fixed edge support was chosen as the final design. In most buildings with a composite floor system, an adjacent slab exists on at least one side which provides in-plane restraint against deformation. Also, the fixed edge support approximately models a continuously attached shear wall. The free edge models a structural steel frame in which the in-plane forces are transferred to the diaphragm along the horizontal member. Stiff edge beams were used for this test frame because they produce a more uniform shear stress distribution in the test diaphragm than do flexible support beams.

A schematic of the test frame facility appears in Fig. 3. As indicated in the figure, the constructed test frame facility consisted of three large reinforced-concrete reaction blocks (for the fixed edge) and three perimeter-framing beams. The frame was designed for a working load of ±400 kips and a displacement capability of ±6 inches.

The three blocks were used to support one edge of the composite floor diaphragm. An imbedded steel plate, simulating a rigid-beam flange, was used to attach the steel deck of the floor slab to the reaction blocks. The blocks were anchored to the laboratory test floor with two-inch diameter high-strength bolts, each post-tensioned to 240 kips. The laboratory test floor was a million pound capacity tie-down floor system.

Two hydraulic double-acting cylinders were used to apply the force to the testing frame. These actuators were front trunnion-mounted and capable of pushing or pulling 200 kips each, giving the test frame a 400-kip capacity.

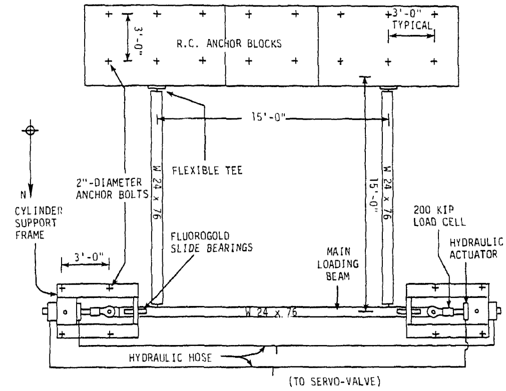

Fig. 3. Diaphragm test frame schematic.

SUMMARY OF TEST SPECIMEN RESULTS

The facilities and instrumentation described in the preceding sections performed very well throughout the test sequence. Nine full-scale composite diaphragm slabs were tested using the cantilever-type test frame. The slabs were 15'4" × 15'4" in out-to-out plan dimensions and ranged in thickness from 3 1/2 inches to 7 1/2 inches (nominally). The first slab specimen tested was used to verify the adequacy of the test frame, controls, instrumentation, and data acquisition systems. No additional supplementary reinforcing was included. All slabs were wet cured for 7-14 days, and then air dried until test time. Material summarizing behavioral results from the test and potential analyses are given in Reference 6.

Summaries of the important parameters and the experimental results for the diaphragm slab specimens tested are given in Tables 2 and 3 respectively. A reversed cyclic displacement program with progressively increasing displacements was used for all slabs except the first (pilot) specimen, which was loaded monotonically.

Of particular interest among the failure modes that relate to the shear-bond type of behavior is Mode 2a in Table 1, i.e., interfacial shear parallel to the corrugations. This mode results in horizontal end slip observed at the edge of the specimen for both gravity and in-plane loaded specimens (Refs. 3,4,6). The failure of Slab 6 in Tables 2 and 3 will be described in more detail.

The maximum load for Slab 6, 146.8 kips, was reached at a 0.1-inch displacement. The load-displacement curve is shown in Fig. 4. The mode of failure for this slab was interfacial shear parallel to the corrugations. The most significant observation to make about this slab is that no cracks formed on the top surface of the concrete throughout the entire test. The concrete simply slipped parallel to the corrugations and rotated about a vertical axis as the frame was cycled back and forth. A very high secondary defense plateau formed at 107 kips, after the maximum load (Fig. 4). The load-carrying mechanism in the nonlinear range was frictional interference between the steel deck and concrete. This frictional force was caused by a conflict between the displaced shapes of the steel deck and concrete, i.e., a warpage of the

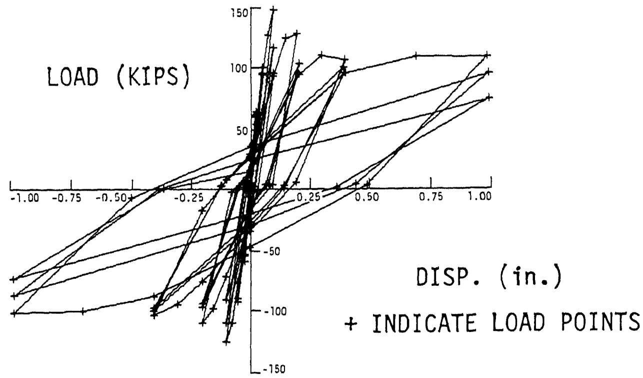

Fig. 4. Load-displacement diagram for Slab 6.

Table 2. Summary of parameters for slab specimens.

Slab Number	Actual Thickness[a] (in.)	f_c' (psi)	Deck Depth (in.)	Steel Thickness (in.)	Connections Per Side
1	5.38	5634	3	0.034	30 studs
2	5.50	5250	3	0.034	30 studs
3	5.65	4068	3	0.034	60 welds
4	5.28	3849	3	0.034	60 welds
5	3.53	2966	1 1/2	0.062	30 welds
6	7.44	4549	1 1/2	0.062	60 welds
7	5.40	5435	3	0.058	60 welds
8	5.47	3345	3	0.035	4 studs (each N-S side) 6 studs (each E-W side)
9	5.48	5412	3(cells)[b] 3(pan)	0.058 0.057	60 welds

[a]Out-to-out thickness.

[b]A cellular type deck was used on Slab 9.

Table 3. Summary of experimental results.

Slab Number	Initial Stiffness (KIPs/in.)	V_u (KIPs)	Failure Mode
1	1800	168	Diagonal tension
2	2000	186	Diagonal tension
3	1600	97.8	Interfacial shear
4	1300	87.7	Interfacial shear
5	1700	116	Diagonal tension
6	2600	147	Interfacial shear
7	1500	137	Interfacial shear
8	1100	54.4	Diagonal tension/ shear connector
9	1900	220	Diagonal tension

deck cells against the concrete cells. In general, for all the slabs tested, a significant amount of load capacity remained after ultimate failure. A strength and stiffness degradation similar to that shown in Fig. 4 occurred for the other failures.

Further illustrations of this particular failure mode and the test frame arrangement will be given during the oral presentation. Additional work is planned for combining the tests for in-plane and gravity shear-bond failure as well as other failure mode combinations.

Design for Composite Diaphragm Slabs

Each of the failure modes shown in Table 1 must be considered for design of composite deck slabs. Conceivably, the designer needs to consider and evaluate load carrying capacities for each mode and determine the controlling failure mode that will produce the lowest in-plane load capacity. Since many more modes of design exist for composite diaphragm slabs than for simple beams or other component structures, the design formulations needed to arrive at the controlling mode are more lengthy. The design mode becomes even more complex when the loading consists of gravity combined with in-plane loading. Work is underway at Iowa State University to investigate such analyses further and to formulate design recommendations for composite steel deck diaphragm slabs to supplement those design recommendations in Reference 2 for gravity-loaded steel deck slabs.

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