ZALLEN ENGINEERING
FORENSIC ENGINEERING IN CONSTRUCTION®
ONLINE EDITION

No. 8 July 2002

Collapse of Flying Formwork During Concrete Placement

A formwork collapse occurred during the construction of a new manufacturing building which was being built in suburban Boston for a large electronics manufacturer. The building is multi-leveled, and for the most part has a structural steel frame with composite concrete and metal deck floors. However, there is one section of the building which has a deep reinforced concrete waffle floor slab supported on reinforced concrete columns and peripheral reinforced concrete walls. During the initial placement of the concrete for the waffle slab, the supporting formwork collapsed, resulting in injury to a number of construction workers.

Figure 1. View of collapse from below. Photo taken from under flying formwork that did not collapse.

The waffle floor construction is 430 feet by 184 feet in plan. Figure 2 (next page) is a part plan at the southwest corner of the floor, showing representative construction; Figure 3 is a section through the west side of the floor, showing the floor and the supporting walls and columns.

The formwork for the waffle slab consisted of fiberglass pans supported by *flying forms*. A flying form is a large section of flat floor formwork, called a table, which is reused many times. It is handled by a crane which "flies" it into place. The table is supported on previously completed construction, either by legs onto a floor below, or by supports on the sides of columns. In order for the flying form system to be of practical use, there has to be a method to drop the large tables down, after the concrete it is supporting has achieved its proper strength, and to either roll the tables to its next position, or to roll the tables to the edge of the slab so it can be moved out and picked up by a crane for its next use.

For this project the tables were supported on the east and west sides of the concrete columns, and by temporary steel columns adjoining the ends of the concrete buttresses shown on Figure 3. Figure 4 (page 3) shows a cross-section through the formwork, taken at the same location as Figure 3. There are proprietary support fixtures attached to the columns by high-strength bolts. At the concrete columns, the bolts pass through sleeves cast into the columns. Figure 5 shows a side elevation of a support fixture. Figure 6 shows support fixtures mounted on a column. Due to the heavy load of the concrete, there are two supports on each side of the concrete columns and two supports on the steel columns.

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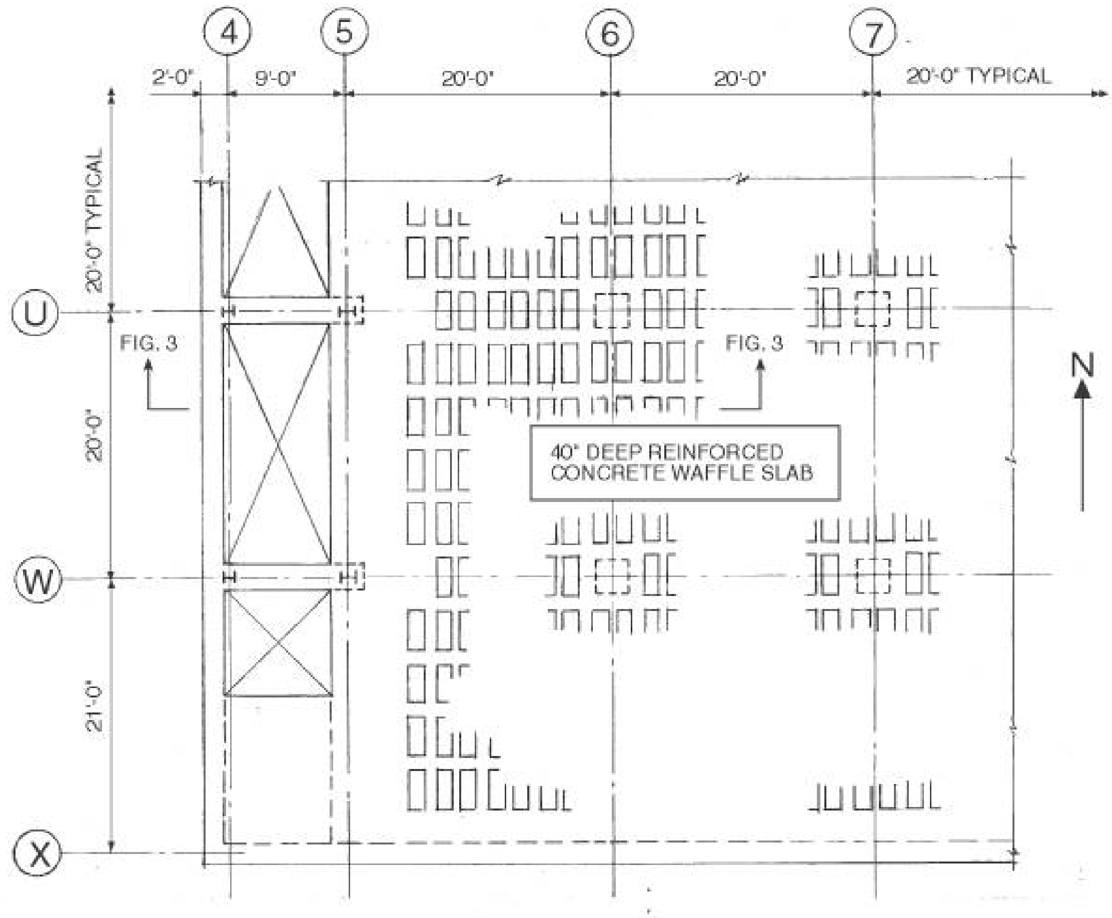

Figure 2

Part plan showing the southwest corner of the waffle floor slab. Adjacent floor construction is not shown.

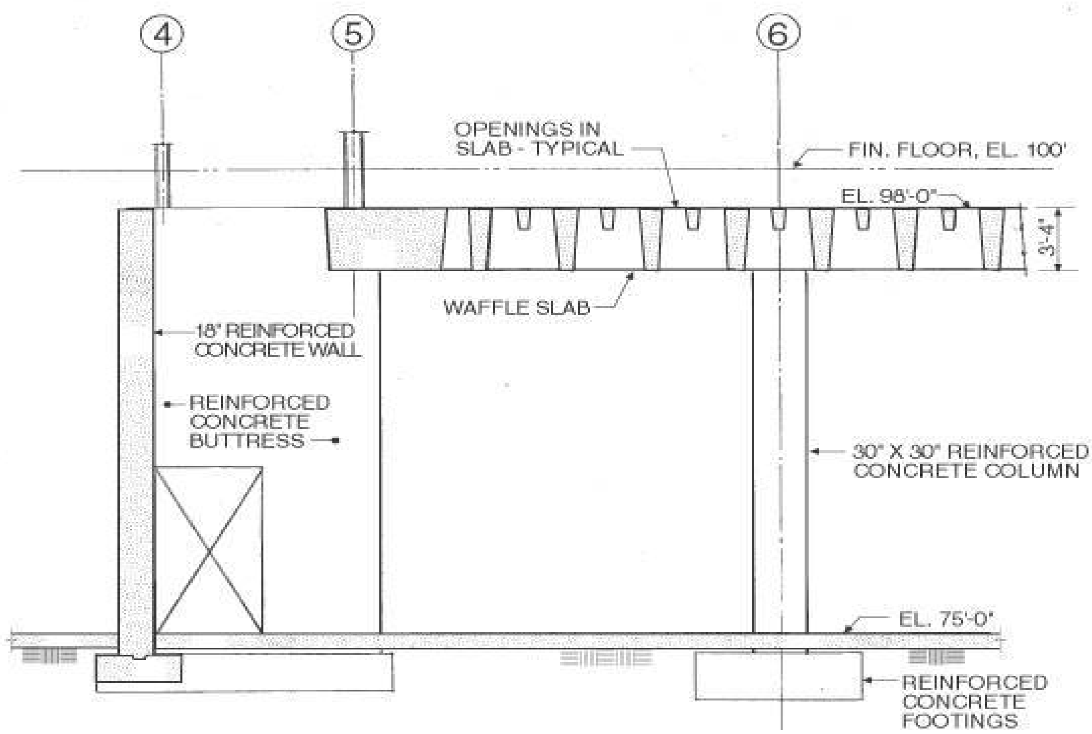

Figure 3

Section through waffle floor slab. Reinforcing steel and adjacent floor construction are not shown.

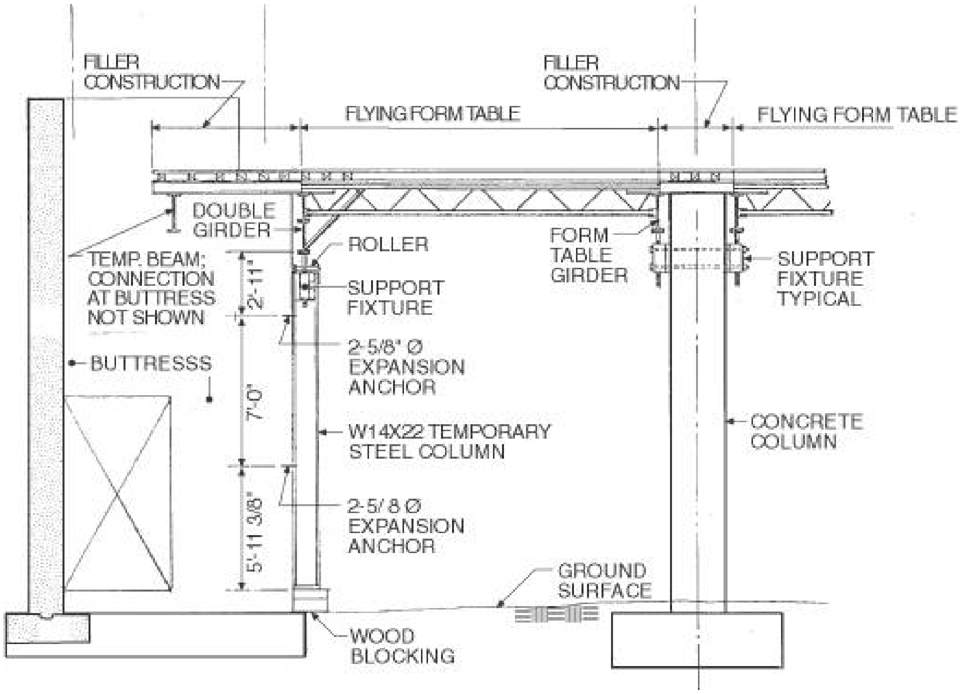

Figure 4. Section through formwork for waffle floor, taken at the same location as Figure 3. Waffle pan forms and side forms are not shown.

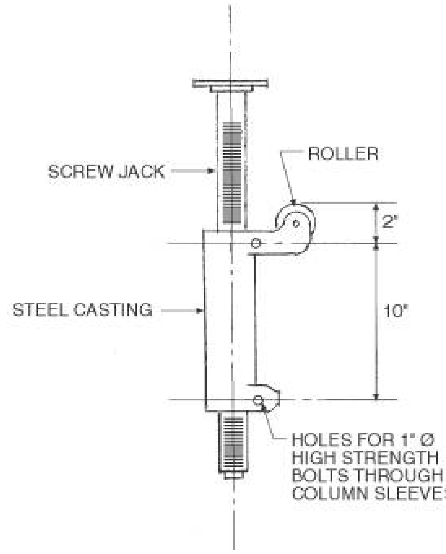

Figure 5. Side view of support fixture.

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Each support fixture at the columns has a screw jack with a bearing plate at the top; the screw jacks are turned to bring the bearing plates to the proper elevation and the form tables are flown in on top of them. Filler pieces of formwork are then placed at the buttresses and between the tables, and the formwork is then ready to receive the requisite reinforcing steel, other accessories, and finally the concrete. When the concrete has achieved its proper strength, the jacks are lowered until the steel support girders rest on top of rollers on the support fixtures (see Figure 5), and the filler pieces at the buttresses and between the tables are removed. The tables are then rolled out to the next position or are rolled out and picked up by the crane.

The design of the flying form system was by the supplier of the system, and it was shown on erection and shop drawings prepared by the supplier. The formwork was erected by the concrete subcontractor, who generally erected it in accordance with the formwork erection drawings.

Figure 6. Support fixtures for flying forms.

Figure 4 shows details of the temporary steel columns at the ends of the buttresses, at the time of the collapse. The formwork erection drawings showed no detail for the support of the base plate of the steel columns adjoining the buttresses; they just indicated that the bottom of the base plate would be at the level of

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the top of the ground floor slab on grade. (The slab would be installed at a later time). The wood blocking supporting the column base plate was added in the field by the concrete subcontractor. See Figure 7.

The flange of the temporary steel columns adjoining the ends of the buttresses was attached to the buttresses with two pair of 5/8 inch diameter expansion anchors. See Figures 4 and 8. One purpose of these anchors was to hold the column and the supported formwork in-place; a second purpose was to provide lateral support to the column so as to prevent lateral buckling of the column perpendicular to the web of the column.[1,2]

The length of each table (and its girders) was 40 feet and the width was set to clear the concrete columns or the ends of the buttresses. The girders of the table thus spanned over three supports, with each end of the girders being simply supported on a single screw jack, and the center of the girders being supported on two screw jacks (see Figure 6).

The Collapse

The concrete pour started at the southwest corner and proceeded north to fill the first bay, between Lines 5 and 6. See Figure 2. The collapse occurred when the concrete in the first bay extended to Line 6 to the east, and approximately 70 feet to the north. Figure 9 (page 5) is a view of the collapse.

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Notes for Non-Engineers

1. These notes explain structural engineering jargon and concepts for non-engineers.

2. A column becomes unstable when the axial load on the column reaches a critical level. Due to this instability, the column suddenly bends laterally, causing it to collapse. This behavior is called buckling.

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Figure 7. Wood blocking supporting base plate of temporary steel column on Line 5; believed to be at the most northerly end of the formwork that collapsed. (The column shown did not collapse).

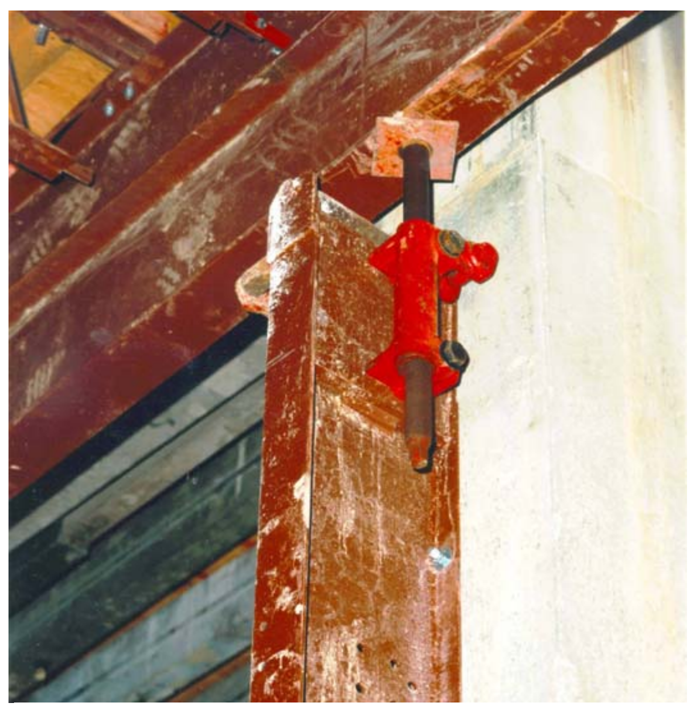

Figure 8. Top of temporary steel column showing one of the top pair of 5/8 inch diameter expansion bolts.

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Figure 9. View of collapse, looking eastward.

When the load from the concrete was imposed onto the steel columns adjoining the buttresses, the columns pushed down on and compressed the wood blocks, and at the same time loaded the expansion anchors in shear. A basic structural principle is that when load is shared between various elements, it will be transferred to the elements in proportion to their respective stiffnesses; the stiffer the element, the greater the percentage of load it will support. Relative to the steel column itself and to the expansion anchors, the wood blocking in compression is flexible, thus a substantial portion of the column load was transferred to the expansion bolts. Since the reaction (the resisting force) of the expansion bolts on the column is eccentric to (i.e., not in line with) the load on the top of the column, the top pair of expansion anchors were subjected to tension in addition to the shear on these anchors.[3]

The failure was initiated at the temporary steel column at grid location W-5, which was one of the two most heavily loaded temporary columns, when the top pair of expansion bolts pulled out of the concrete in a concrete cone mode of failure, and the bottom pair of bolts sheared off. The vertical load was then completely transferred to the wood blocks; however, at the same time the column buckled laterally and collapsed, since, with the failure of the expansion anchors, it lost its intermediate lateral support. The failure of Column W-5 precipitating the collapse of the whole bay with most of the other temporary columns failing in a similar mode. The estimated load on the column when it failed was 90,000 lbs. The calculated ultimate capacity of the column with one flange braced laterally by the expansion anchors is 118,000 lbs. However, the calculated ultimate capacity without that flange being braced is only 40,000 lbs.

Notes for Non-Engineers

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3. The eccentricity causes the column to try to rotate away from the end of the buttress. This rotation effect, which is called a moment, is resisted by an opposite moment created by tension in the top expansion anchors and an equal and opposite compression of the column against the end of the buttress at the bottom of the column.

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The form designer, the concrete subcontractor, and the general contractor all made errors: 1) the form designer did not specify how the steel columns were to be supported at their base, 2) the form designer did not detail the columns to prevent vertical load transfer to the expansion anchors, 3) the concrete subcontractor did not request and obtain a support detail for the steel columns, and 4) the general contractor did not insist that the concrete subcontractor request and obtain said support detail.

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The form designer used a slender steel shape for the column which is intended for use as a beam, which resulted in the requirement for intermediate lateral support to prevent buckling of the column perpendicular to the web. Had the designer provided a column that did not need intermediate lateral support, a shape that is normally used for columns, the wood blocks may have crushed, but the column would not have buckled.[4] There would have been a downward displacement of the form table with the concrete along Line 5, but the form probably would not have collapsed.

Principal Rubin M. Zallen, P.E. investigated this collapse.

Notes for Non-Engineers

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4. A simple beam under load will have compression on the top flange and tension on the bottom flange. The compression flange will have a tendency to buckle whereas the tension flange will not. The compression flange of most beams will be supported laterally by the floor construction so that the flange cannot buckle; thus a slender deep cross-section is efficient for beams. A column on the other hand will normally have both flanges in compression. Column sections are usually proportioned as stocky members so that bracing is unnecessary between their ends.

Forensic Engineering in Construction® is published by Zallen Engineering, 1101 Worcester Road, Framingham, MA 01701. Comments are welcome. Please direct comments to Rubin M. Zallen, P.E., by telephone at 508-875-1360 or by e-mail at rmzallen@zallenegineering.com.