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Collapse of 112 Foot Long Deep Longspan Steel Joists

Deep longspan steel joists with a span of 112 feet collapsed during the construction of a large middle school complex in New England in 1996. See Figure 1. The complex consists of many independent structures linked together to form an "L." At one end of the "L," there is a high bay library building. Figure 2 (on page 2) is a framing plan of part of the library building. The building is 113 feet wide and 120 feet deep. The roof height is 28 feet.

Figure 1 **View of collapse taken the same day, looking southwest.**

As shown on Figure 2, the typical joist spacing is 3'-11". The joists are braced against buckling during erection by 5 rows of cross-bracing, called cross-bridging, in which the top of a joist is braced to the bottom of the adjacent joists and the bottom of the joist is braced to the top of the adjacent joists. See Figure 3. The columns are irregularly spaced and the columns on Line 53 do not line up with the columns on Line 65. Normally, tie joists are located on the column centerlines and are supported by and bolted to a cap plate or seat angle on the columns. Tie joists prevent relative movement between lines of columns, and are necessary for safe erection. In this case, however, the tie joists are not at the column centerlines but are supported on and bolted to the tops of the steel girders along Lines 53 and 65.

An unusual feature of the design are 3 ganged joists at 1'-0" o.c. near Line A_A. The purpose of these ganged joists is to support a mansard roof as shown in Figure 3. The close spacing of the ganged joists precluded the use of cross-bridging; horizontal bridging (horizontal links) are substituted for the cross-bridging at the top and bottom of the joists.

The Collapse

Figure 4 (on page 3) is a plan of the steel framing of the library roof that was erected in place before the collapse. Figure 5 is a section through this framing. There were 7 joists in place, along with 4 bays of cross-bridging and 2 bays of horizontal bridging along each bridging row. In addition, the erector had added 3"x3" angle strong backs so he could erect the first two joists, two welded to the top chord and two welded to the bottom chord.

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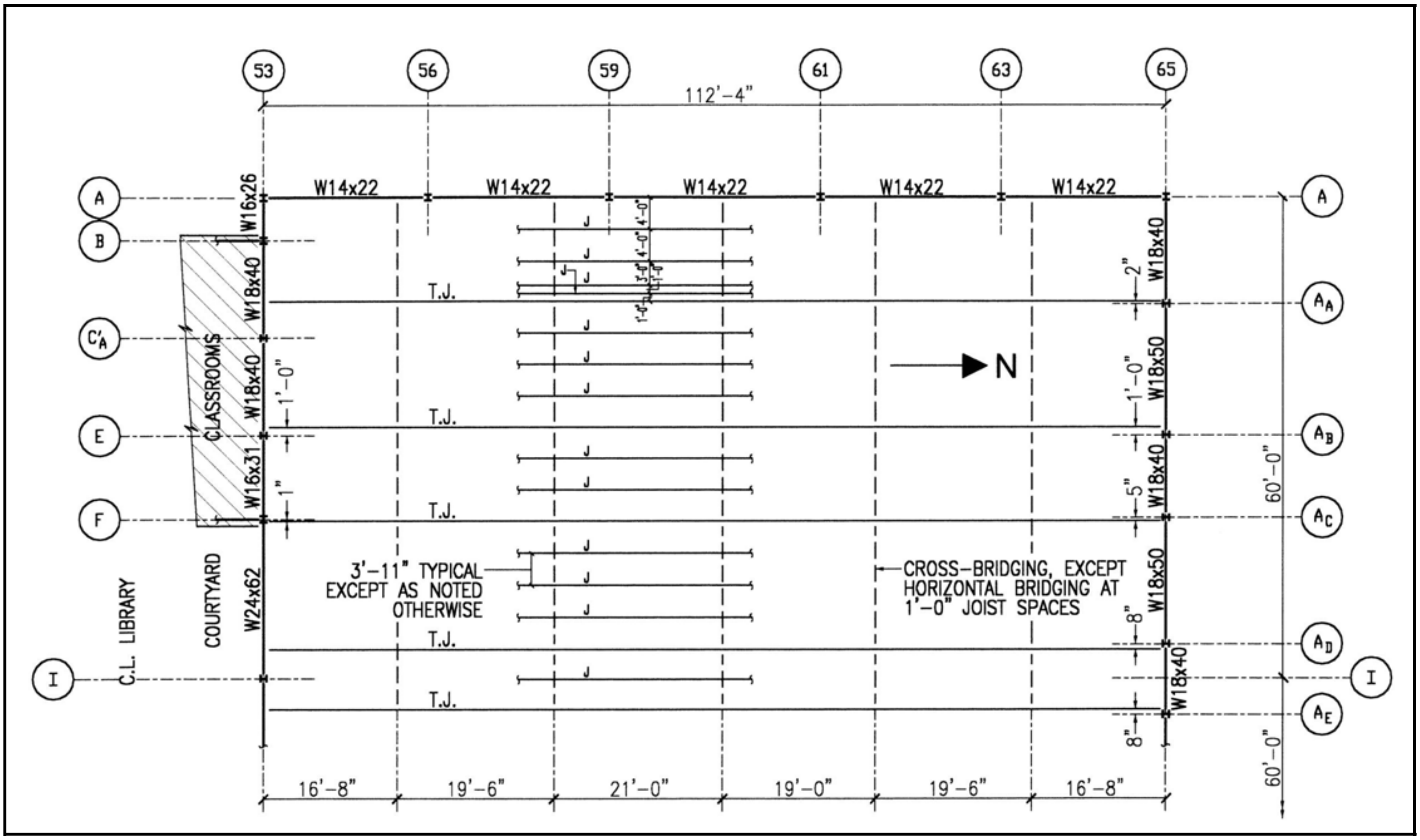
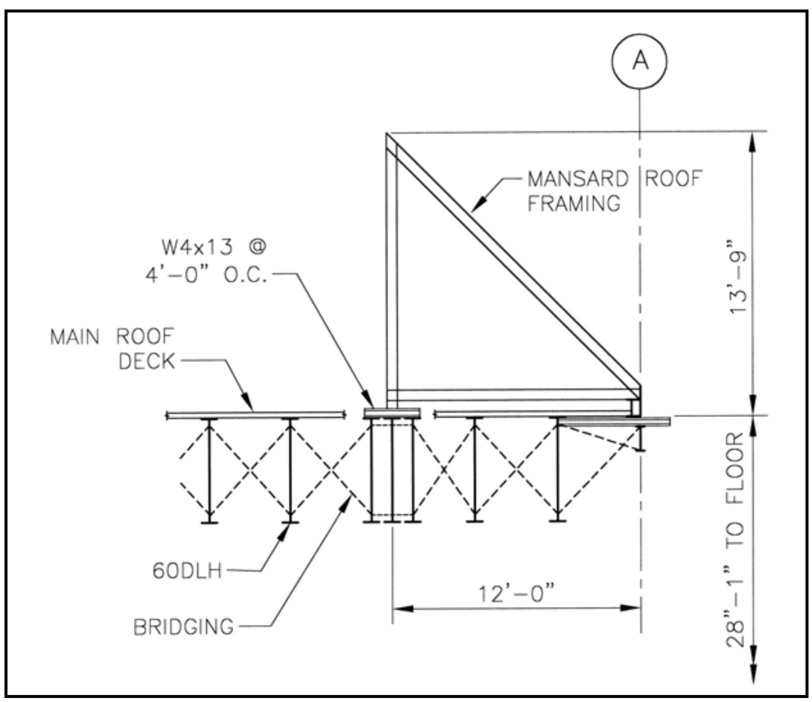


Figure 2 **Roof framing plan at west side of the library building. The east side is symmetrical about Line I. An adjoining 2-story classroom building is connected to the library building along Line 53. All joists are 60 DLH15s; T.J. means a tie joist bolted to the support framing; J means a joist welded to the support framing.**

Figure 3 **Schematic section through mansard roof. The mansard roof is an architectural feature at the edges of the main roof, all around the entire building.**



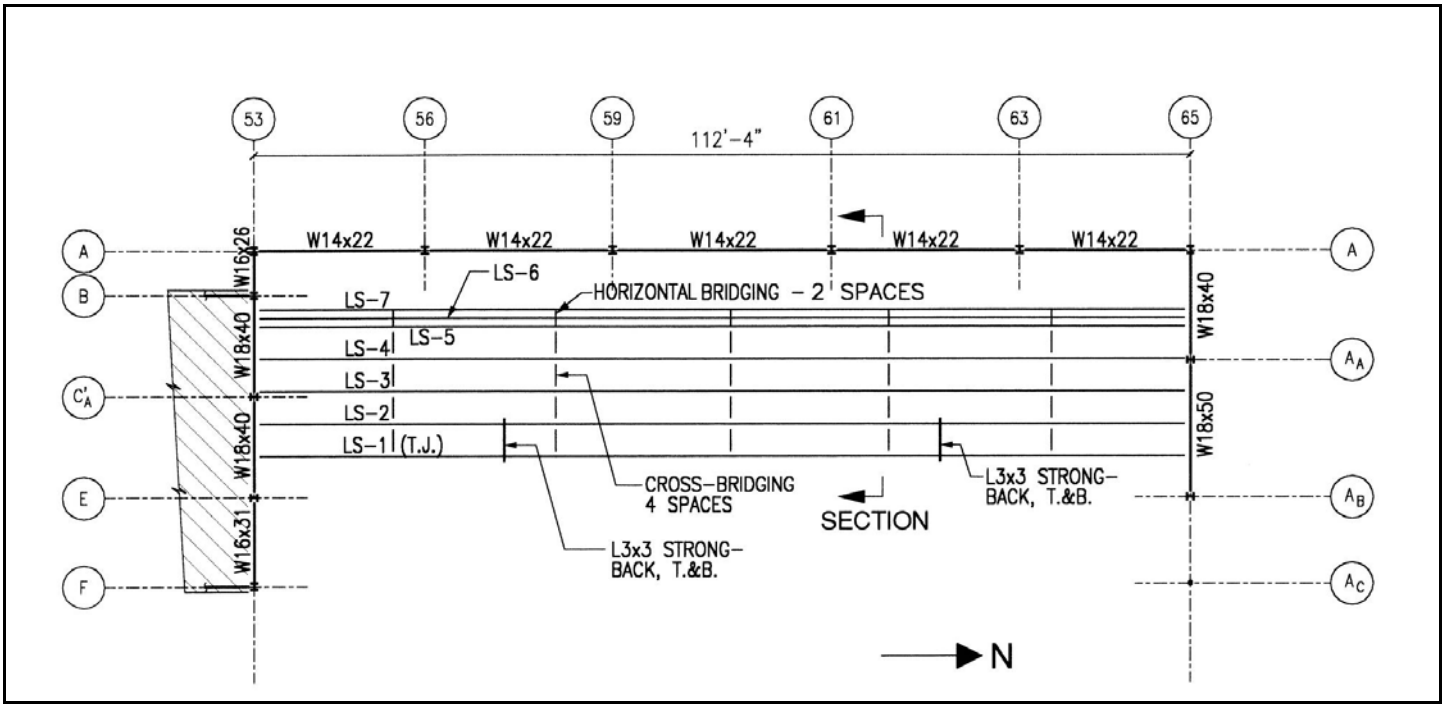


Figure 4 Steel erected before the collapse. Joist numbers are those assigned by OSHA during its investigation. For section, see Figure 5.

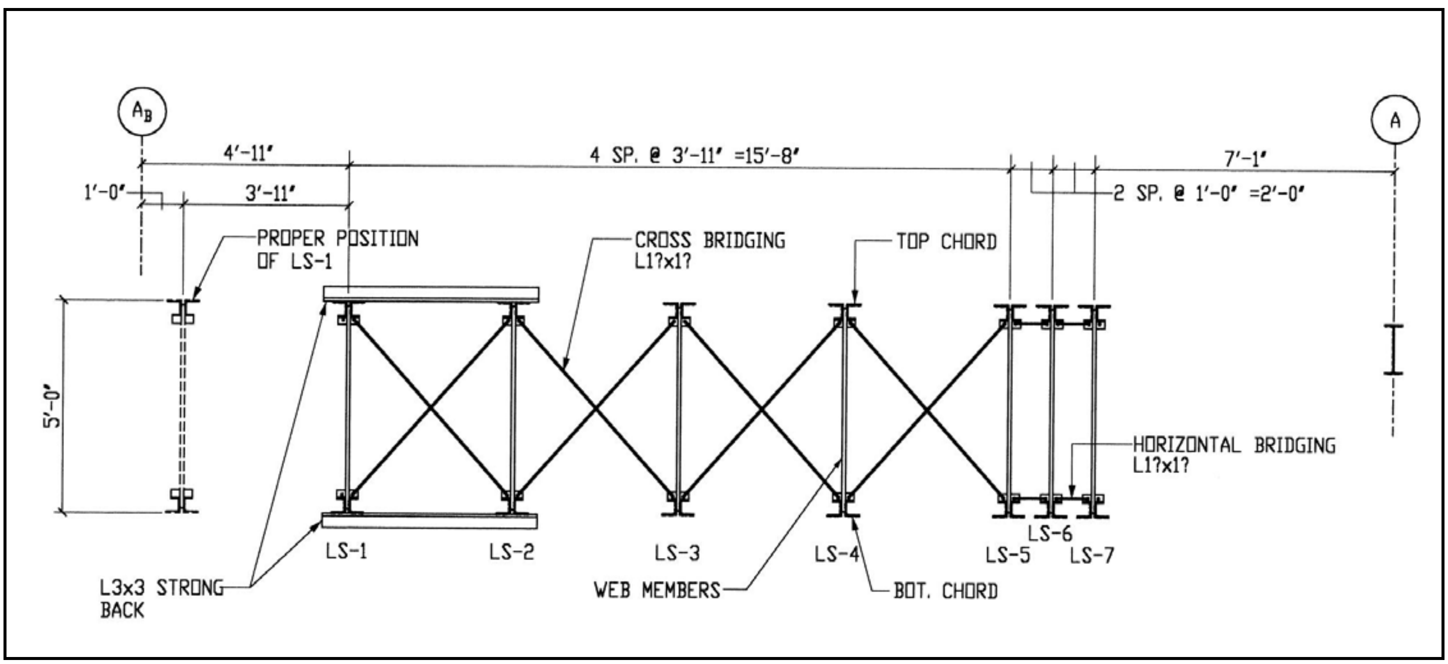


Figure 5 Section through steel erected before the collapse.

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The first two joists that were erected are LS-1 and LS-2 (see Figures 4 and 5). A single joist cannot be erected in place, since it is laterally unstable. In order to provide lateral stability, the cross-bridging for the first two joists needs to be connected on the ground. With the cross-bridging so connected, and the two joists erected as a pair, a stable platform with lateral stability is established. The strong backs are required to prevent the squashing of the cross-bridging between the first two joists when they are being hoisted into place.

As shown on Figure 5, LS-1 was not installed in its proper position. It should have been installed a joist space (3'-11") to the left. The structural steel shop drawings did not show holes in the top flanges of the girders along Lines 53 and 65 for the tie joists, and the beams were fabricated without the holes. The erection superintendent noticed that there were no holes in the top flanges of the girders on Line 53 when he erected them with the adjoining classroom building; however, he did not so inform either the general contractor or the fabricator. When the time came to erect the deep longspan joists for the library building, he drilled holes in the top flanges of the girders for the first tie joist (LS-1). Unexplainably, he drilled these holes at the wrong location. When LS-7 was erected in place, the erection superintendent saw that he had space for only one joist rather than the two that were supposed to be erected after LS-7 (see Figure 3), and realized that he had made an error.

At this point, the erection superintendent stopped erection work to decide what to do. He then decided that he had to move LS-4 to the intended position of LS-1. At that time, the crane operator was on break and the crane was idling. While waiting for the crane operator, he instructed the steel workers up on the joists (they are called *connectors*) to disconnect the bolts at LS-4 that connected bridging rows 2, 3, and 4 to LS-5. The ironworkers removed the bolts at rows 2 and 4. Then an ironworker started to remove the bolts at row 3; however, he had great difficulty getting the bolts out and was instructed by the erection superintendent to bang them out with his hammer. When he banged out the last bolt, LS-5, LS-6, and LS-7 rolled (buckled) toward the west as a group and collapsed. At the start of the buckling, LS-5 was still connected by cross-bridging to LS-4 at rows 1 and 5; as a result the collapsing joists LS-5, LS-6 and

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Figure 6 **View of collapse looking in a northeast direction from a point near Column A-53.**

Figure 7 **View of collapse looking southeast. Framing running from left foreground to the right background is Line A.**

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LS-7 pulled LS-4, LS-3, and LS-2 down with them and buckled LS-1 to complete the collapse. See Figures 6 to 11. LS-1 was hung up in the air in its buckled shape because it was bolted to the supporting girders; see Figures 6, 8, and 10. Due to its weight, LS-1 pulled over part of the framing on Line 65; see Figures 1, 6, and 10.

As shown in Figure 11, LS-5, LS-6, and LS-7 fell together in one pile closest to Line A (the left pile in Figure 11). LS-2, LS-3, and LS-4 fell in another pile (the pile on the right in Figure 11).

Cause of Collapse

The loads imposed on the joists during their erection were the weight of the joists, approximately 45 lbs/ft of joist including bridging, or 5050 lbs per joist, and the weight of the 3 iron workers (connectors), say 170 lbs each. These are gravity loads, all acting downward. In addition there are small incidental horizontal dynamic loads from the movement of the connectors; these loads are insignificant with regards to structural safety.

Figure 8 South end of collapsed joists. The Line 53 steel runs from the left to the right; The Line A steel is on the right. LS-1 is hung up on the roof girder; LS-2 and LS-3 are hung up on the 2nd floor of the classroom building.

There are two possible modes of failure of the joists as erected, due to the above mentioned gravity loads: 1) the top chord of an individual joist buckling laterally accompanied by the twisting of the joist between

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Figure 9 View of joists to the right of that shown in Figure 8. The angle on the ground is one of the strong backs.

Figure 10 View under joists looking north. LS-1 is hung up in the air on the right. The near ends of LS-2 and LS-3 were also hung up in the air.

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lateral supports (e.g. between the bridging); and 2) overall horizontal buckling of the entire joist/ bridging system. The latter mode involves bending of the cross-bridging and overall twisting of the individual joists between their end supports.

A buckling analysis of an individual joist in the first mode shows that the joists will not buckle if the 2nd and 4th rows of cross-bridging are not in place; however, with the 2nd, 3rd, and 4th rows not in place, the joists will buckle. This fact explains the lateral buckling of LS-5, LS-6, and LS-7 when the bolts for the 3rd row of cross-bridging between LS-4 and LS-5 were knocked out. The joists buckled in the first mode; however, the horizontal links between them kept them together as they collapsed.

A buckling analysis for LS-1 through LS-4 with the 5 rows of bridging between them in-place, and with the strong backs shown in Figures 4 and 5 in-place, shows that the safety factor against collapse of LS-1 through LS-4, acting together in the second buckling mode, is 3.6. However, further analysis shows that the horizontal loads on LS-1 through LS-4, imposed through the 1st and 5th rows of bridging by the weight of LS-5, LS-6, and LS-7 as they were collapsing, reduces the buckling capacity of LS-1 through LS-4 below the gravity loads they were supporting. This result explains the collapse of LS-1 through LS-4.

Figure 11 View of collapse from 2nd floor of classroom building, looking north, after the joists that were hung up on the framing were cut down, and after the framing on Line A and Line 65 was dismantled. The north half of LS-1 is on the left; the south half of LS-1 is lying across the right pile.

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

See On-Line Edition No. 10 for discussion of erection procedures for longspan steel joists.

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@zalleneginеering.com.