Investigation of the April 14, 2021, Collapse of a Bridge Span under Demolition, Herbert C. Bonner Bridge, Dare County, NC

U.S. Department of Labor
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Directorate of Construction

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REPORT

Investigation of the April 14, 2021, Collapse of a Bridge Span under Demolition, Herbert C. Bonner Bridge, Dare County, NC

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1 Introduction

On April 14, 2021, at approximately 5 p.m., the last span of the Herbert C. Bonner Bridge (Bonner Bridge) under demolition collapsed in Dare County, North Carolina. An employee of PCL Civil Constructors, Inc. (PCL), engaged in the steel cutting, was killed. The collapsed span was the navigation span of the Bonner Bridge measuring 180 feet long, 24 feet wide, and approximately 60 feet above sea level, with a total weight of 980 kips.[1]

Personnel from OSHA's Raleigh Area Office (AO) arrived at the scene after the incident. Federal OSHA's regional administrator for Region IV requested assistance from OSHA's Directorate of Construction (DOC) in the national office in Washington, DC, to aid in the technical assessment of the collapse and determine the cause of the incident.

A structural engineer from DOC's Office of Engineering Services (OES) visited the incident site on April 20, 2021, to examine the collapsed span and interview key personnel. Photographs were taken, and construction documents were obtained to aid in the investigation. The engineer reviewed the demolition plan and supporting calculations and conducted an independent analysis to determine the cause of the collapse.

OSHA's investigation included the following items:

1) On-site information collection.
2) Review of witness accounts.
3) Review of demolition plans.
4) Review of actual demolition activities.
5) Structural analyses to determine the probable failure mechanism of the structure.

Based on the evidence collected, observations of the collapsed structure, and structural analyses performed, OSHA concludes that:

[1] A kip equals 1000 pounds-force.

1. The contractor retained a structural engineering firm to develop a demolition plan for the three high-rise spans of the bridge. However, the contractor did not follow the plan to remove the bridge spans.
2. The contractor used different demolition sequences and developed its own demolition plans without performing any engineering surveys and calculations to determine the adequacy of the structure and the potential for unplanned collapse of any portion of the structure during the demolition. Unfortunately, the contractor carried out the demolition operation of the three high-rise spans in such a way that the structural members were loaded beyond their load-carrying capacities, resulting in the premature collapse of the navigation span.

2 The Project

Built in 1963, the Bonner Bridge was a 2.4-mile-long[2], 206-span, two-lane automobile girder bridge[3] that spanned Oregon Inlet in Dale County, North Carolina (see Figure 1).

Figure 1 – Bonner Bridge
(Modified from Google Maps)

The Bonner Bridge consisted of a three-span high-rise navigation portion and trestle portions (see Figure 2). The three high-rise spans, numbered from the north as Span 144, 145, and 146, consisted of four three-span continuous haunched plate girders[4] with spans of 160′-0″–180′-0″–160′-0″ (see Figure 3). The navigation channel beneath the high-rise Span 145 was 130 feet wide with a vertical clearance of 66 feet. Other than the three high-rise spans, the rest of the bridge spans were pre-stressed concrete girder spans.

[2] Source: NCDOT: Bonner Bridge Replacement – Facts About the Project
[3] A girder bridge consists of horizontal girders that are supported at each end by piers.
[4] Haunched plate girders are steel plate girders with deeper webs over the interior piers than near the center of the spans.

Figure 2 – Bonner Bridge – Aerial view[5]

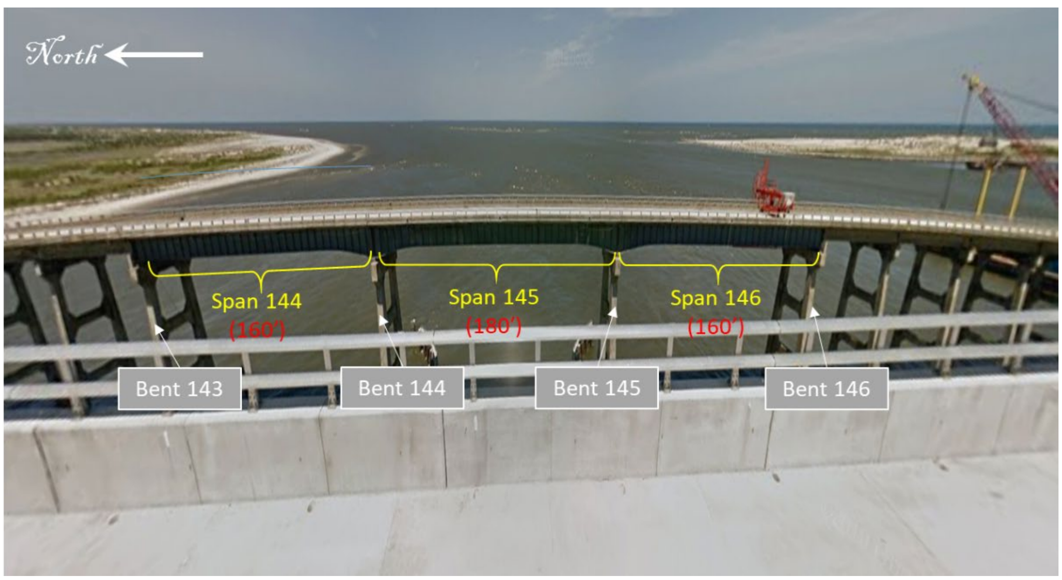


Figure 3 – High-rise spans of Bonner Bridge – Looking east

The Bonner Bridge was designed to have a 30-year design life and reached its lifespan in 1993. In July 2011, the North Carolina Department of Transportation (NCDOT) contracted with a design-build team consisting of a contractor, PCL, and a designer, HDR Engineering Inc. (HDR), to design and build a new bridge, Marc Basnight Bridge, to replace the Bonner Bridge (see

[5] Bridges of the Outer Banks | Connecting the OBX, NC Islands (carolinadesigns.com)

Figure 4 for both bridges). Construction of the Marc Basnight Bridge began in 2016 and was completed in 2019. On February 25, 2019, the Marc Basnight Bridge opened to traffic, and the Bonner Bridge closed. Soon after, the demolition of the Bonner Bridge began. NCDOT planned to keep approximately 1,000 feet of the bridge for pedestrians at the south end rather than demolish the entire bridge. PCL hired KCI Associates of North Carolina, P.A. (KCI) as its engineer to develop a demolition plan to remove the bridge from Spans 1 to 187.

Figure 4 – Two bridges
(Photo courtesy of NCDOT)

On April 14, 2021, when PCL employees were dismantling the last span left of the Bonner Bridge (Span 145), the span collapsed prematurely. A PCL employee engaged in steel cutting operations was killed.

The following discussion relates to the three high-rise plate girder spans.

3 The Structure

3.1 Span Arrangement

The superstructure[6] of the three high-rise spans was supported on four bents, numbered from the north as Bent 143 to 146 (see Figures 3 and 5). Bents 144 and 145 had fixed bearings, meaning that the bridge superstructure rested on these bents, and there was no mechanism for allowing movement of the structure relative to the bents at these locations (see Figures 5 and 6). At Bents 143 and 146, there were expansion bearings between the bridge superstructure and the bents. These expansion bearings allowed the thermal expansion or contraction of the bridge superstructure relative to the bents at these locations (see Figures 5 and 6). The center span (Span 145) across the navigation channel was 180 feet long. The northern (Span 144) and southern (Span 146) spans were each 160 feet long.

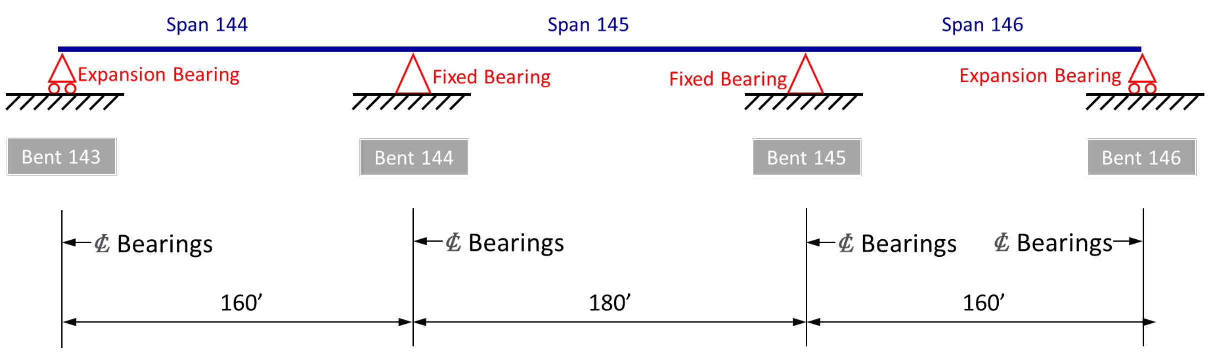


Figure 5 – Span configuration

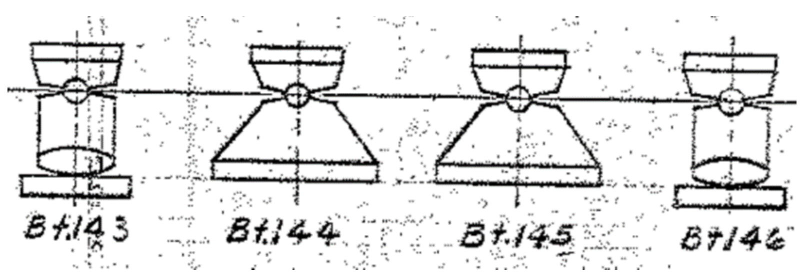


Figure 6 – Bearings for spans No. 144, 145, and 146[7]

[6] Superstructures are defined by AASHTO as "Structural parts of the bridge that provide the horizontal span."
[7] Taken from original design drawing, S-40.

3.2 Bridge Bents 144 & 145

Bents 144 and 145 were two-column bents, each consisting of two rectangular, reinforced concrete columns sitting on a pile cap footing (see Figure 7). At the top of each bent was a continuous reinforced concrete pier cap, extending the entire width of the bridge. The two bents were cast-in-place with four construction joints, as shown in Figure 7. According to the design drawing S-106, the structural concrete was Class A.

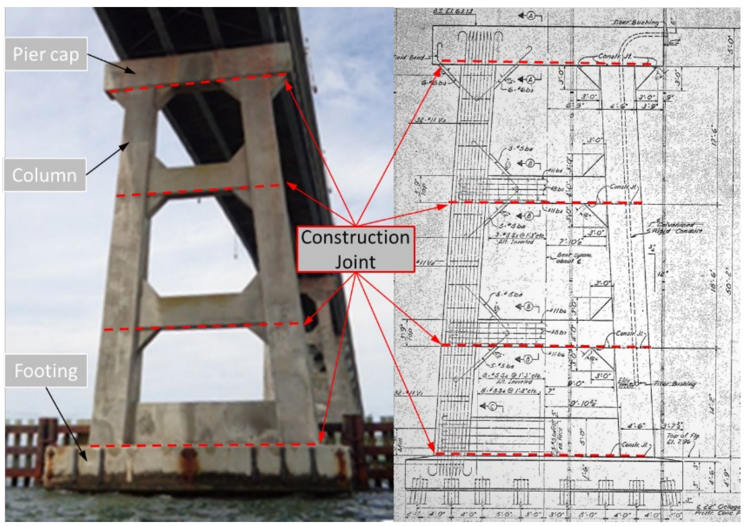


Figure 7 – Bent 144/145

3.3 Bridge Cross-Section

The bridge cross-section (see Figure 8) consisted of four plate girders spaced at 8′-0″ on center, with 4′-7½″ deck overhangs and an out-to-out deck width of 33′-2½″. The 28′-0″ roadway width accommodated two 12-foot-wide traffic lanes.

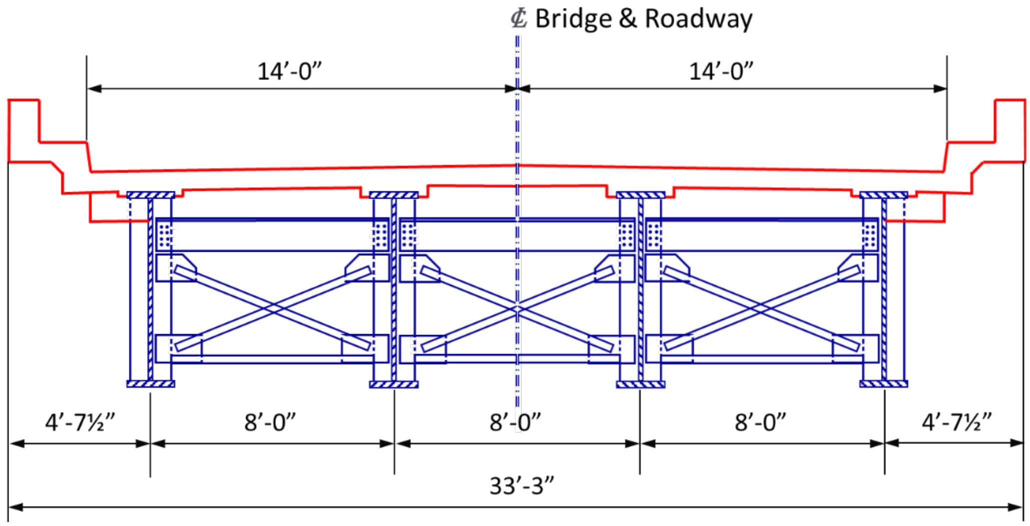


Figure 8 – Typical cross-section

The plate girders were I-beams made up from separate structural steel plates, which were welded together to form the vertical web and horizontal flanges. The webs were 6′-0″ deep near the center of the spans, and 8′-9″ deep over the interior piers. The top and bottom flange plates were reinforced in the middle portions of Spans 144 and 146 and the interior support portions at Bents 144 and 145. Vertical stiffeners were uniformly spaced along the girders with additional stiffeners over the supports. X-type vertical cross-frames and bottom lateral bracing frames were used to stabilize the girders (see Figure 8). The reinforced concrete deck was 7¼″ thick, including the main traffic lane slab between the centerlines of the two exterior girders and the cantilever deck overhangs beyond the centerlines of the exterior girders. Concrete parapets were placed at the edges of the deck overhangs (see Figures 8 and 9). The reinforced concrete deck, including overhangs, curbs, and parapets were structurally continuous and cast-in-place (see Figure 9).

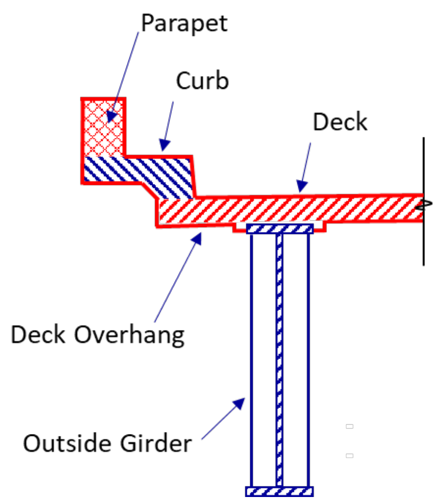


Figure 9 – Deck, overhang, curb, and parapet

4 Demolition Plan

4.1 Demolition Plan Revisions

On January 28, 2019, KCI issued the initial demolition plan to PCL, including two options for removing the three high-rise spans. Option One specified that the demolition should begin at one exterior span and proceed linearly to the other exterior span. Option Two stipulated to remove one exterior span, then the other exterior span, and finally the middle span. Both options required the use of a crane located on a barge under the bridge for loading bridge components onto a cargo barge located under the bridge. The demolition plan included drawings and calculations. PCL submitted the plan to NCDOT for their records on the same day.

On August 23, 2019, KCI modified the initial demolition plan and allowed PCL to use cranes on a trestle positioned alongside the existing bridge instead of a crane on a barge.

On October 10, 2019, KCI issued the modified demolition plan specific for the three high-rise spans, which incorporated the following five requests from PCL:

1) remove trestle and add the “Crofton” crane on a barge below for removing Spans 144 to 146;
2) cut diaphragms/lateral bracing[8] between the two interior girders before securing rigging to girders;
3) remove the previously designed excavator from the bridge deck (no equipment on top of the bridge deck);
4) increase deck panel pick size; and
5) rigging updates.

On January 27, 2021, KCI provided PCL with the final demolition plan for the three high-rise spans. In the final demolition plan, KCI did not include Option Two because PCL would remove the three spans in a linear process.

[8] X-frame cross-frames and bottom flange lateral bracing frames between two adjacent girders.

4.2 Final Demolition Plan by KCI

KCI planned to demolish the three high-rise spans in five phases. The demolition plan is reproduced in Figure 10 and outlined in the steps below:

1. Make transverse cuts on concrete deck in Span 146. The transverse cuts shall extend one foot past the centerline of the exterior girders (see Phase 1 in Figure 10).
2. Remove overhang/parapet sections in Span 146, including:
   (a) Install rigging on the overhang/parapet section to be removed;
   (b) Make longitudinal cuts on the centerline of the exterior girders supporting the overhang/parapet section to be removed to free the concrete section (see Figure 11);
   (c) Lift the overhang/parapet section and lower the section onto a barge below the bridge; and
   (d) Repeat steps (a) to (c) to remove remaining overhang/parapet sections in the span.
3. Make longitudinal cuts over girder centers to free concrete deck pieces. The longitudinal cuts shall be made on parts that will be immediately lifted, and the entire concrete deck of the span shall not be precut. Concrete deck pieces shall be rigged and lowered onto a barge below the bridge.
4. Cut diaphragms and bottom lateral bracing between the two interior girders.
5. After the concrete deck is completely removed in Span 146, install rigging on steel girder sections, and the four girder sections shall be rigged and lowered onto a barge below the bridge in pairs.
6. Repeat steps 1 to 3 to remove the concrete deck slabs and parapets in the middle Span 145. The steel girders and bracing shall be uncut and remain in place after removing concrete deck slabs and parapets.
7. Repeat steps 1 to 3 to remove the concrete components in Span 144.
8. Once the concrete components in Spans 144 and 145 are removed, repeat steps 4 and 5 to remove steel girders in Span 145.
9. Repeat steps 4 and 5 to remove steel girders in Span 144.

Even though the demolition plan illustrated that demolition begins on Span 146 (see Figure 10), the demolition could start on either the northernmost Span 144 or the southernmost Span 146 and extend through the middle Span 145 down to the other end span as per the note on the demolition plan, as reproduced below.

NOTE:

ORDER OF STEEL SPAN DEMOLITION MAY BE REVERSED, HOWEVER STEEL BEAMS AND DIAPHRAGMS IN SPAN 145 MUST REMAIN IN PLACE UNTIL DECK ON FINAL EXTERIOR SPAN (SPAN 144 OR 146) IS REMOVED.

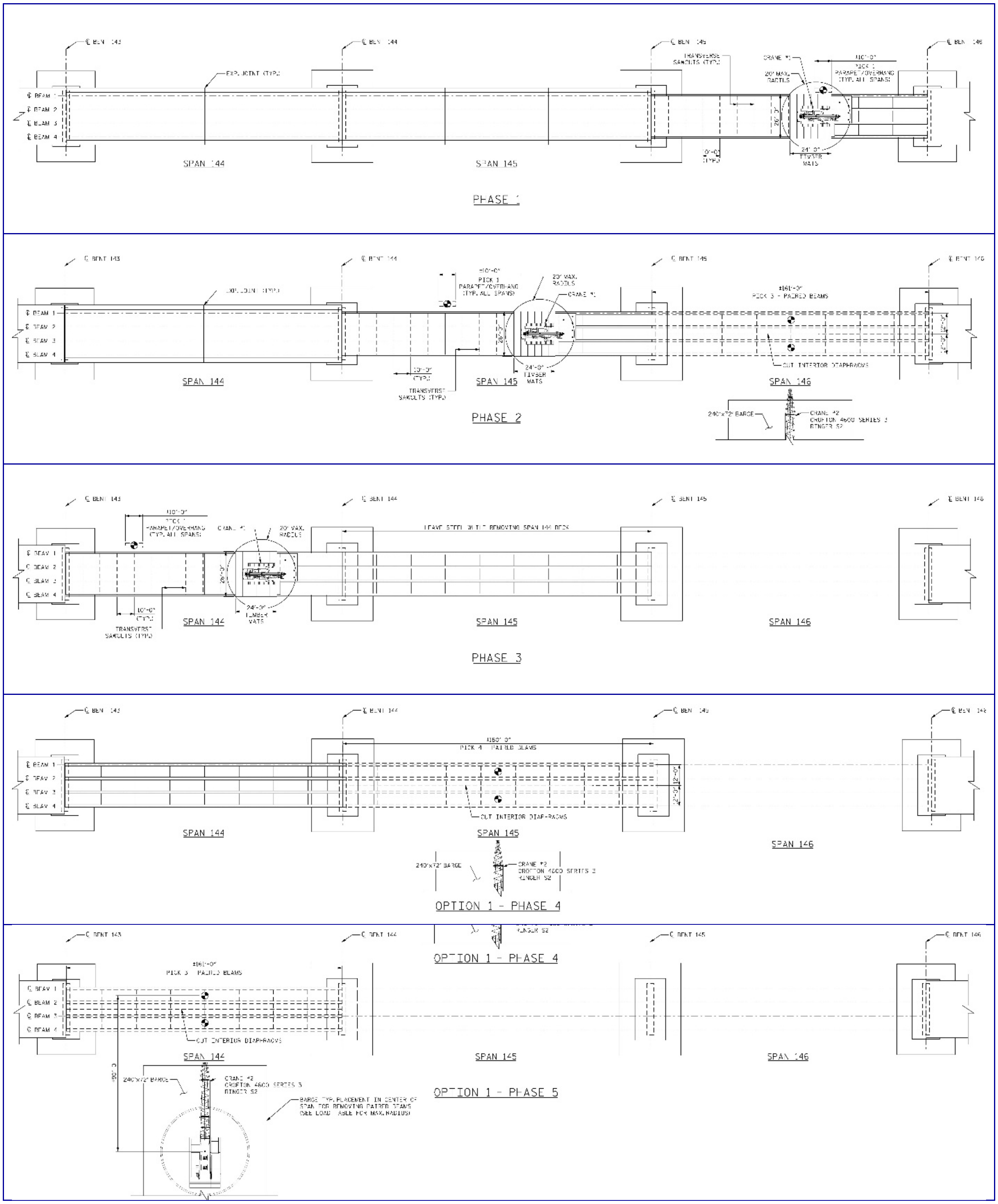


Figure 10 – Demolition sequence developed by KCI

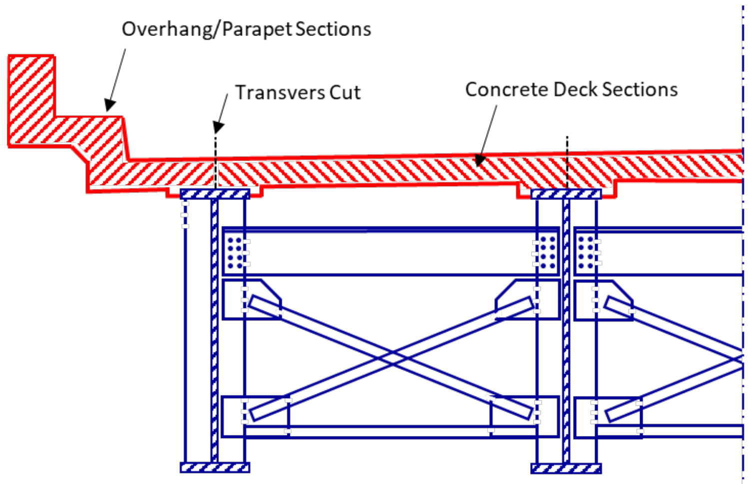


Figure 11 – Demolition of concrete planned by KCI

4.3 Structural Calculations by KCI

KCI's calculations focused mainly on the structural adequacy of the steel girders. KCI engineers modeled the steel girders using a line girder approach, and a single girder was modeled using a line element from node to node. After reviewing KCI's calculations, we found no computations to determine the lateral support reactions at the pin supports at the ends of the girders in Span 145. KCI did not check the structural adequacy of the two interior bents supporting Span 145.

5 Actual Demolition Activities

5.1 Demolition Timeline

PCL decided to demolish the concrete deck beginning from the northernmost of Span 144 and gradually proceeding towards the south. During OSHA's investigation, PCL provided a timeline of demolition activities, per OSHA's request. PCL and NCDOT provided OSHA with progress photographs of the demolition. Based on the information received, OSHA prepared the demolition activity timeline:

January 27, 2021, PCL received from KCI the final demolition plan for Spans 144 to 146.

February 15, 2021, PCL began saw cutting and removing concrete panels in Span 144 (see Figure 12, a photograph taken by NCDOT on 2/15/2021). PCL did not follow KCI's demolition plan from the initial of the demolition in that:

1. PCL removed the center bay of the bridge deck immediately after removing the deck overhang and parapet sections in the same area. In contrast, KCI's demolition plan specified that the center bay of the bridge deck in a span could only be removed after all deck overhang and parapet sections within that span were removed.
2. PCL placed the removed sections of concrete on the deck behind the crane until they were placed on the barge (see Figures 13 and 14)

Figure 12 – Demolition of Span 144
(photographed on 2/15/2021 by NCDOT)

Figure 13 – Demolition of Span 144
(photographed on 2/15/2021 by NCDOT)

Figure 14 – Demolition of Span 144
(photographed on 2/17/2021 by NCDOT)

February 23, 2021, PCL's field engineer contacted KCI's engineers and indicated that PCL wanted to store the concrete materials on top of the spans before loading them onto the barge and proposed two options for the plan change, including:

Option 1. Set up a concrete debris storage area behind the crane on the deck.

Option 2. Place a forklift on the bridge deck to transport concrete debris to the adjacent spans.

In an email between PCL's field engineer and KCI's engineers, PCL's field engineer stated that, "After talking with [redacted] earlier this morning it sounds like both of these options have potential issues, in regards to over loading the girders in certain areas of the span. It sounded like there may be locations (i.e. center of span) where the loads would be too high to add the weight of the forklift and potentially even store the materials behind the crane. But in the areas nearer to the bent centerlines it could be possible."[9]

[9] The author of this report redacted the name of the KCI engineer.

February 25, 2021, KCI issued a sealed memorandum to PCL with plan changes and additional calculations, stating that, "KCI takes no exception to utilizing the forklift provided all of the following conditions are met:

1. Forklift maintains a minimum 15' clearance from crane tracks.
2. Crane boom remains centered between tracks at all times while forklift is operating in the same span.
3. Both the crane and forklift shall remain centered on the bridge.
4. Contractor shall not store multiple panels on the bridge deck. Forklift shall remove each panel prior to additional panels being placed on deck."

KCI also emphasized that "all demolition procedures not specifically addressed in the memo shall be per KCI's original demolition plan dated 1/27/2021."

After examining the demolition progress photographs taken by NCDOT on February 24 and 25, 2021 (see Figure 15), OSHA found that PCL did not stop stacking concrete debris on the deck while they were coordinating the plan changes with KCI.

Demolition progress on 2/24/2021 Demolition progress on 2/25/2021

Figure 15 – Demolition of Span 144
(photographed by NCDOT)

March 2, 2021, PCL began cutting the concrete deck in Span 145 (see Figure 16). PCL stockpiled deck overhang and parapet segments on Span 145 (see Figures 17 and 18). PCL did not follow KCI's demolition plan, nor the supplemental memorandum dated February 25, 2021.

Figure 16 – Demolition of Spans 144 and 145
(photographed on 3/2/2021 by NCDOT)

Figure 17 – Demolition of Span 145
(photographed on 3/4/2021 by NCDOT)

Figure 18 – Demolition of Span 145
(photographed on 3/5/2021 by NCDOT)

March 8, 2021, PCL started saw cutting the concrete deck in Span 146

March 10, 2021, PCL developed a plan for stacking deck overhang and parapet segments on Span 146 (see Figure 19). Figure 20 illustrates that PCL placed all overhang and parapet segments on Spans 145 and 146.

March 12, 2021, PCL developed a plan for the removal of the steel girders in Span 144 (see Figure 21).

PCL neither consulted with KCI regarding PCL's demolition plans created on March 10 and 12, 2021, nor submitted the plans to NCDOT.

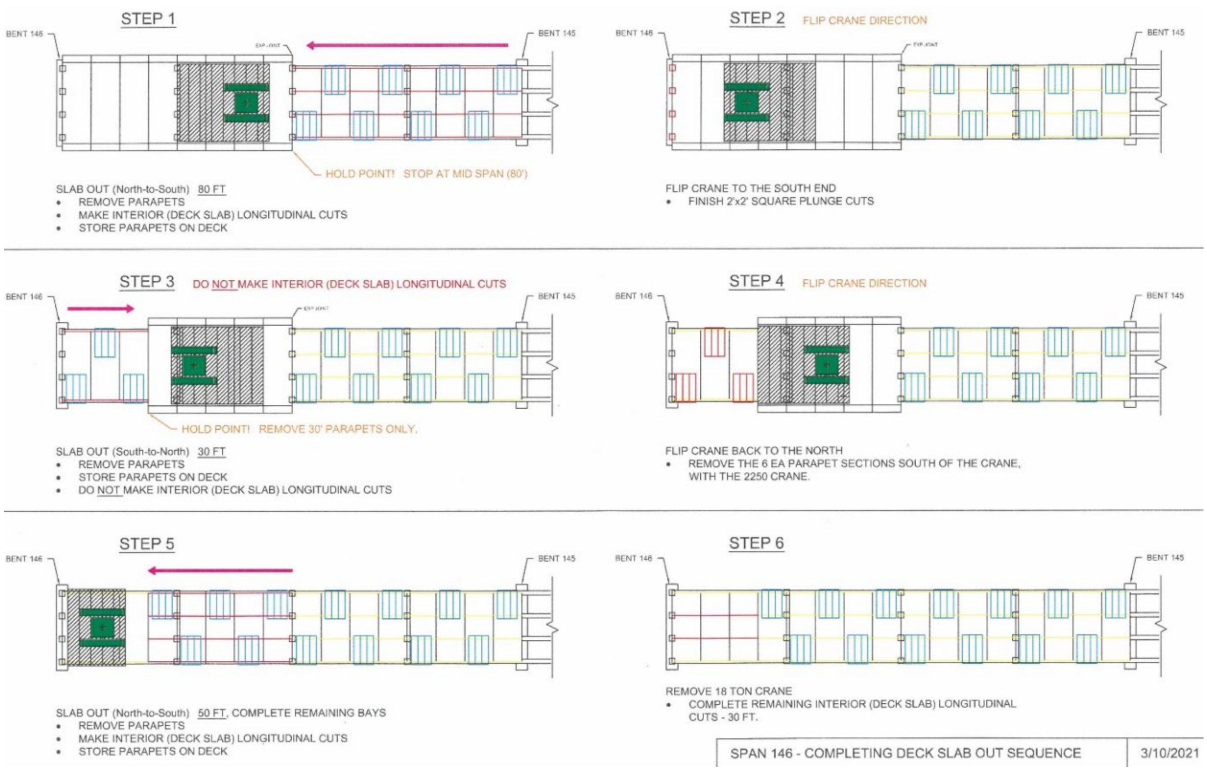


Figure 19 – PCL's demolition plan for Span 146 deck removal

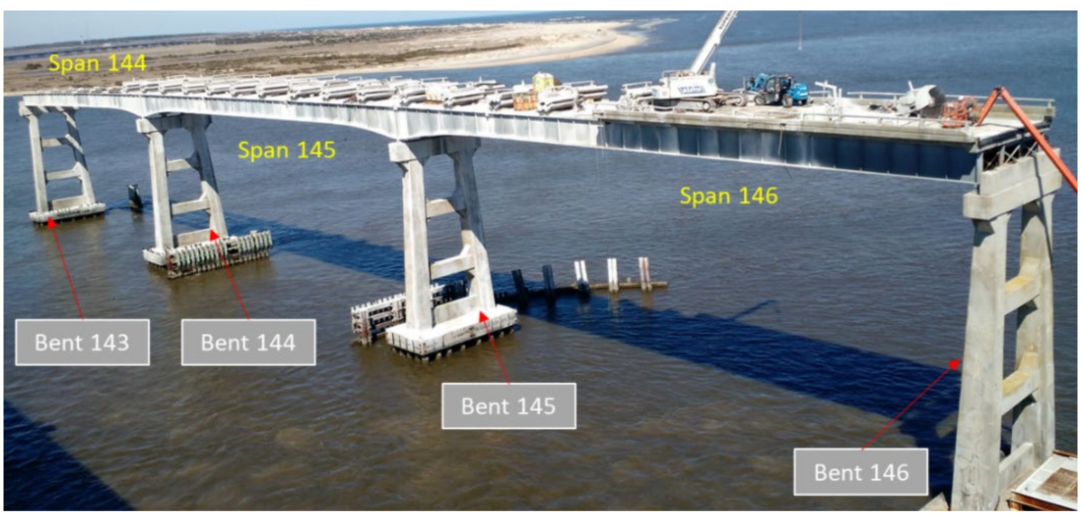


Figure 20 – Three steel girder spans under demolition – Looking north
(photographed on 3/11/2021 by NCDOT)

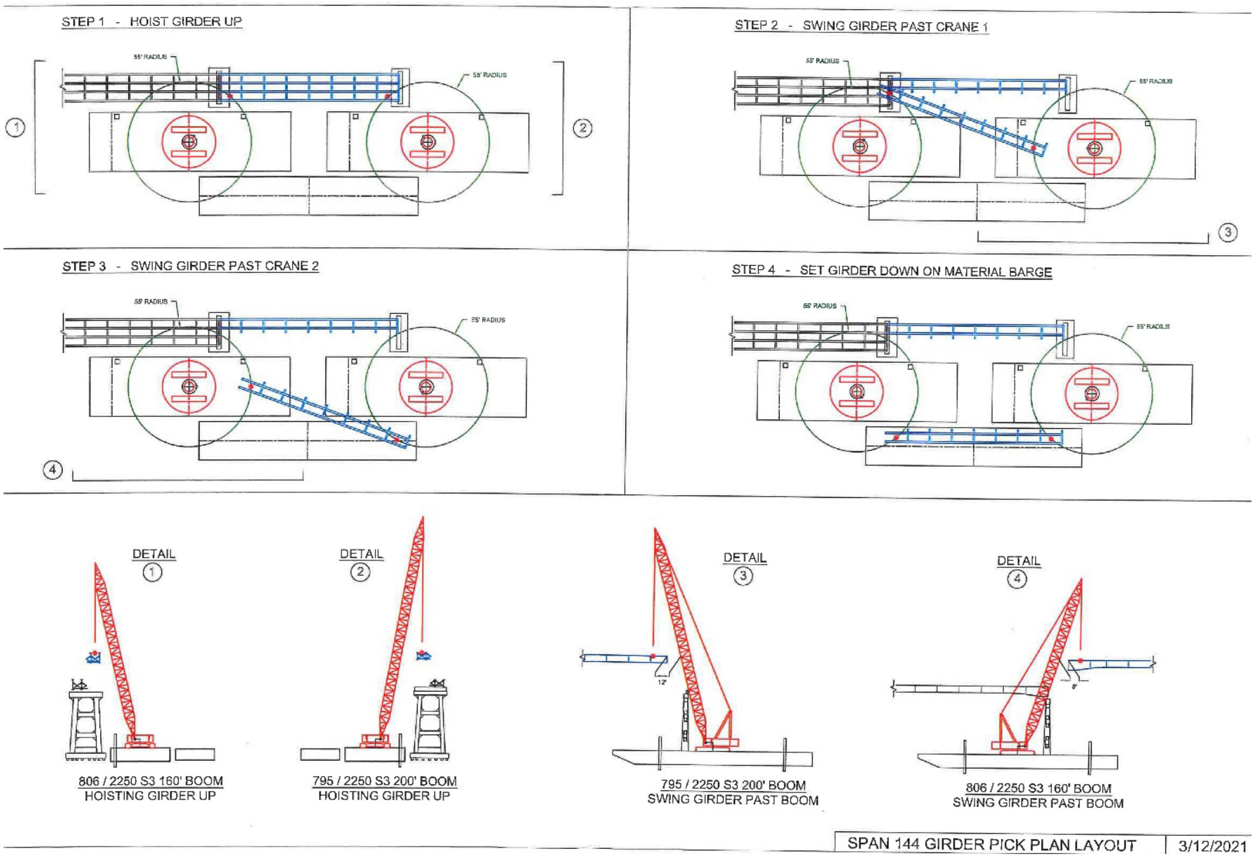


Figure 21 – PCL's demolition plan for Span 144 girder removal

March 30, 2021, PCL removed all steel girders in Span 144 (see Figure 22).

Figure 22 – Removal of Span 144 girders
(photographed on 3/30/2021)

April 7, 2021, PCL started removing the deck in Span 146 (see Figure 23).

April 12, 2021, PCL started dismantling steel girders in Span 146 (see Figures 23 and 25).

April 14, 2021, PCL cut the four steel girders in Spans 145 and 146 at Bent 145 and removed the four girder segments in Span 146 utilizing two marine cranes (see Figure 25). Shortly after Span 146 was removed, Span 145 collapsed (see Figure 26).

Figure 23 – Parapet segments in Span 146 had been removed
(photographed on 4/7/2021)

Figure 24 – Concrete in Span 146 had been removed
(photographed on 4/13/2021 by NCDOT)

Figure 25 – Steel girders in Span 146 had been removed
(photographed on 4/14/2021 by NCDOT)

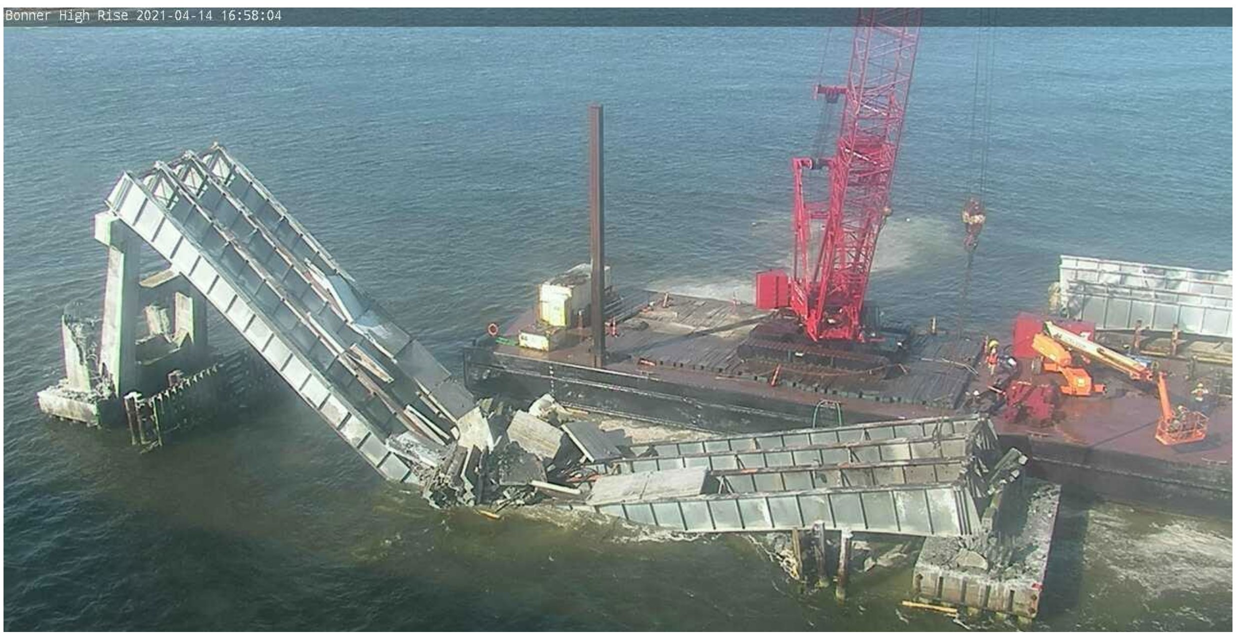


Figure 26 – Collapsed steel girders in Span 145
(photographed on 4/14/2021 by NCDOT)

Per OSHA's request, PCL's competent person provided the following timeline of the demolition activities on April 14, 2021.

- Crane barge was in position for girder hoisting of Span 146.

- The crew completed cutting rigging holes and diaphragm bracing between the two interior girders in the morning.
- The 2250 crane barge was mobilized into position for a two-crane-pick around 1:00 p.m.
- Cranes were rigged up to the first set of beams around 2:00 p.m.
- The first two girders were cut free from the south side of Bent 145, and girders were hoisted and placed onto the material barge around 2:45 p.m.
- The second set of girders were rigged around 3:00 p.m.
- The second set of girders were cut free from the south side of Bent 145. The girders were hoisted and placed onto the material barge around 4:00 p.m.
- Shortly after 4:00 p.m., Span 145 collapsed.

5.2 PCL Did Not Follow the Approved Demolition Plan

PCL did not follow KCI's demolition plans to remove the three high-rise spans:

1. PCL did not follow the demolition sequence established by KCI to remove the three spans sequentially from one end to the other.
2. PCL did not follow the demolition sequence established by KCI to remove the entire deck overhangs and parapets in a span before removing the center bay of the deck.
3. PCL stacked concrete overhang and parapet segments on the decks in Spans 145 and 146.
4. PCL cut the four, 2-span continuous girders in Spans 145 and 146 at Bent 145, while the girders in Span 145 were still supporting concrete overhang and parapet segments and the bridge deck.
5. PCL used two barge cranes to lift steel girders.

PCL developed its own demolition plans without conducting any engineering surveys or calculations to demonstrate that its demolition sequence and means would not overload any structural members.

6 The Collapsed Structure

Figure 26 shows the condition and failure pattern of the girders in Span 145 after the collapse. The girders formed a “V” shape at failure, with concrete deck and parapet segments on top at the mid-span region, indicating a significant amount of bending took place in the middle of the span. Bent 145 crumbled completely, leaving the south ends of the girders resting on the footing (see Figure 27). The two columns of Bent 144 fractured at the construction joint approximately 18′ above the waterline and dropped onto the footing (see Figure 28). The north ends of the girders remained attached to the cap of Bent 144 after the collapse occurred. All girder bearings were still attached to the bottom flanges of the four girders after the incident (see Figure 29).

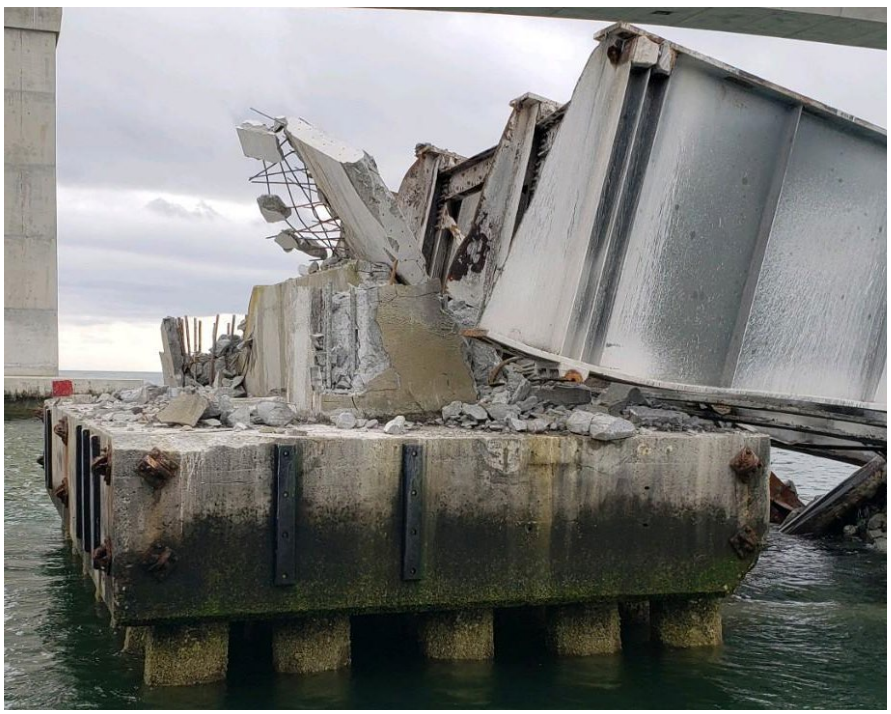


Figure 27 – Collapsed Bent 145

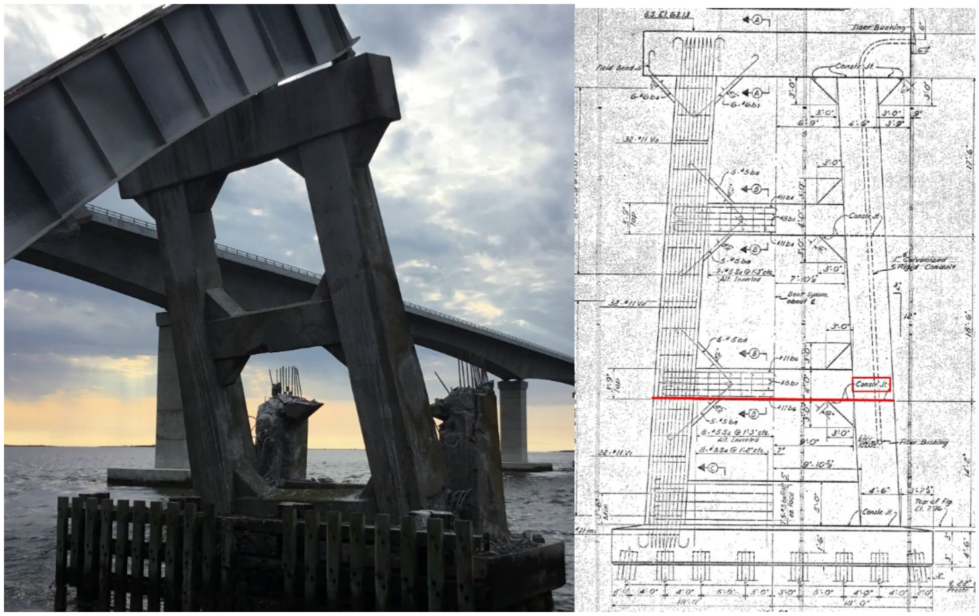


Figure 28 – Collapsed Bent 144

Figure 29 – South girder bearings after the incident

OSHA observed during its field investigations severe reinforcement corrosion and corresponding concrete deterioration, including scaling, delamination, spalling and cracking of the concrete in the reinforced concrete columns of Bents 144 and 145 (see Figure 30). Photographs of Bents 144 and 145 taken before the demolition revealed signs of steel reinforcement corrosion and concrete spalling, i.e., concrete surface cracking, rust staining, and concrete plating (see Figure 31). The concrete deterioration is mainly due to the aggressive exposure conditions for these concrete structures in the marine environment. The structural integrity of the bridge bents might have been compromised before the incident.

Figure 30 – Collapsed Bent 144/145

Figure 31 – Concrete deterioration

7 Structural Analysis and Discussion

7.1 Introduction

The purpose of the structural analysis was to determine whether the girders and the two bents in Span 145 had sufficient strength to support the imposed loads during the demolition. The dimensions of the bridge and member sizes were taken from the following existing bridge drawings provided by PCL:

(1) Superstructure Details Spans No. 144, 145, 146, Sheet No. S-34;
(2) Moment, Shear and Deflection Curves, Sheet No. S-36;
(3) Plate Girder, Sheet No. S-37;
(4) Plate Girder Details, Sheet No. S-38;
(5) Bearings for Spans No. 144, 145 & 146, Sheet No. S-40; and
(6) Substructure Bent No. 144 or 145, Sheets No. S-105 and S-106.

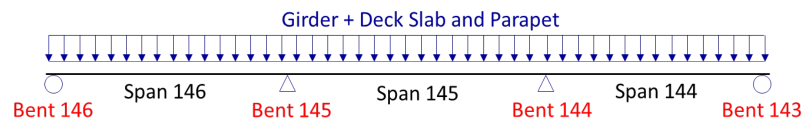
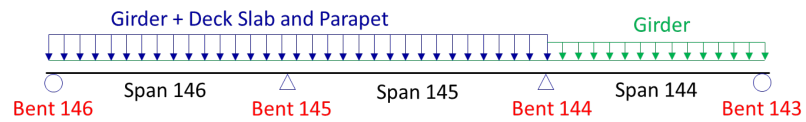
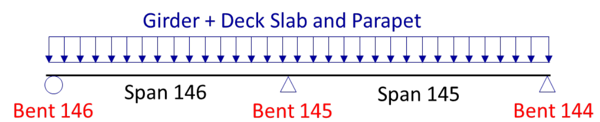
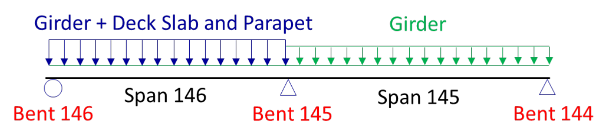
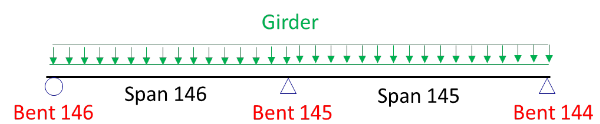
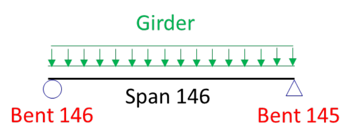
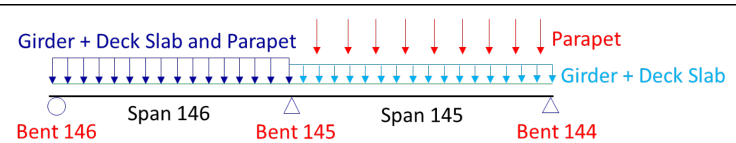
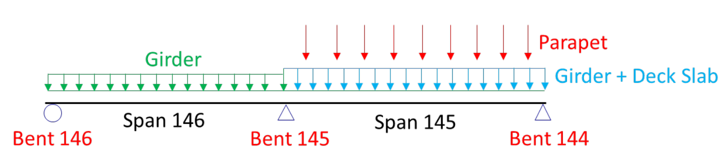
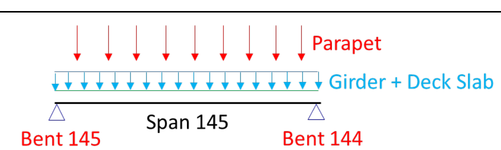
As per the as-built drawings (Sheet No. 36), the steel used to build the steel framing included,

(1) ASTM A373 for web and flange plates; and
(2) ASTM A7, A36 or A373 for stiffeners, bracing, gusset plates, bearing assemblies, and all other parts.

Therefore, OSHA's evaluation used the yield value of 32 ksi. OSHA also considers the compressive strength of the existing cast-in-place concrete to be 3 ksi based on the information given in Sheet No. S-36.

Three-dimensional finite element (FE) models of the girders and the bents were developed using STAAD.Pro software to compute the forces and stresses in the girders and the bents. The actual construction loads, including the combined material weights of the steel and concrete, were considered. For modeling, the weight of the concrete deck was assumed to be uniformly distributed on the girders based on the effective width. The weights of the deck overhang and parapet segments on Span 145 were simplified as concentrated loads on the girders. No strength reduction was considered. The analysis cases that we studied to determine the support reactions and the maximum stresses in the girders are tabulated in Table 1.

Table 1 Summary of numerical analysis cases

Case	Description	FE model schematic
1	3 spans before demolition	
2	3 spans with Span 144 decking removed	
3	2 spans with Span 144 girders removed	
4	2 spans with Span 145 decking removed	
5	2 spans, girders only	
6	Span 146, girders only	
7	Spans 145 and 146, with parapets placed on Span 145	
8	Spans 145 and 146, with parapets placed on Span 145, and Span 146 decking removed	
9	Span 145 with concrete decking and parapet segments	

The FE analyses of the girders were carried out first. The support reactions from the girder analyses were then used as inputs in the FE analyses of the concrete bents.

7.2 Bridge Girder Analysis

Figure 32 illustrates the 3D FE model of the steel girders created in STAAD.Pro using coarse meshes[10] for all analysis cases in Table 1. Main plate girder components, including flanges, webs, and stiffeners, were modeled using 4-noded (quadrilateral) plate elements, which had both attribute membrane (in-plane effect) and bending (out-of-plane effect). The supports at both ends of Span 145 were pin supports, and the supports at Bents 143 and 146 were rollers, as shown in Figure 32.

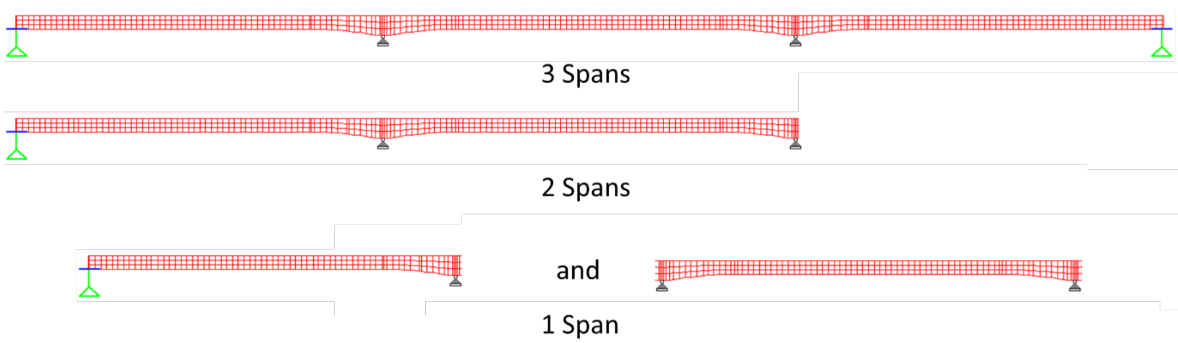


Figure 32 – FE model of steel girders in three spans

For Cases 7 to 9 in Table 1, 3D FE models of the complete steel framing, including steel girders and lateral and vertical bracing, were developed in STAAD.Pro using fine meshes[11] (see Figure 33). Uniaxial tension only TRUSS type elements were used to model the lateral and vertical cross-bracing between two adjacent plate girders.

[10] Coarse meshes are elements of large size.
[11] Fine meshes are elements of much smaller size. The fine mesh predicts more accurate results, however, it takes more computer time to complete an analysis.

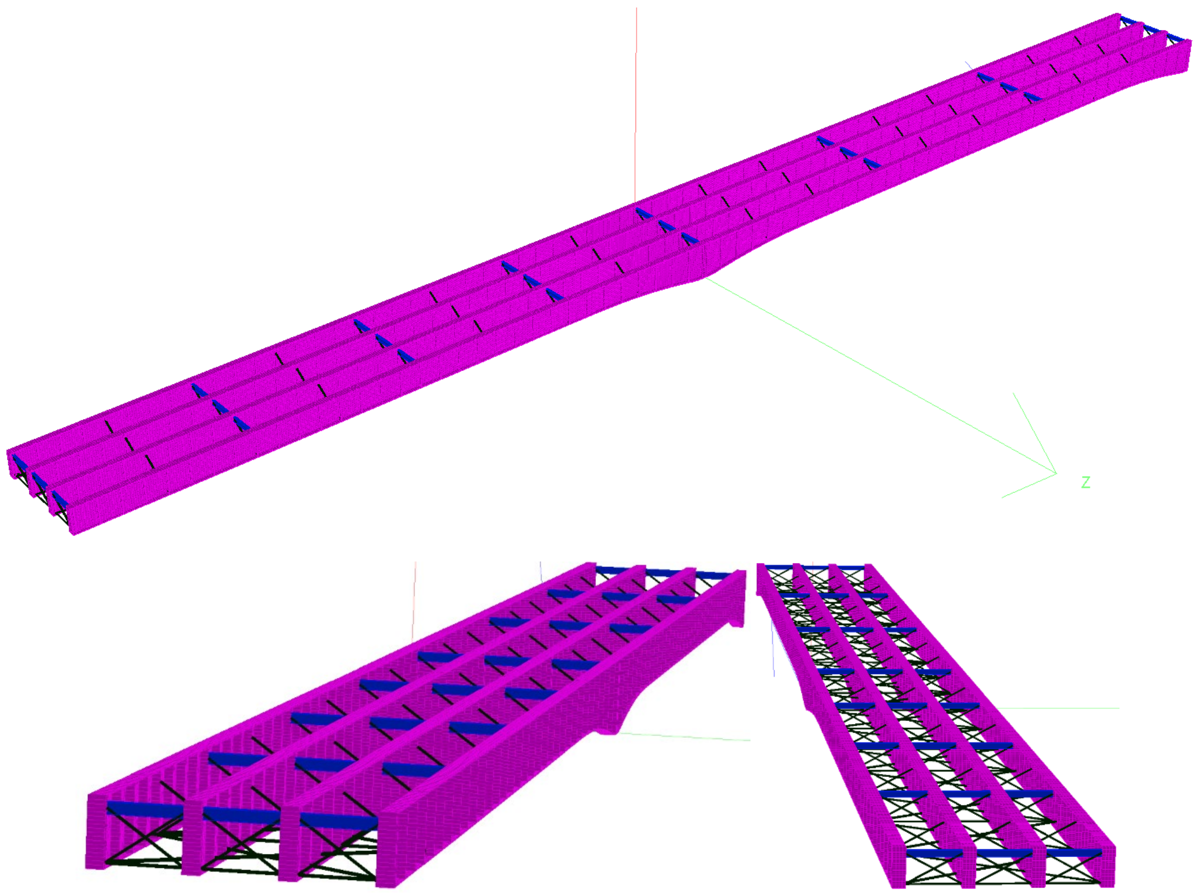


Figure 33 – FE model of steel framing in Spans 145 and 146

7.3 Analysis of Concrete Bents 144 and 145

Figure 34 shows the 3D FE solid model for Bents 144 and 145 developed in STAAD Pro. Support reactions from the girder analyses were applied as vertical and horizontal concentrated forces at the four bearing supports on the top of the bent (blue arrows in Figure 34). The column section forces, including axial and shear forces and bending moments, were obtained after the analyses. Hand calculations were also performed using the column section and material properties from the as-built drawing to determine the load-carrying capacities of the columns (see Figure 35). We did not consider concrete deterioration and reinforcement corrosion in the columns when determining their load-carrying capacities.

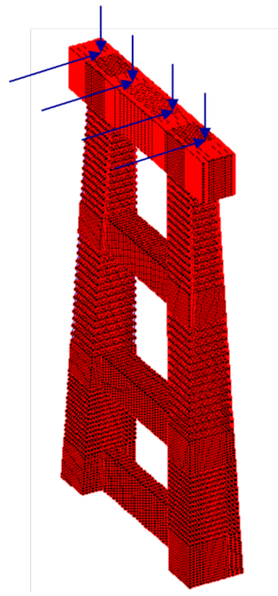


Figure 34 – 3D FE model of Bent 144/145

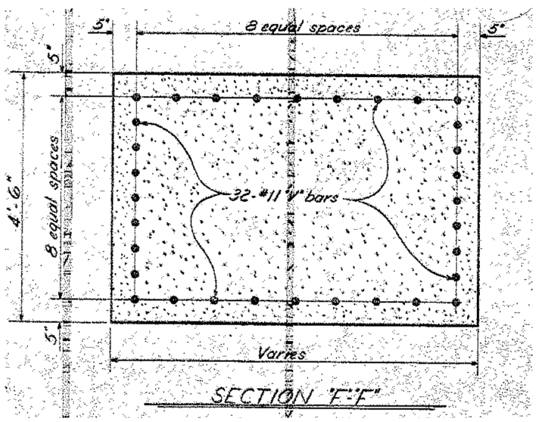


Figure 35 – Column cross-section[12]

[12] Refer to drawing S-106.

8 Analysis Results and Discussion

8.1 Plate Girder Analysis Results

Analysis results of Case 1 through 6 indicated that the maximum stress in the girders would have been well below the yield stress of the steel if PCL had followed KCI's demolition sequences. Analysis Cases 7 to 9 confirmed that the bridge girders in Span 145 were overstressed after PCL cut the four girders in Span 145/146 at Bent 145.

On the day of the incident, before PCL cut the four plate girders in Spans 145 and 146 at Bent 145, these girders were 2-span continuous girders, extending over three supports at Bents 144 to 146 (see Figure 36). Once PCL cut the four girders at Bent 145, the girders remaining in Span 145 became simply supported girders with a much less load-carrying capacity than the 2-span continuous girders before cutting. Our FE analyses confirmed that the maximum Von Mises stress in the girders in Span 145 due to the imposed loads exceeded the yield stress of the A-373 steel, indicating that yielding of steel at some point in these girders occurred when the incident happened.

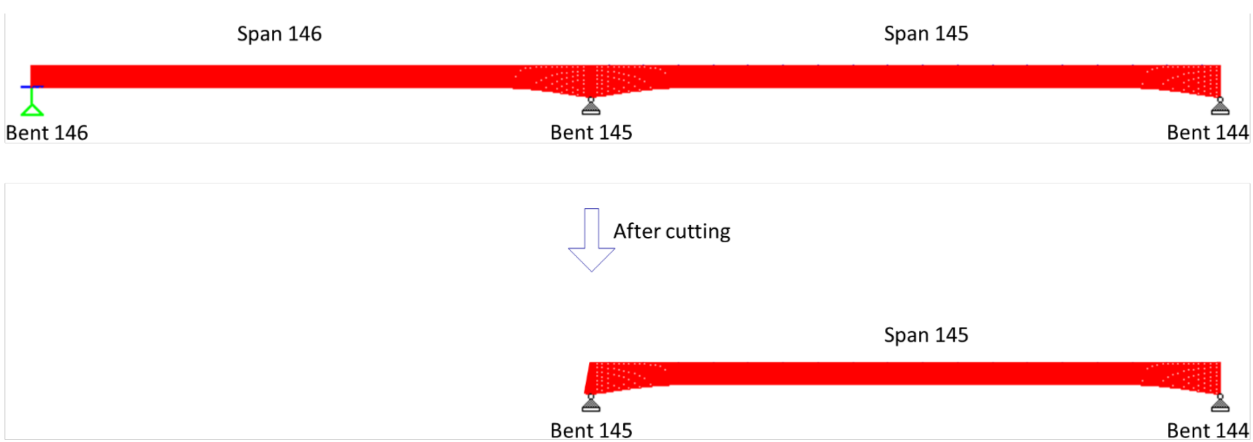


Figure 36 – Plate girders before and after cutting

8.2 Concrete Bent Analysis Results

Because the supports at both ends of the girders in Span 145 were pin supports, which allowed rotation but prohibited vertical and horizontal displacement, the bottom flanges of the girders were prohibited from extending when subject to tension caused by positive moment.[13] This restraint of the bottom flange extension resulted in substantial horizontal reactions at the pin supports on top of the two interior bents (blue arrows in Figure 37). As a result, the columns of Bents 144 and 145 were subjected to axial and transverse loads and bending moment.

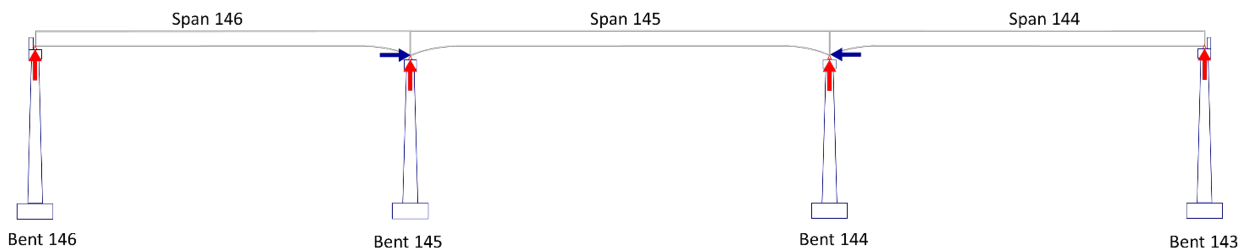


Figure 37 – Support reactions at Bent 144/145[14]

OSHA's analysis indicated that the weight of the steel and concrete in Span 145 overloaded Bents 144 and 145 at the time of the incident.

8.3 Discussion

PCL did not follow KCI's demolition plan to remove the three high-rise spans. Instead, PCL utilized different demolition sequences and developed its own demolition plans. PCL made no engineering calculations, nor did it complete an engineering survey of the structure to determine its adequacy and possible unplanned collapse of any portion of the structure during demolition. OSHA analyses indicated that the plate girders and the two bents in Span 145 were overloaded at the time of the incident.

[13] Positive moment is the bending moment induced by vertical gravity loads.
[14] Red arrows represent loads on bent caps induced by vertical gravity loads, i.e., weights of the girders and concrete decking.

9 Conclusions

Based on the evidence collected, observations of the collapsed structure, and structural analyses performed, OSHA concludes that:

1. The contractor retained a structural engineering firm to develop a demolition plan for the three high-rise spans of the bridge. However, the contractor did not follow the plan to remove the bridge spans.
2. The contractor used different demolition sequences and developed its own demolition plans without performing any engineering surveys and calculations to determine the adequacy of the structure and the potential for unplanned collapse of any portion of the structure during the demolition. Unfortunately, the contractor carried out the demolition operation of the three high-rise spans in such a way that the structural members were loaded beyond their load-carrying capacities, resulting in the premature collapse of the navigation span.