Modjeski and Masters Evaluation of Docket Items from Louis Berger

Miami, FL

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MODJESKI and MASTERS

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10/17/2019

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RE: PN3897
FIU Bridge Collapse
Review of NTSB Information

Dear Mr. Willian and Ms. Karis:

At your request, Modjeski and Masters, Inc. has performed a review of the information recently released by the NTSB related to Louis Berger as part of the factual reports arising from their investigation. There are several issues that we believe should be clarified in order to provide a more complete and accurate basis for the final NTSB report on the collapse. A brief summary of the background of Modjeski and Masters (M&M) is provided, followed by our opinions regarding the issues that are of concern.

Firm Qualifications

Modjeski and Masters, Inc., (M&M) a bridge design and engineering firm headquartered in the United States, has completed several major bridge failure investigations over its 125-year history, including providing assistance to the NTSB. The firm is focused on all aspects of bridge engineering, from applied research to development of design specifications and criteria, conceptual studies, preliminary and final design, inspection, rehabilitation, and failure analysis. Beginning with the investigation of the Silver Bridge collapse in 1967, in which M&M led the investigation which eventually resulted in the adoption of mandatory bridge inspections in the United States, M&M has been involved in collapse and failure investigations of bridges of all types, including cable supported structures, trusses, and girders. We have extensive experience working as part of multi-disciplinary teams, combining our knowledge of bridge behavior and complex analysis with materials and geotechnical experts to quickly get to the root causes of bridge failures.

Collapse Investigation Experience

Chirajara Bridge Collapse Investigation. *Chirajara, Colombia* | While under construction, on January 15, 2018 at approximately noon, the north concrete tower of the cable stayed bridge collapsed suddenly, destroying that half of the structure and resulting in 9 fatalities. M&M was contacted and subsequently retained to conduct an investigation of the causes of the collapse, and provided a comprehensive report and expert witness testimony.

Dysart Truss Bridge Collapse Investigation. *Cambria County, PA* | The Dysart Truss Bridge was a simple span pin-connected Pratt-type through-truss which carried one lane of S.R. 1012 over the Clearfield Creek in Cambria County. M&M was contacted to perform a forensic investigation for the collapse of this 116 year-old Pratt Truss. We delivered a detailed report, with FEM analysis and findings, in just 1 month.

Atlanta Botanical Gardens Walkway Collapse Investigation. *Atlanta, GA* | On the morning of Friday, December 19, 2008, the "canopy walk" pedestrian bridge at Atlanta's Botanical Gardens collapsed during construction. The collapse killed one construction worker and injured 18 others. M&M was contacted and subsequently retained to provide expert witness testimony and forensic engineering.

I-40 Bridge Collapse Investigation. *Webbers Falls, OK* | A barge left the navigation channel and struck the I-40 bridge, resulting in the collapse of four spans and loss of life. Our investigation included documenting the chronology of events leading to the barge collision and catastrophic collapse of the bridge, as well as the cause of the collapse. Finite element modeling and materials sampling and testing were utilized during the investigation

Mianus Bridge Collapse Investigation. *Greenwich, CT* | The bridge had a 100-foot (30.5 m) section of its deck of its northbound span collapse on June 28, 1983. Three people were killed when two cars and two tractor-trailers fell with the bridge into the Mianus River 70 feet (21.3 m) below; three people were seriously injured. M&M led the investigation of the bridge and determined the collapse was caused by the failure of two pin and hanger assemblies that held the deck in place on the outer side of the bridge

Yadkin River Bridge Collapse Investigation. *Siloam, NC* | Four people were killed and 16 people injured when the one-lane steel span bridge connecting Yadkin and Surry counties in Siloam collapsed on February 23, 1975. M&M led the investigation of the collapse of this bridge and provided the NTSB with the cause of the bridge's collapse. M&M completed the physical inspection and technical analysis of the steel truss bridge with a follow-up report

Silver Bridge Collapse Investigation. *Point Pleasant, WV* | First Bridge collapse that led to introduction of the National Bridge Inspection Safety Standards in the United States. M&M led the investigation, which found a deficiency in the eye-bars without redundancy of support.

Scope of Peer Review

Several documents, such as the Wiss, Janney, Elstner Associates, Inc. report included in FIGG's Party Submission to the NTSB, assert that Louis Berger failed to perform certain tasks as part of their independent peer review. These statements appear to be largely incorrect, as they assume that the scope of Louis Berger's review was all-encompassing of the design and they appear to misinterpret the requirements of the FDOT Plans Preparations Manual, Chapter 26.12 - Independent Peer Review of Category 2 Bridges. The scope of work agreed upon between FIGG and Louis Berger included modifications to the FDOT independent peer review requirements, and did not specify performance of an all-encompassing review of FIGG's design. Notably, emails indicate that FIGG had direct communications with FDOT regarding the scope of Louis Berger's peer review and had responsibility for informing FDOT of the scope negotiated with Louis Berger. It is clear Louis Berger believed that a limited and specific scope of review had been negotiated between FIGG and Louis Berger. Our opinions are supported by the following:

- Specific modifications to the peer review requirements in FDOT Chapter 26 were made by MCM/FIGG. For instance, contrary to the FDOT Chapter 26 requirements:
  - Louis Berger was not contracted to provide a review of the 90% plan submittal (see Design Services Scope of Work document – last page of "Bridge Factors Attachment 19 – Agreement entered into by FIGG Bridge Engineers, Inc. and Louis Berger dated September 16, 2016")
  - Louis Berger was directed to not provide written review comments for the superstructure; review comments were instead relayed and resolved via phone (see Louis Berger Interview Transcript - Interview of Dr. Ayman Shama –18:18 - 19:20).
  - We note that FIGG later informed FDOT that Louis Berger did not develop any comments on the superstructure (see FIGG141015). Several pieces of evidence, including the interviews of Manual Feliciano of FIGG and Dr. Ayman Shama of Louis Berger confirm that was not an accurate written statement to FDOT.
- Email correspondence from FIGG to Louis Berger indicated that from the outset, FIGG required that the scope be as streamlined as possible, that keeping the schedule was of utmost importance, and that Louis Berger was not to "make a science project out of this." This all supports that FIGG did not intend to contract with Louis Berger for a full scope review. (LOUISBERG_00000665 and FIGG169690)
- FIGG internally recognized among its highest executives and General Counsel that it contracted with Louis Berger for a limited scope: "The request we sent for the independent review had scope/limitations of what independent review was covered." (FIGG 168085)
- Despite the issues the FIGG design staff was encountering with accurately determining the demands for the shear-friction checks on the nodes, noted later in this document, neither the FIGG internal peer review nor the scope of the external Louis Berger peer review included a check of the capacity of the nodes with respect to the demands placed on them.
- If FIGG had intended that Louis Berger review the demand and capacity of the nodes, industry standards require that FIGG specify this in the scope of the peer review. Per ASCE-Quality in the Constructed Project, Chapter 22 Peer Review:

  - "The reviewer(s) work with the owner, design professional or constructor to develop a detailed scope of review."
  - "The scope of a peer review should be focused and well defined, distinguishing it from other, more general reviews."
- The timeframe (7 weeks) and budget allocated to Louis Berger to perform the work is consistent with an understanding that there would be a limited review. It was not sufficient to perform a comprehensive review of all aspects of the design (see Interview Transcript - Interview of Dr. Ayman Shama – 9:14-10:5, 13:4-13:7, 27:14-27:22).
- The peer review activities indicated in the scope of work between FIGG and Louis Berger are shown below. Item #1 specifically identifies the development of demands on all elements, but does not include the calculation of capacities or sufficiency checks for the bridge elements. Nodes and nodal regions are not mentioned at all.

2. The Independent Peer Review will include the following activities:

Item #	Item Description
1	Develop finite element model for the bridge and estimation of demands on all elements due to different load combinations
2	Peer review of foundation plans
3	Peer review of substructure plans
4	Peer review of superstructure plans

- If FIGG and Louis Berger had intended that Louis Berger check the capacity of the nodes, this is estimated to have required 100+ hours of additional hand calculations with respect to determining capacities, which would have taken another several weeks of additional work.

Additionally, it is noted that:

- FIGG performed an internal peer review in a separate office from the one performing the design work. FIGG had previously claimed that this internal review, purportedly a requirement of their insurer, met the requirements of FDOT Plans Preparations Manual, Chapter 26.12 such that an external reviewer was not needed (FIGG165316, FIGG169919).
- State DOTs and other transportation agencies that wish to require comprehensive reviews by independent peer reviewers have mandatory and more specific language in their policy documents to indicate the scope expected to be undertaken by the reviewer. As an example, the Minnesota DOT (Mn/DOT) LRFD Bridge Design Manual – Section 1.3.3 – Peer Review for Major or Specialty Bridges is compared with the FDOT Chapter 26 requirements in Table 1 below:

Table 1. Comparison of Peer Review Requirements

FDOT Plans Preparations Manual, Chapter 26.12 - Independent Peer Review of Category 2 Bridges (excerpt – ***emphasis*** added)	Mn/DOT LRFD Bridge Design Manual – Section 1.3.3 – Peer Review for Major or Specialty Bridges (excerpt – ***emphasis*** added)
All independent peer reviews must include but not be limited to the independent confirmation of the following ***when applicable***: 1. Compatibility of bridge geometry with roadway geometrics including typical sections, horizontal alignment, and vertical alignment. Minimum lateral offsets and vertical clearance requirements. 2. Compatibility of construction phasing with Traffic Control Plans. 3. Conflicts with underground and overhead utilities. 4. Compliance with AASHTO, Department and FHWA design requirements. 5. Conformity to Department Design Standards. 6. Structural Analysis Methodology, design assumptions, and independent confirmation of design results.* 7. Design results/recommendations (independent verification of the design).* 8. Completeness and accuracy of bridge plans. 9. Technical Special Provisions, and Modified Special Provisions where necessary. 10. Constructability assessment ***limited to*** looking at fatal flaws in design approach. *When Category 2 superstructure elements are designed with software using refined analyses (e.g. Grid, Finite Element Method, etc.), the peer review consultant must verify the design results by a different program/method.	The following stages of design ***will be reviewed by the Peer Reviewer*** for concurrence: • Design and Load Rating Criteria: Design specifications, construction specifications, design loads and load combinations, construction loads for design, materials and allowable stresses, foundation type, factored pile resistance and resistance factors, and permit trucks. • Concept Design: Bridge geometrics, typical sections and dimensions, component sizes, framing plan, location and type of expansion joints, location and type of bearings, computer models for girder design, **construction staging**, construction sequence, river foundation report, vessel impact study, and outline of special provisions. • Superstructure Final Design: Independent calculations and design; method of analysis (line girder or three dimensional); modeling assumptions; composite and non-composite section properties, member capacities, dead load and live load moments, shears, and stresses at 1/10th points along girder lines, ***all primary connections*** and other points of interest; dead and live load deflections; deck design; deck stresses; and deck pour sequence. • Substructure Final Design: Independent calculations and design, assumptions, points of fixity, cofferdam design, and pier design and details. • Constructability: Shipping limitations, erection sequence and stability issues, crane sizes and boom lengths, construction overhead clearances, interference/restrictions on construction due to site conditions, shoring tower locations, falsework review. • Plan: adequacy of construction plans and specifications provided to contractor.

When comparing FDOT requirements to those from Mn/DOT, for example, it is clear that FDOT does not require a complete check of all components of a bridge, and in fact allows for limitations on the extent of the review. The content of this subset is not clearly defined in the FDOT Plans Preparation Manual, and thus the contract scope of services between FIGG and Louis Berger establishes the limits of the subset of checks to be performed on this project. Presumably, FIGG or MCM - which had received the contract between Louis Berger and FIGG -

would have made FDOT aware of the negotiated scope with Louis Berger. However, we have seen no communication by either party transmitting Louis Berger's negotiated scope contract to FDOT.

Constructability vs. Construction Stage Analysis

On page 140 of 206 of the Bridge Factors Group Chairman's Factual Report it states:

> "Louis Berger was obligated to check constructability considerations of the bridge by AASHTO LRFD Bridge Design Specification, Section 2.5.3, and by FDOT Structures Design Guidelines, Sections 2.13, 4.58, 4.59 and 6.10. Both of these documents are requirements of Louis Berger's scope and require investigations of the structure during various construction phases."

The above quoted text describes tasks for a constructability review which are beyond the realm of the typical definition of constructability, and confuses constructability with a construction stage analysis. Per FIGG's Design Quality Management Plan for the FIU project (see FIGG009464):

> **Subject: Constructability Reviews**
>
> **PURPOSE**
>
> A Constructability Review (CR) is completed to formally obtain input from the construction team associated with the project into a selected deliverable and to take advantage of opportunities identified as well as avoid design that is awkward or unnecessarily difficult to construct.
>
> **SCOPE**
>
> This procedure defines the items that are specific to Constructability Reviews associated with deliverable packages for Design-Build projects. Deliverables include all design documents delivered to FIU. These include reports, drawings, specifications, management plans, design memoranda, and other documents. Constructability Reviews focus on the drawings and specifications, but may also include management plans and other procedure-related documents that impact construction activities.

Furthermore, FIGG's Design Quality Management Plan indicates the following:

> 5. The Constructability Reviewer will focus on the following criteria:
>   - General completeness of information
>   - Achievability of specified tolerances
>   - Existence of adequate site access for work proposed
>   - Restrictions to site access have been addressed
>   - Environmental constraints have been addressed
>   - Utility conflicts have been addressed
>   - Availability of materials
>   - Minimizing environmental impacts
>   - Storage area for required materials is available
>   - Design is prudent, economical, and consistent with design objectives
>   - Any other items that reflect construction perspective and improve deliverable

Definitions of constructability and constructability review from additional sources, such as other state DOTs and industry trade groups, are similar in content. For instance, see the portion of the excerpt from the Mn/DOT section on peer review, provided in the table above, which discusses constructability checks. All of this information indicates that the focus of a constructability review is to ensure that the structure as shown in the plans and other contract documents is not un-constructible and that the contractor can successfully complete construction without encountering unnecessary difficulties. A constructability review does not involve explicitly checking the capacity and demands on the structure throughout the stages of construction.

Source of the Error in Demand Estimation

The FHWA report[1] identifies deficiencies in the modeling used by FIGG to determine the demands on the joints. Specifically, "the analytical modeling relied upon by FIGG Design was inadequate or misinterpreted, resulting in a significant underestimation of demand at critical and highly loaded nodal regions." However, the report does not appear to investigate why or how this happened. Based on a review of FIGG's calculations and correspondence with LUSAS support (see Table 2), the reasons why FIGG's modeling produced forces that were almost half of the correct results can be attributed to two modeling aspects: mesh density and the method used to integrate the interface forces.

Mesh density

Results from finite element models are sensitive to the number of elements used to create the model, known as the mesh refinement. A mesh can be characterized as coarse when relatively few elements are used to model a region, or fine (or refined) when a relatively large number of elements are used. Some models (or regions of a model) are more susceptible to the mesh size effect depending on factors such as element type, stress variations, and analysis type, among others. In particular, volume elements need to meet a maximum aspect ratio requirement to avoid excessive geometric distortions that may affect the accuracy of the results.[2]

A common practice to evaluate whether the mesh size used in a model is adequately refined is to start with a coarse mesh and refine it progressively until no significant changes are observed in the results. In fact, this was the recommendation provided by LUSAS, on at least two different occasions, when responding to FIGG's inquiries about how to improve the mesh (FIGG156539 dated 8/10/16) and the accuracy of the stresses (FIGG421364 dated 10/13/16) of their FIU truss model. The day after requesting assistance with the accuracy issue (FIGG421375 dated 10/14/16), FIGG acknowledged that updating the model to use quadratic elements (elements with intermediate nodes along the edges, and hence a more refined mesh density) improved the results considerably. However, by the time this update was made, the 90% Superstructure Design Calculations had already been submitted (10/5/16), and the corresponding design forces were not

[1] NTSB Bridge Factors Factual Report Attachment 73 – FHWA Assessment of Bridge Design and Performance, Miami, FL, 2019.

[2] FHWA, Manual for Refined Analysis in Bridge Design and Evaluation, 2019.

updated in the final submission to reflect the implementation of the quadratic element formulation, as discussed later.

Extraction of interface forces

The solid element modeling FIGG chose to use for determining the design forces on the nodal regions does not directly produce design forces, but rather the stresses must be processed in order to obtain the forces. FIGG was in contact with LUSAS regarding this issue since they were obtaining inaccurate interface forces in a simplified test model of a nodal region (FIGG150147 dated 9/15/16). To get the interface shear forces, FIGG was extracting the element stresses directly from the model and integrating them separately in a spreadsheet. LUSAS recommended using their "slice" function, which is directly incorporated within the software and accomplishes automatically the integration of stresses into forces (FIGG15018 dated 9/15/16). According to the final design calculations, FIGG did follow this recommendation, but the interface forces were extracted from a model with a coarse mesh that compromised the accuracy of the results.

FIGG did not appear to have correctly utilized the slice function, since the model was cut right at the interface between the truss elements and the deck (or canopy). This can result in inaccurate results, particularly if only one side of the interface is active when the slice is taken. It appears likely that FIGG applied the slicing function at the interface with only one side active, and therefore did not obtain accurate results. The slices are usually taken within the element boundaries to avoid this issue. MCM's investigation of the collapse also addressed this problem.[3]

M&M was able to identify the specific model that FIGG used to extract the interface shear forces of the nodal region 11-12 (FIGG278027, see Figures 1 and 2). It was verified that this model has a coarse mesh, especially at the nodal regions (Figure 3), and uses linear solid elements instead of the enhanced quadratic elements. FIGG's original model was modified by M&M as part of the investigation in order to evaluate the effects of the mesh density and the location of the slice plane on the automatically generated LUSAS forces. Figure 4 shows that changing the element formulation from linear to quadratic is more effective than decreasing the size of linear elements. On the other hand, Figure 5 indicates that the issue of inaccurate integration results practically disappears by moving the slice plane a minor distance from the deck within the truss elements.

Thus, despite being aware of potential inaccuracies in the use of a model with a coarse mesh, FIGG proceeded to use their original design forces without verifying the results were accurate and despite the guidance and advice provided by the software supplier.

[3] MCM, Accident Investigation Report – Pedestrian Bridge Collapse at Florida International University, 2019.

Table 2. Chronological description of available FIGG's correspondence with LUSAS support.

Date	Document #	Description
8/8/2016	FIGG218844	Original contact from FIGG to LUSAS Support regarding issues with meshing the model at the intersection of truss and deck.
8/10/2016	FIGG156539	Response from LUSAS indicating the mesh is too coarse and needs to be refined for better accuracy.
8/19/2016	FIGG218832	LUSAS follows up asking if FIGG had solved their issues.
9/15/2016	FIGG150147	FIGG contacts LUSAS support about integrating stress results to get forces.
9/15/2016	FIGG150118	LUSAS responds that integrating stresses manually is a complicated process and recommends using the LUSAS slicing feature instead.
10/12/2016	FIGG421352	FIGG contacts LUSAS support about differences between hand stress calculations and LUSAS results.
10/13/2016	FIGG421364	LUSAS responds and indicates to FIGG that they need to refine their mesh because it is too coarse.
10/14/2016	FIGG421375	FIGG responds and states they started using quadratic rather than linear elements and are getting much better results.
10/14/2016	FIGG421384	LUSAS responds that it is good the results are matching up better and emphasizes the importance of having a proper mesh in the model to get the most accurate results.
11/11/2016	FIGG421397	FIGG contacts LUSAS support regarding mesh-related warning messages.
11/11/2016	FIGG421402	LUSAS responds that there are some overlapping nodes caused by an irregular geometry and recommends using the "equivalence" function.
11/14/2016	FIGG421436	LUSAS follows up message noticing that there are overlapping surfaces at the location where the issue is exhibited. As an alternative solution, LUSAS recommends merging the surfaces.
11/14/2016	FIGG421410	FIGG contacts LUSAS support regarding how to add time effects to the model (creep and shrinkage) in order to perform a staged construction analysis.
11/14/2016	FIGG421424	LUSAS responds giving directions on both the staged constructions analysis and the concrete time dependent effects.

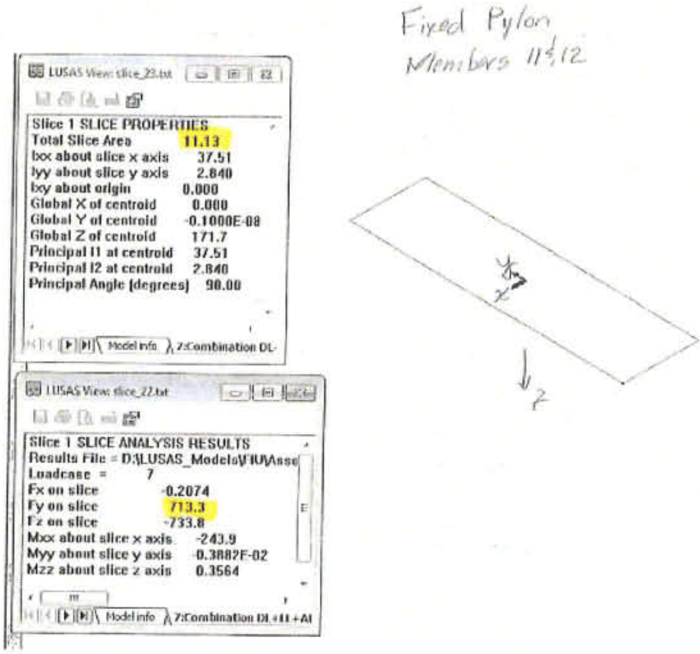

Figure 1. Excerpt from FIGG's calculations (FIIU_0000000045 page 1398)

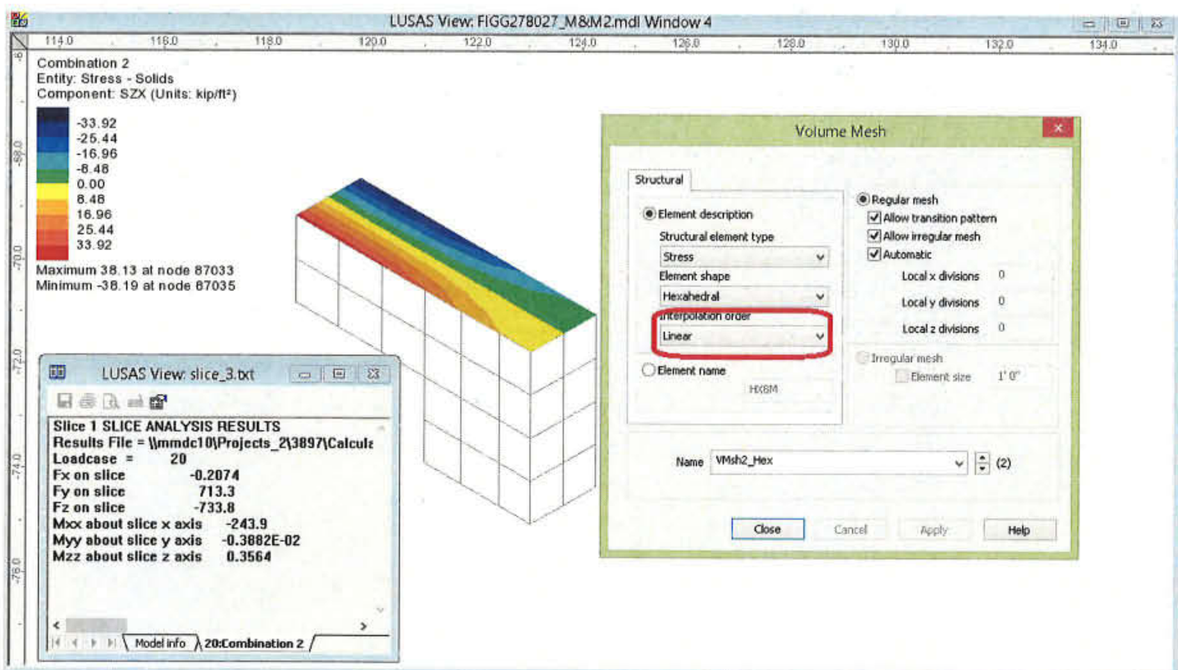

Figure 2. M&M's generated results using FIGG278027 model

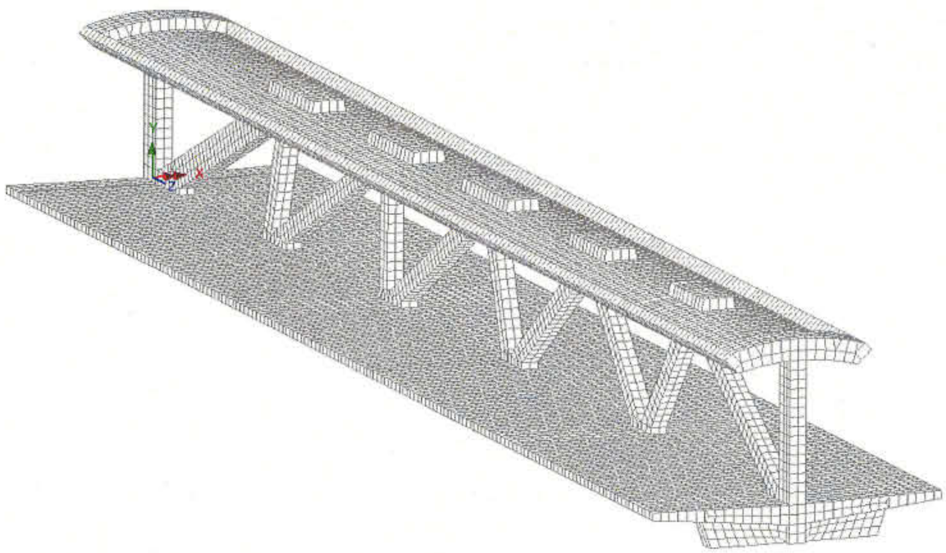

Figure 3. Mesh view of FIGG278027 model

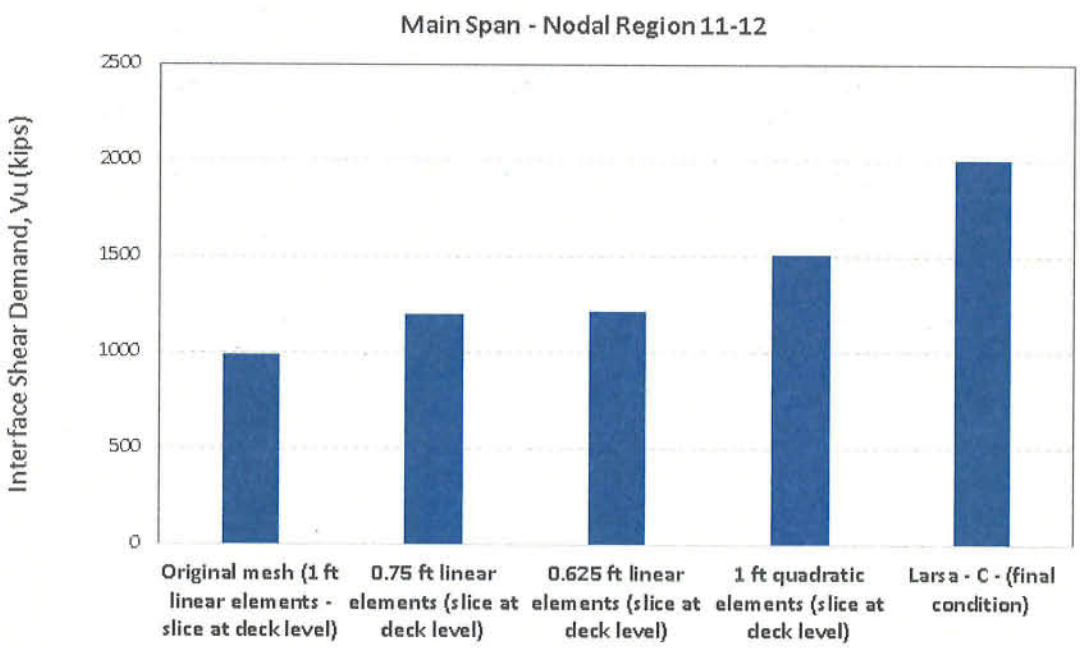

Figure 4. Mesh density effect on interface shear demands

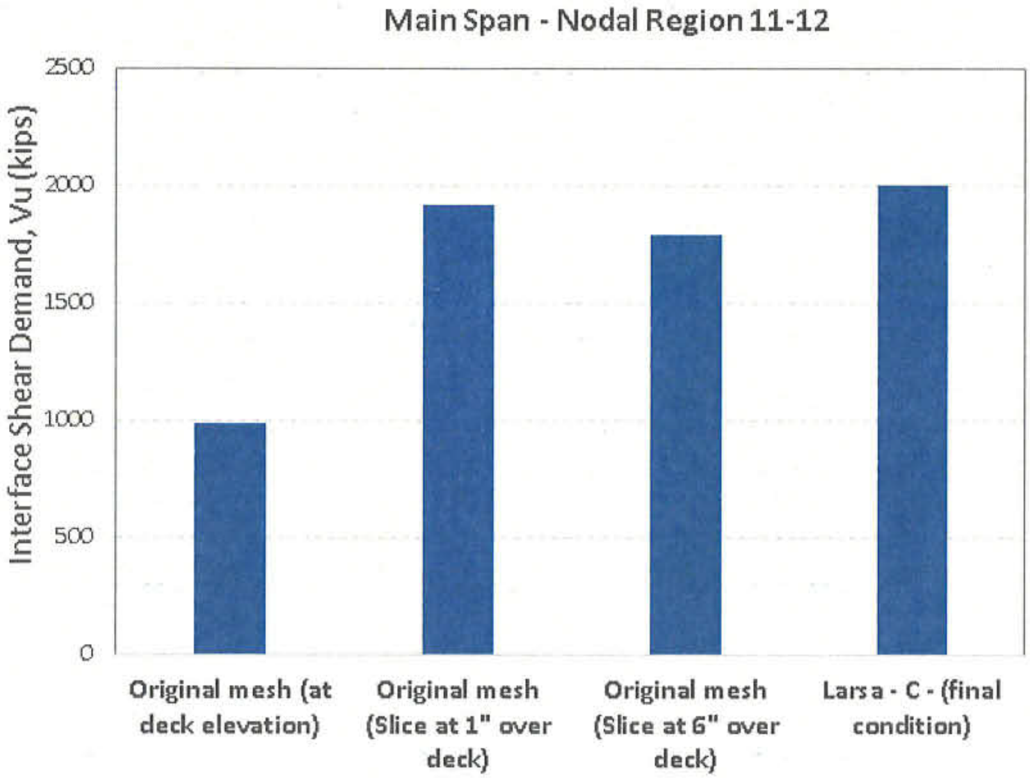

Figure 5. Slice location effect on interface shear demands

We hope these clarifications will be of assistance to the Board in developing its final determination as to the cause of this tragedy.

Very truly yours,

[redacted]

Thomas P. Murphy, Ph.D., P.E., S.E.
Vice President, Chief Technical Officer