INVESTIGATION OF THE MAY 23, 2013 PARTIAL COLLAPSE OF A PRESTRESSESED CONCRETE DOUBLE TEE AT MONTGOMERY MALL IN BETHESDA, MD

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This report prepared by
Scott Jin, Ph.D., P.E.
Office of Engineering Services
Directorate of Construction

Contributions to this report made by
Dinesh Shah, P.E.
Gopal Menon, P.E.
Office of Engineering Services
Directorate of Construction

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Introduction

A construction incident occurred on May 23, 2013, at approximately 1:45 p.m., when a prestressed concrete double tee partially collapsed while it was being jacked, killing one employee and injuring another. The double tee was 60' long and 9' wide, with a depth of 2' 3" and a slab thickness of 4". The weight of the double tee was approximately 42,800 pounds. The incident site was the Westlake Garage of the Westfield Montgomery Mall in Bethesda, MD.

The State of Maryland, Department of Labor, Licensing and Regulation, Maryland Occupational Safety and Health (MOSH) asked the Directorate of Construction (DOC), OSHA National Office in Washington, DC for technical assistance in the investigation of the incident and to determine the cause of the collapse. An engineer from DOC accompanied by two MOSH officials visited the incident site on May 24, 2013 to observe the failure and to take photographs and measurements. During the visit, the investigation team also discussed the jacking procedures and the collapse with Scott Peterson, the superintendent of the general contractor (GC), Whiting-Turner Contracting Company (WT). Through MOSH, DOC requested additional technical information related to the incident.

We have reviewed the following technical information:

- Approximately 350 still photographs and 11 video movies taken by MOSH and Montgomery County, MD, dated May 23-24, 2013.
- Proposed shoring, jacking and skating procedures for precast removal, prepared by WT, two pages, dated May 6, 2013.
- Precast jacking/shoring plans, elevations and details, prepared by WT, five double letter size drawings, dated May 5, 2013.
- Pre-jacking training, prepared by WT, one page cover letter and six photographs, dated May 31, 2013.
- Equipment rental list from Safway Services, LLC, two pages, dated June 19, 2013.
- Adjust-A-Shore™, Heavy Duty Shoring, published by Safway, nine pages, No date.
- Rental Quote for 4 hydraulic jacks and associated hand pumps, from Zenmar Power Tool & Hoist Systems, four pages, dated May 9, 2013.
- Signed statements from 5 witnesses, twenty-four pages, dated June 20, 2013.
- Partial precast tee collapse at Westlake Garage of Westfield Montgomery Mall in Bethesda, MD, prepared by KCE Structural Engineers, PC, August 30, 2013, 23 pages.

We also performed engineering analyses in accord with the described jacking procedures, actual installed shoring and upper support configurations, and the measured individual member sizes. Please note that we did not have an opportunity to ask additional follow-up questions to the jacking crew.

The Project

The project consisted of constructing new floors at the top of the existing Westlake Garage, west of the Macy Department Store, at Westfield Montgomery Mall to create new facilities for the planned arclight cinemas and dining terrace. The project was located at 7125 Democracy Boulevard, Bethesda, MD. Westfield LLC was the project owner. The Whiting-Turner Contracting Company of Baltimore, MD was the general contractor (GC).

The construction was in its early stages. The construction of new floors required erection of a tower crane in the middle of the existing garage. An opening was therefore being made by removing two existing double tees on the roof and another two at the second floor. The four double tees had to be disconnected and removed to provide the opening for the new tower crane. The two double tees on the roof were safely removed by a mobile crane and stored at a nearby location within the project site. The roof double tees were not to be reused. However, the two double tees at the second floor were to be reused, and, therefore, were to be removed by hydraulic jacking and skating method.

One of the double tees at the second floor was successfully removed earlier. Based on the WT's precast jacking/shoring plans, it is believed that the following procedure was employed to remove the first (east) double tee from the second floor:

- Eight shoring towers were erected under the stems of the double tee, four on the north end and four on the south end. Of the four towers, two inside, called jacking towers, were meant for the hydraulic jacks to raise the double tee in approximately 8" increments. The other two outside, called shoring/skating towers, were meant to support the stems as a second line of defense.
- A combined upper support system was used on top of the two shoring/skating towers to support the double tee. A similar heavier support system was used on top of the two jacking towers to support the two hydraulic jacks during the jacking operation.
- The double tee was jacked up and then supported by the shoring/skating towers at the raised position. The jacking operation started at one end of the double tee and then at the other end. The same process was repeated until a vertical space of 1'-3" above the second floor was reached.
- The two skate beams and channel assemblies were slid through the space between the bottom of the jacked-up double tee and the top of the second floor. The two assemblies were then properly supported on top of the four shoring/skating towers on the north and the south ends of the double tee. The weight of the double tee was then transferred from the jacking towers onto the assemblies, which was supported on the four shoring/skating towers and the existing slab of the second floor.

- The double tee on the assemblies was then pulled eastward for approximately 18' to the second bay of the garage opening. The double tee was then transferred onto the wood cribbing on top of the second floor for temporary storage.

The entire moving process for the east double tee on the second floor took approximately 15 hours on Tuesday, May 21, 2013. On Wednesday, May 22, the GC construction crew erected another eight shoring towers from the ground level to the stems of the west double tee on the second floor (See Figure 1, below). On Thursday, May 23, at approximately 8:30 a.m., the GC started the jacking operation on the west double tee. The incident occurred during the jacking operation at approximately 1:45 p.m.

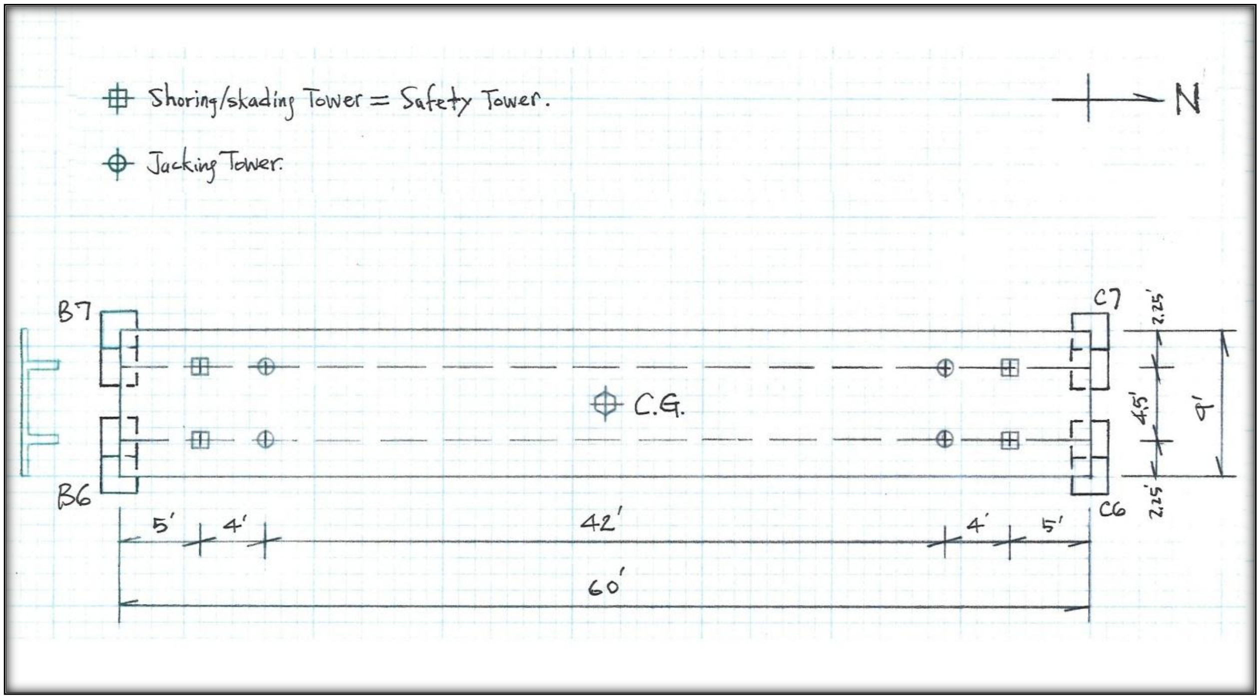


Figure 1. Locations of the Supporting Towers under the Sterns of the Double Tee.

Description of the Events Leading to the Collapse

Photographs and witness statements indicated that the support system and the jacking procedure for the west double tee on the second floor were different from what was originally planned. The manner in which the west double tee was supported during its jacking is described below:

1. Eight independent shoring towers, four for jacking and four for shoring/skating, were used to raise the double tee. The locations of these towers under the bottom of the double tee stems are shown in Figure 1.

2. All eight towers were 2' by 2' in size and were seated over W6x9 floor beams (Figures 2 and 3) at the ground level. For the jacking tower, the upper support system for the hydraulic jack consisted of four 36" long W8x31 steel beams and a 10" long W8x31 spacer (spreader). They were installed on the U-heads of the tower (Figures 4 and 5). For the shoring/skating towers (hereafter referred as “safety towers”), two levels of three 36" long W8x10 beams and a 10" long W8x31 spacer (spreader) were installed on the U-heads of the tower to support the double tee at the bottom of its stems (Figures 6 and 7).
3. The double tee was 9' wide and 60' long, spanning in the north-south direction. The slab thickness was 4" minimum. The total depth of the stems was 2'-3" and they were 4'-6" apart (See Figure 1, above). The weight of the double tee was calculated to be approximately 42,800 pounds. It was supported near the ends of the stems by either four jacking towers or four safety towers, or both during the load transfer.
4. When the double tee was being raised, each tower was tended by an employee. Four employees were operating four hydraulic jacks at the jacking tower, one employee for each jack. The foremen gave the orders to “coming up” and pump the hydraulic jacks to raise the double tee. He was frequently checking the level of the double tee with a laser.
5. The other four employees at the safety towers were adjusting the height of the towers by raising up the screw jacks to closely follow the height of the double tee and to ensure its stability. The project manager of the GC was standing on the second floor to supervise the jacking and supporting operation. It should be noted that while the double tee was being jacked, vertical extensions on each frame of the safety towers had to be installed.
6. The double tee was raised in a nearly leveled condition. This was essentially due to the fact that the hydraulic jacks could raise the double tee in small increments, i.e., one-sixteenth to one-eighth of an inch per each pumping of the hydraulic oil. Since the maximum stroke for the hydraulic jack (H2508) was 8.11", the double tee in each jacking cycle was raised approximately 7" to 8".
7. At the end of each jacking cycle, the weight of the double tee was transferred to the four safety towers. The four hydraulic jacks were retracted and removed from the jacking towers.
8. The four jacking towers were then raised and four hydraulic jacks were repositioned to begin the next jacking cycle; the jacks again picked up the weight of the double tee and jacked it further up for another 7" to 8".
9. Step 7 and Step 8 were repeated until the bottom of the double tee was approximately 1'-3" above the top of the second floor, i.e., the clearance required for the skating assemblies to slide under.
10. At the lunch break, at approximately 12:00 noon, the double tee was jacked up approximately 2'-6". The crew checked and ensured the level of the double tee both before and after lunch.
11. After lunch break, at approximately 12:30 p.m., the jacking operation continued. At approximately 1:30 p.m., after the weight of the double tee was transferred from the jacking towers to the safety towers, the foreman noticed that the top flange of the top 36" long

W8x10 steel beam under W8x31 spacer beam had bent and twisted (buckled) at the southeast (SE) safety tower.

12. To correct this condition and to replace the buckled beam, the foreman asked the employee at the SE jacking tower to jack up the SE corner of the double tee. Note that in this jacking procedure, only one hydraulic jack was used without any blocking or cribbing.
13. The SE corner of the double tee was jacked up and the buckled beam was separated from the east stem of the double tee and was freed from any loads. When the two employees from SE and SW safety towers were removing the buckled beam from the SE safety tower, the double tee suddenly shifted and fell from the SE hydraulic jack, killing one employee and catching the arm of another. The incident occurred at approximately 1:45 p.m.
14. After the collapse, the SE corner of the double tee dropped about 2'-4" and landed on the upper W8x31 beam of the jacking tower (Figures 4 and 5). The NW corner dropped about 12" and landed on the flattened upper W8x10 beam (Figure 6). The NE corner dropped about 8" and landed on the upper W8x10 beam (Figure 7). The SW corner dropped more than 4' and was suspended in the air.
15. In the meantime, the north end of the double tee shifted about 9" toward the west and the south end shifted about 6" toward the east. During the collapse, the double tee also caused the collapse of the SW safety tower and the other three jacking towers.
16. We noticed that the NE safety tower and its upper support system did not suffer any damage, although this system experienced the shifting and falling of the double tee at its top.

Figure 2. Bottom Support of the Towers at the Ground Level
(Looking from the North End of the Double Tee toward South).

Figure 3. Bottom Support of the Towers at the Ground Level
(Looking from the South End of the Double Tee toward Northwest).

Figure 4. Final Conditions of the SE Jacking Tower and its Upper Support System.

Figure 5. Close-up of the Upper Support System of the SE Jacking Tower.
Note that the most damaged area of the east stem occurred at the SE jacking tower.

Figure 6. Final Conditions of the NW Safety Tower and its Upper Support System.

Figure 7. Final Conditions of the NE Safety Tower and its Upper Support System.
Note that the tower and its upper support system remained intact after the collapse.

Analysis and Discussion

<u>Height of the Safety and Jacking Towers</u>

The minimum vertical clearance of the parking garage was marked at its entrance as 6'-7". However, from Figure 3, the actual vertical clearance or the height of the safety tower in the vicinity of the incident area from the ground level to the bottom of the second floor was estimated to be:

6" (floor beam) + 5" (bottom screw jack with U-head) + 5'-0" (base frame) + 6" (top screw jack with U-head) + 8" (lower beams) + 8" (upper beam) = 7'-9".

Based on the undamaged NE safety tower (Figure 7), the height of the four safety towers at the time of the collapse was estimated to be:

6" (floor beam) + 5" (bottom screw jack with U-head) + 5'-0" (base frame) + 2'-0" (extension frame) + 12" (top screw jack with U-head) + 8" (lower beams) + 8" (upper beam) + 8" (Spacer) = 10'-11".

Thus, the total jacking height at the time of the collapse was 3'-2" (10'-11" minus 7'-9"). If the average jacking height was 7.5" for each jacking cycle, it would take approximately five jacking cycles to reach the desired height. Note that the jacking foreman stated that *"The T was approximately up 2'-6" when we took lunch."* Thus, the double tee was jacked up at least four times (cycles) before lunch without any major problems.

The difference in elevation between the ground floor and the second floor was estimated to be 10'-0". Thus, the height of the safety tower would have to be at least 11'-3" above the ground level or 1'-3" above the top of the second floor. Therefore, if the collapse had not occurred, the double tee would have been jacked up an additional 4" (11'-3" minus 10'-11") for the skating assemblies to slide under it.

From Figure 4, the height of the four jacking towers before the collapse was estimated to be:

6" (floor beam) + 5" (bottom screw jack with U-head) + 5'-0" (base frame) + 16" (top screw jack with U-head) + 8" (lower beams) + 8" (upper beam) + 8" (Spacer) + 1'-8" (extended hydraulic jack) = 10'-11".

As indicated above, the four jacking towers and the four safety towers were estimated to be of the same height, i.e., the double tee was in a leveling condition before the buckling of upper W8x10 beam at the SE safety tower around 1:30 p.m.

It should be noted that, at least for the last jacking cycle before the collapse, 10" long and 8" deep W8x31 steel spacers were used at all eight towers to increase the height of each tower. The effects of the spacer on the stability of the tower are discussed below.

W8x31 Size Steel Spacer

For the jacking towers, the 10" long and 8" deep W8x31 steel spacer was placed on top of the 36" long upper W8x31 beam to increase the height of the tower and to provide the seat for the hydraulic jack. Since the spacer and the upper beam were the same size and their webs oriented in the same direction, this could slightly decrease the rigidity of the jacking tower in the north-south direction.

For the safety towers, however, a spacer of the same size was also placed on top of 36" long upper W8x11 beam to increase the height of the tower and to spread the contact pressure of the concentrated load from the weight of the double tee. Since the flange of the spacer was wider than that of the upper beam, the bottom flange of the spacer cantilevered over the top flange of the upper beam as shown in Figure 8. The webs of these two members were oriented in the east-west direction. Thus, the weak axis of the upper support system was in the north-south direction. In addition, the weak axis of the safety tower (in the direction of the braces) was also in the north-south direction. Therefore, adding the spacer on top of the safety tower would significantly decrease the rigidity of the safety tower in the north-south direction.

We identified at least four deformed spacers at the incident site. The basic pattern of the failures was the deformation along the depth of the web. Figure 9 presents the first deformed spacer that fell from the top of the NW safety tower. Figure 10 shows an intact spacer and the badly buckled W8x10 beam near the SE safety tower. It is believed that this beam came from the SE safety tower after it experienced the collapse. Figure 11 indicates the second deformed spacer near the SE corner of the double tee. Figure 12 presents the same second deformed spacer and the third deformed spacer away from the NE corner of the double tee. Figure 13 shows the fourth deformed spacer with a length of only 6" near the SW corner of the double tee.

It should be noted here that a concentrated load, even from the entire weight of the double tee (42.8 kips), could not have caused the spacer web to undergo the observed flexural deformation. Thus, there must have been the presence of a certain force to cause the bending moment at the bottom flange of the spacer or at the upper flange of the W8x10 beam below.

Figure 8. Close-up View of Figure 7 at the Connection of the W8x10 beam and the W8x31 Spacer.
Note that the bottom flange of the space was cantilever over the upper flange of the W8x10 beam.

Figure 9. The First Deformed Spacer Fell from the Top of the NW safety Tower.

Figure 10. An Intact Spacer and the Badly Buckled Upper W8x10 Beam near the SE Safety Tower.

Figure 11. The Second Deformed Spacer near the SE Corner of the Double Tee.

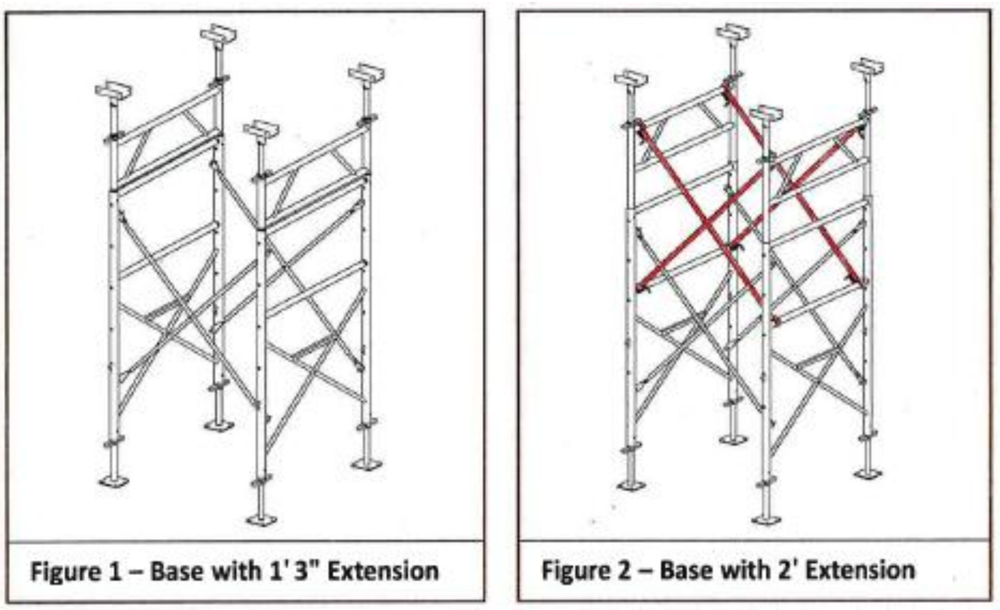
Figure 12. The Same Second Deformed Spacer and the Third Deformed Spacer away from the NE Corner of the Double Tee.

Figure 13. The Fourth Deformed Spacer with a length of only 6" near the SW Corner of the Double Tee.

<u>Lack of Diagonal Braces for the Safety Towers</u>

When the extension frame was installed, with its post inside the post of the base frame, and the extension frame was raised 2' or more above the base frame (Figure 14), the diagonal gooser braces must be installed as per the instructions of the manufacturer of the shoring tower. The purpose of the braces was to ensure the rigidity of the shoring tower and the stability of its upper support system. Figure 15 shows that the extension frames were raised 2' above the top of the base frame at all four safety towers, but without the required diagonal gooser braces.

It should be noted here that the minor axis (the axis of the braces) of the safety towers was in the north-south direction. Lack of diagonal gooser braces would decrease the rigidity and impair the stability of the safety tower in the north-south direction. Thus, due to the flexibility of the safety tower and the weakness of the spacer beam in the north-south direction, the upper W8x10 beam of the safety tower was not only subject to the vertical load from the double tee, but also subject to the bending moment across the width of its flanges. Therefore, the cantilever flexural resistance of the compression flange of the upper W8x10 beam must be considered in assessing the as-built stability of this beam.



Note that this requirement is from SAFWAY Adjust-a-Shore System, Product Selection Guide, Page 4.

Figure 14. The Diagonal Gooser Braces (marked in red) Are Required When the Extension Frame Has a 2' or More Extension.

Figure 15. The Diagonal Gooser Braces Were Not Installed for All Four Safety Towers When the Extension in These Towers Was Set at 2'.

Assessing the As-built Stability of the Upper W8x10 Beam

The weight of the double tee was calculated as 42.8 kips. It was supported evenly by four safety towers at its four corners. Thus, the applied load on each of the upper level W8x10 beams was 10.7 kips (42.8 kips divided by 4). The W8x10 beam was simply supported with a 2' span. Based on the LRFD method, the primary flexural stress along its major axis was within its strength limit. However, the W8x10 beam had noncompact flanges, the maximum combined stresses in the compression flange due to the cantilevering action of the concentrated load (10.7 kips) and the main bending exceeded its strength limit of the 45 ksi (50 ksi yield strength steel). Thus, the W8x10 beam was undersized to support the actual load in the manner it was configured. The W8x10 beam should have been increased to W8x31 as in the jacking tower, or stiffeners should have been welded to the flanges and web at the locations of the load.

It should be noted that based on the non-factored analysis, the maximum combined stresses in the compression flange due to the concentrated load (10.7 kips) were still within the strength limit of 50 ksi. Thus, the W8x10 did not fail in the normal jacking operation, i.e., four hydraulic jacks to raise the double tee simultaneously, but it did not have the code-required factor of safety (load factors).

Estimating the Loads on the Four Safety Towers at the Time of the Collapse

Prior to the collapse at 1:45 p.m., the crew was using a hydraulic jack at the SE jacking tower to raise the SE corner of the double tee to replace the deformed or buckled W8x10 beam at the SE safety tower. After the SE corner was jacked up, the crew foreman specifically stated that *"I shook the* (SE safety) *tower to make sure it was loose."* Thus, immediately prior to the collapse, the double tee should have been supported at four points – the NW, NE and SW safety towers and the SE jacking tower.

Since only the SE jack was used to raise the double tee and the centroid of the double tee was not aligned with the resultant of the four reactions, structural analyses were performed to obtain the support reactions for the double tee as listed below:

R_{NW} = 19.7 kips.

R_{NE} = 0 kips.

R_{SW} = 1.7 kips.

R_{SE} = 21.4 kips.

It should be noted that R_{NE} = 0 kips was due the fact that the centroid of the double tee was on the southwest side of the diagonal line between R_{NW} and R_{SE}, i.e., the double tee would tilt toward the SW. As a result, the double tee was supported only on three towers prior to the collapse. The suspended status of the NE corner of the double tee was also demonstrated by the intact or non-damaged condition of the NE safety tower and its upper support system after the collapse. In addition, due to the closeness of the centroid of the double tee to the diagonal line between R_{NW} and R_{SE}, the SW tower would carry little weight of the double tee. Instead, the NW and SE towers would carry most of the double tee weight as shown above.

Since the hydraulic jack at the SE jacking tower had a cylinder capacity of 25 tons (50 kips) and its upper support system consisted of W8x31 beams, the jack and the upper support system was capable of supporting a load of 21.4 kips without failure. However, the load at the NW safety tower was also increased from 10.7 kips to 19.7 kips. Based on the non-factored analysis of the top W8x10 beam, the maximum combined stresses in the compression flange due to the cantilever bending from a concentrated load (19.7 kips) and the main bending far exceeded the strength limit of 50 ksi. Thus, the top W8x10 beam at the NW safety tower failed or buckled.

Describing the Collapse

The following descriptions were based on the examination of the final conditions of the four standing towers and the scratching marks and cracks on the double tee stems:

After the failure of the top W8x10 beam at the NW safety tower, the NW corner of the double tee dropped approximately 12", the NE corner dropped approximately 8" and the north end also moved approximately 9" toward the west. After the north end of the double tee dropped, the majority of its weight was picked up by the SW and NE safety towers due to the higher elevation of the diagonal between these two supports. Thus, the top W8x10 beam at the SW safety tower also failed or buckled in a similar manner.

As a result of the above failures, the 20" high and 2.24" to 3.35" diameter hydraulic jack (unblocked or non-cribbed) at the SE jacking tower became an unstable vertical post. The south end of the east stem, directly supported on the hydraulic jack, kicked out the hydraulic jack and its 8" high spacer below. The SE corner of the double tee then suddenly dropped 2'-4" and landed on the upper W8x31 beam of the SE jacking tower. During the fall, the south end of the east stem killed one employee and caught the right arm of another. They were on the SE safety tower removing the buckled top W8x10 beam.

It appears that when the SE corner of the double tee dropped, the south end of the west stem caused the collapse of the SW safety tower and the SW jacking tower. After the SW corner of the double tee dropped, the existing double tee flange in the north end also caused the double tee to move approximately 6" at its south end during its fall. In addition, the vibrations from the above activities caused the collapse of the NW and NE jacking towers. However, if the hydraulic jack at the SE jacking tower was blocked or cribbed during the re-jacking, the fall and movement of the south end of the double tee might have been limited and might have caused fewer damages.

Other Factors Contributing to the Collapse

We located a short deformed spacer 6" in length instead of the normal 10" at the incident site (Figure 13). If this particular spacer was installed on top of the SE safety tower, it could explain the cause of the initial failure of the upper W8x10 beam at the SE safety tower at approximately 1:30 p.m.

Conclusions

1. The partial collapse of the double tee at approximately 1:45 p.m., on May 23, 2013 was caused by:
   - The placement of the 8" high spacer beam between the double tee stem and the upper W8x10 beam, this configuration weakened the rigidity of the upper support system on top of the shoring/skating towers in the north-south direction.
   - Lack of the diagonal gooser braces on the extended frames decreased the rigidity of the shoring/skating tower in the north-south direction.
   - The single re-jacking at the SE jacking tower significantly increased the vertical load at the NW shoring/skating tower.

   As a result of the above factors, the upper W8x10 beam of the NW shoring/skating tower buckled at its compression flange and initiated the collapse.

   The failure could have been avoided if a bigger beam, W8x31, rather than a W8x10 beam was used or if stiffener plates had been welded to the flanges and web at the loading locations.

2. During the re-jacking of the double tee, at approximately 1:45 p.m., blocking or cribbing of the hydraulic jack was not installed at the SE jacking tower. Thus, the employer did not comply with the OSHA Standard §1926.305 (d)(1)(i). If blocking or cribbing were installed, the downward movement and shifting of the south end of the double tee would have been limited and would have caused only limited damages.

3. At the time of the incident, the extension frames were raised 2' above the base frames without installing diagonal gooser braces for all four shoring/skating towers. Lack of braces was a violation of the manufacturer's instructions. Without the diagonal gooser braces, the shoring/skating towers became more flexible and less stable, contributing to the collapse.