

Indiana State Fair Collapse Incident

August 13, 2011 Collapse Incident Investigation
Report on Findings to the Indiana State Fair Commission

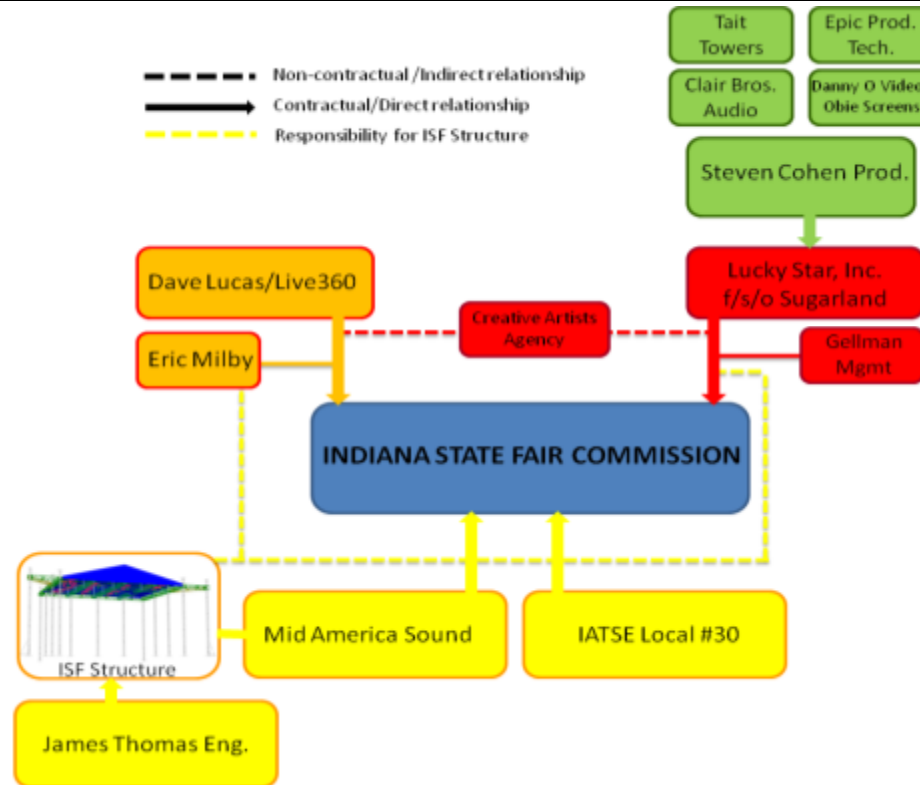
Scott G. Nacheman, MSc.Eng., AIA
Vice President

April 12, 2012

Role of Thornton Tomasetti

- > Independent Engineering Cause and Origin Investigation
 - Documentation of site components
 - Access Protocols
 - Chain of Custody Protocols
 - Coordination with other agencies and parties
 - Code analysis
 - Analysis of collapse
 - Limited Document Review
- > Final report
 - Findings
 - Recommendations

Involved Parties



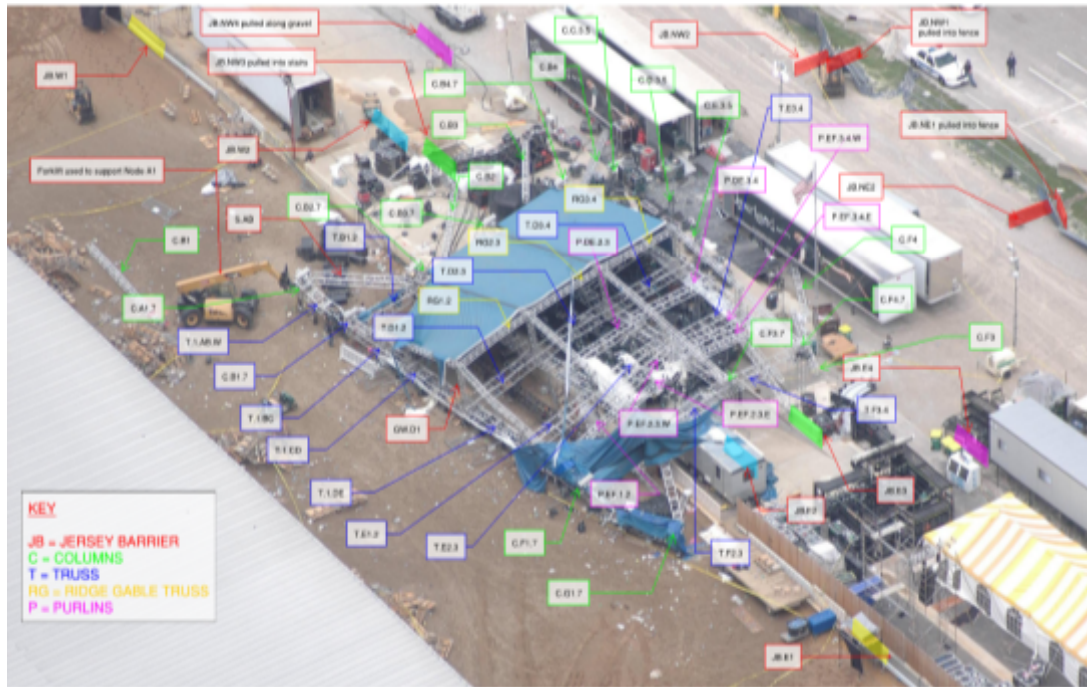
Investigation Methodology



- > Site Survey
- > On-site Testing
- > Wind Tunnel Testing
- > Metallurgical Evaluation
- > Computer Modeling
- > Analysis / Calculations

Documentation of Components

“Tag” system



Items in database:

Unique “serial number” for all components on site.

RAFTER TRUSS
 BETWEEN GRID LINES B AND C
 ON COLUMN LINE 1
 WEST SECTION
 RF.CD.1.W
RAFTER TRUSS

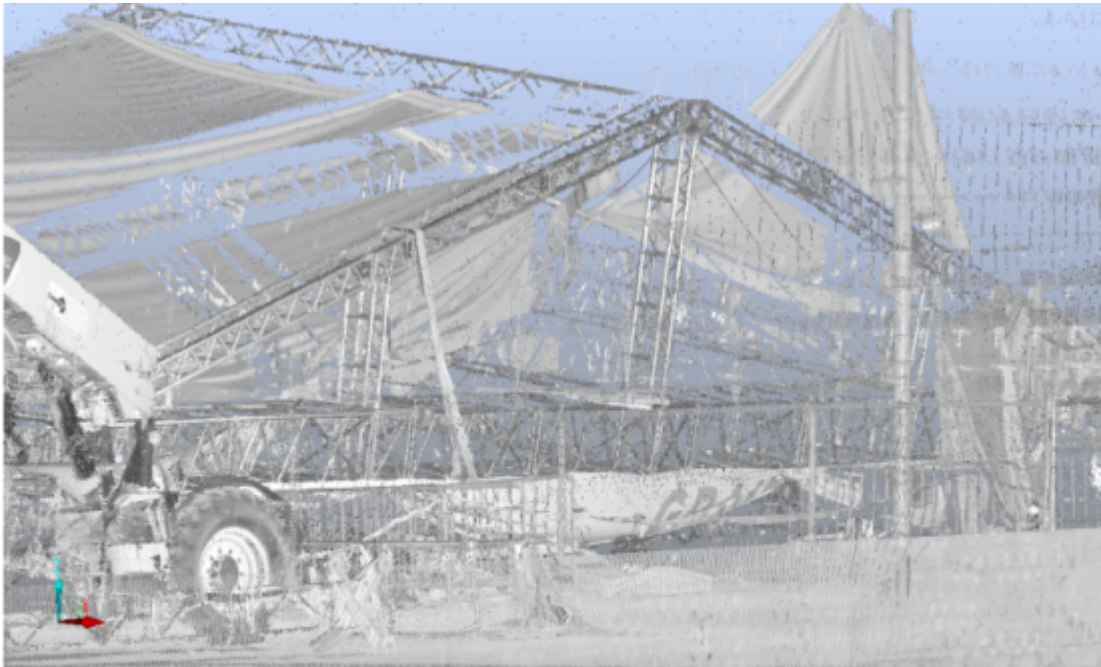
GABLE WEB TRUSS
 COLUMN LINE C
 SECTION 1
 GRID LINE 1
 GW.C1.1
GABLE TRUSS

Documentation of Components

Forensic Database:

- >Over 2500 entries
- >Superstructure
- >Suspended Trusses
- >Entertainment Tech. Eqpt.
- >Guy Lines
- >Jersey Barriers (K-Rails)

Laser Scan

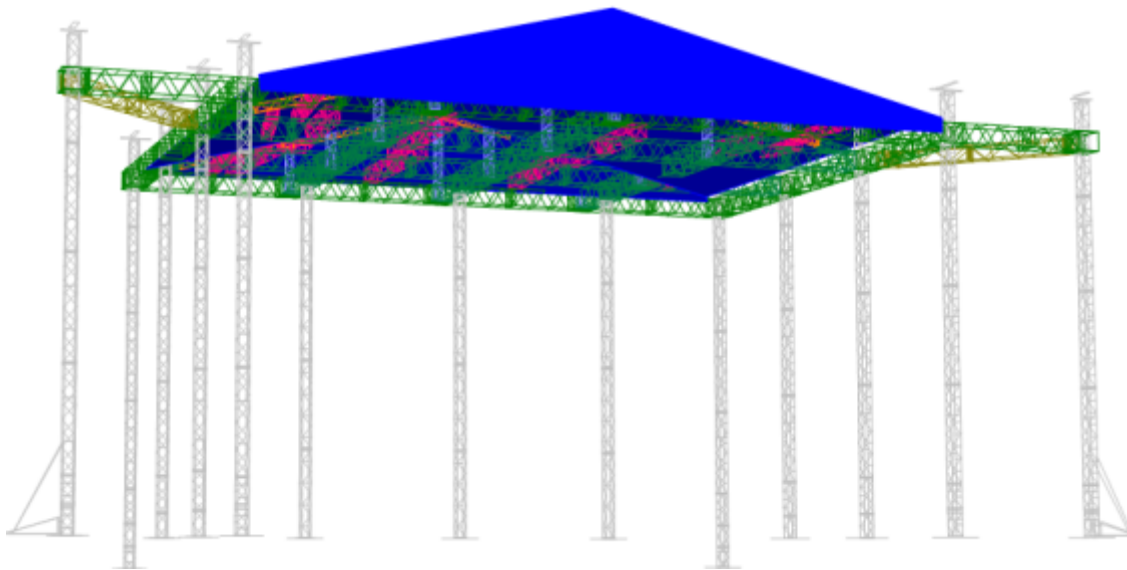


TDS, Inc.

3-Dimensional Point
Cloud

Millions of Measured
Points

FEM Analysis & Other Calculations



Finite Element Analysis

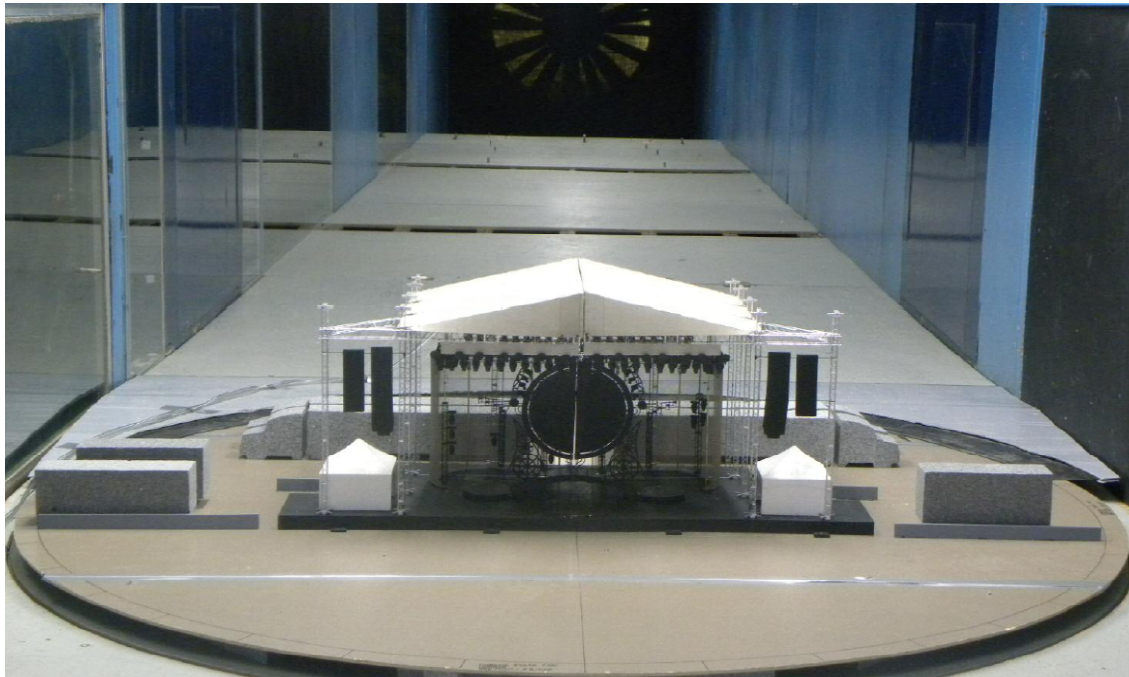
Site measurements

Catalog data

Reverse engineering
of structure

“Reasonable Engineer”
Study

Wind Tunnel / Meteorological



RWDI:

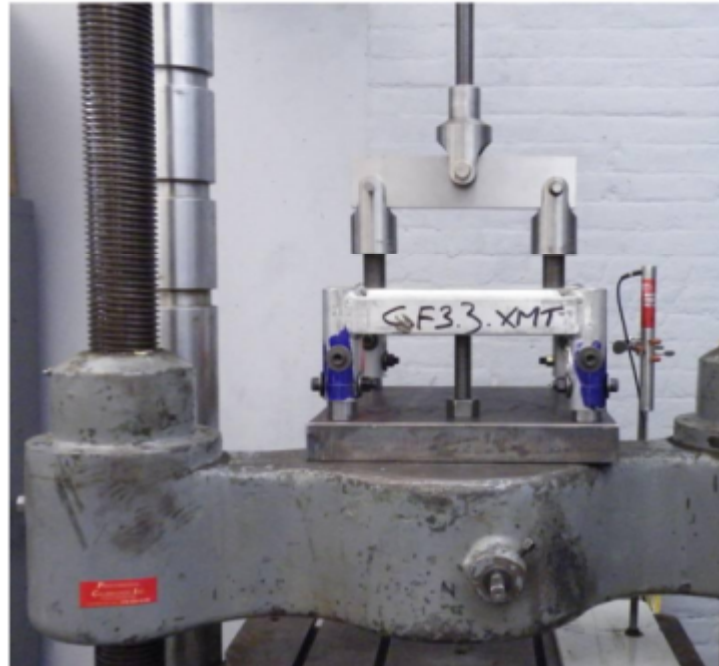
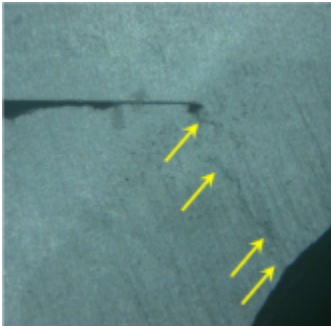
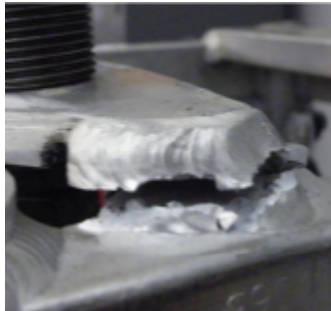
Review of weather data

Wind analysis and modeling

Wind Tunnel Force Balance Tests

Determination of wind speeds at site

Metallurgical Evaluations



Lucius Pitkin, Inc.:

Physical testing

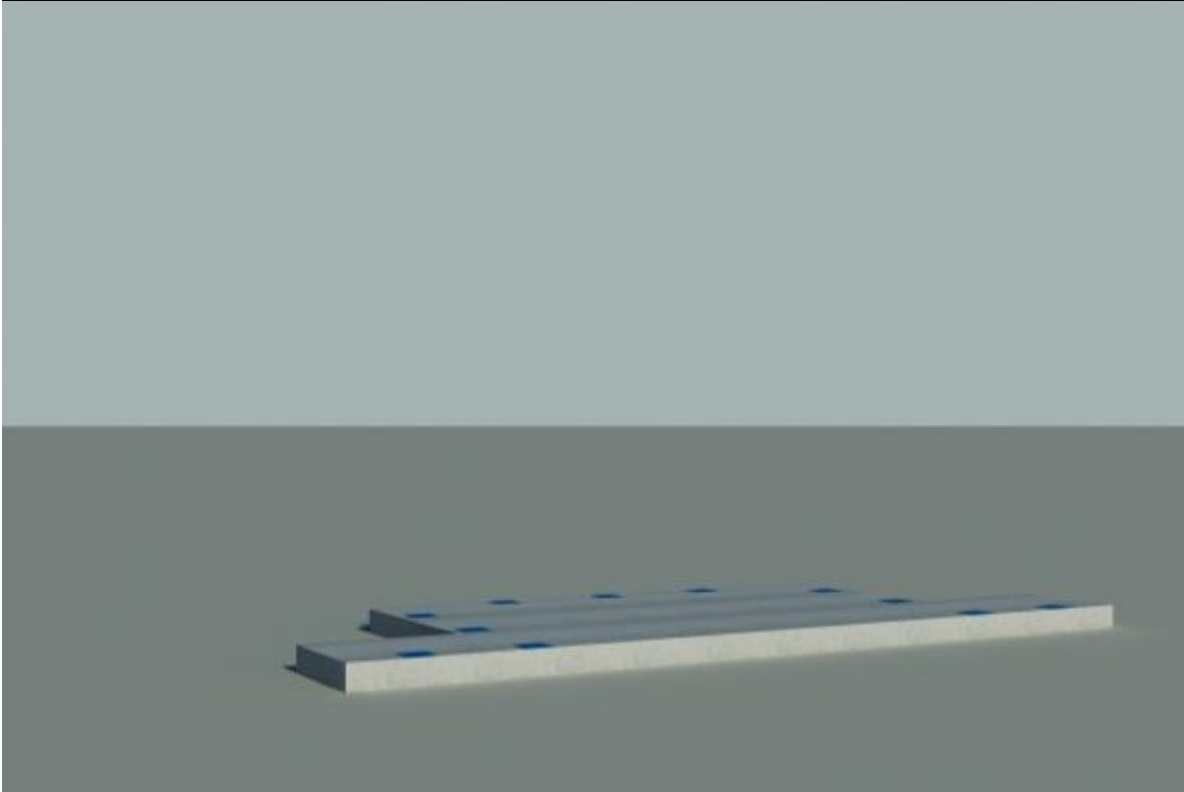
Microscopy

Alloy and filler metal
identification

Components of the ISF Structure



Components of the ISF Structure

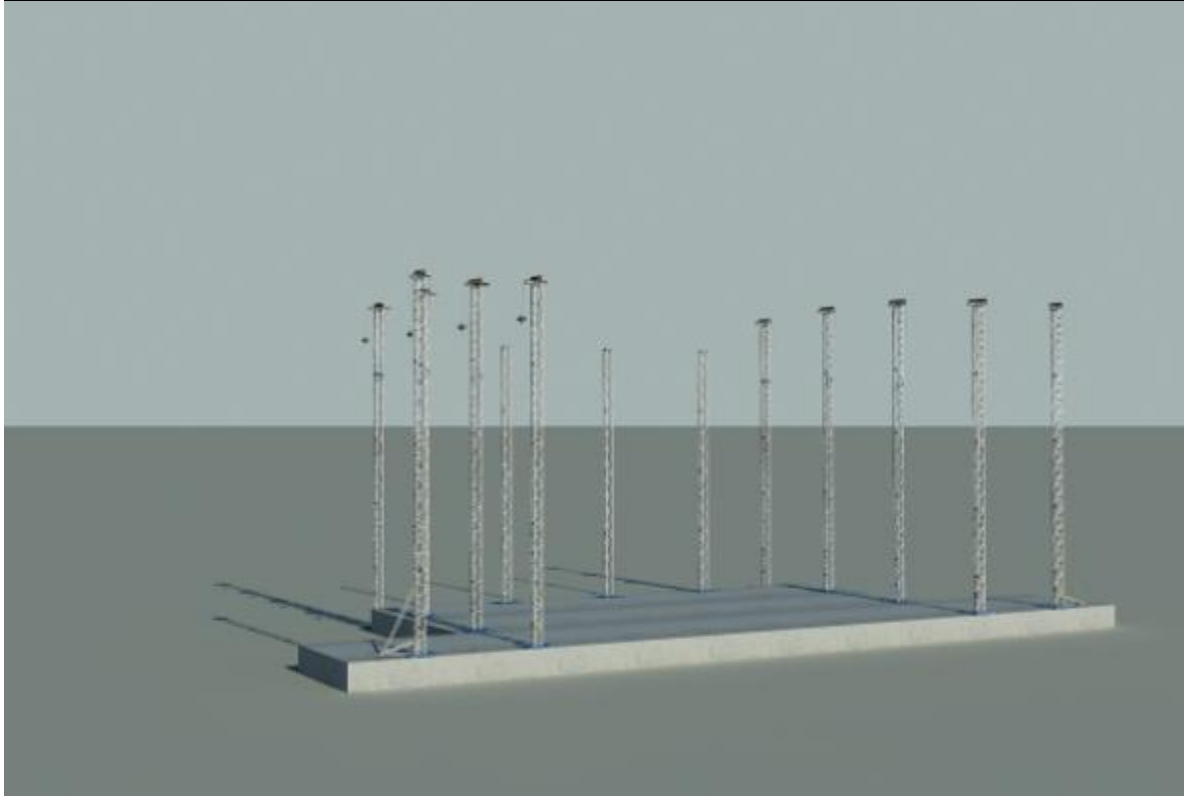


The Stage

Reinforced Concrete

Below-grade rooms

Components of the ISF Structure

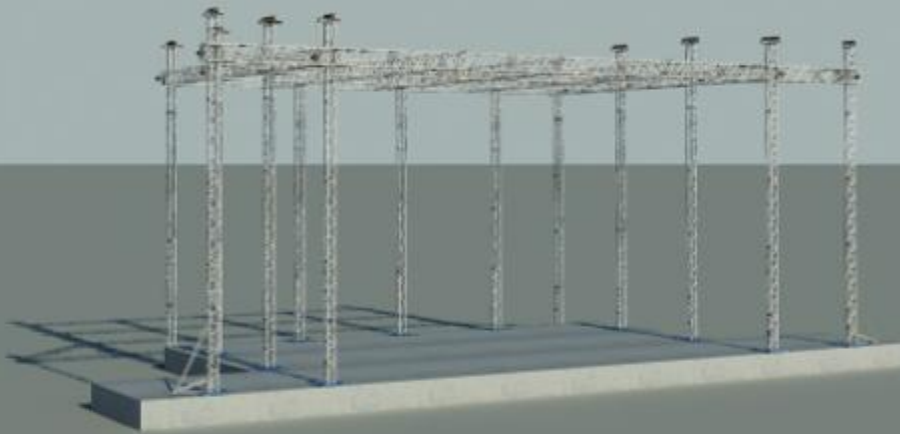


Columns:

10 Primary

3 Supplemental

Components of the ISF Structure



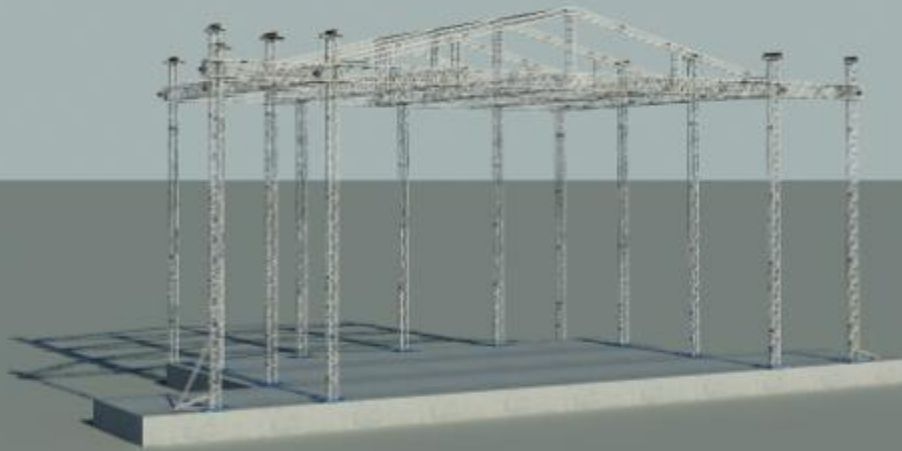
Main Trusses:

2'-6" x 2'-2" box trusses

8' length modules

Includes connective
'Nodes'

Components of the ISF Structure



Gable Roof:

Rafter Trusses

Gable Web Trusses

Ridge Trusses

Components of the ISF Structure



Purlin Trusses

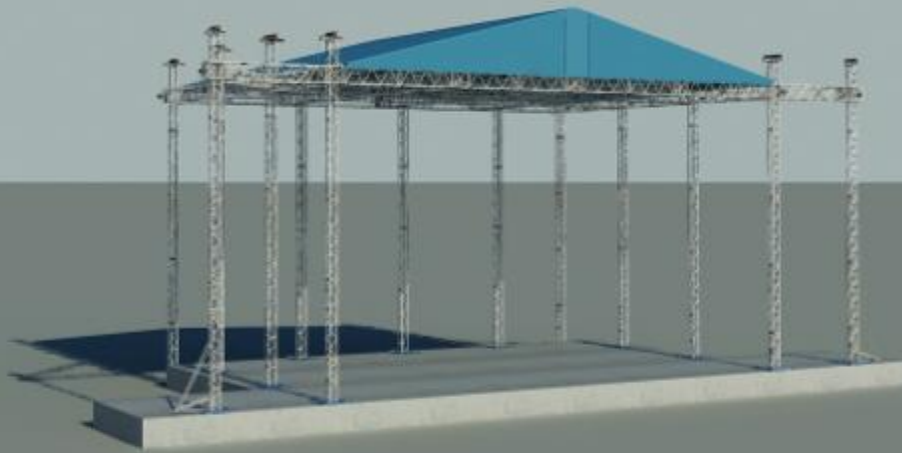
14 Trusses

Lashed to Main Trusses

15" and 20.5" Square

10' Length

Components of the ISF Structure



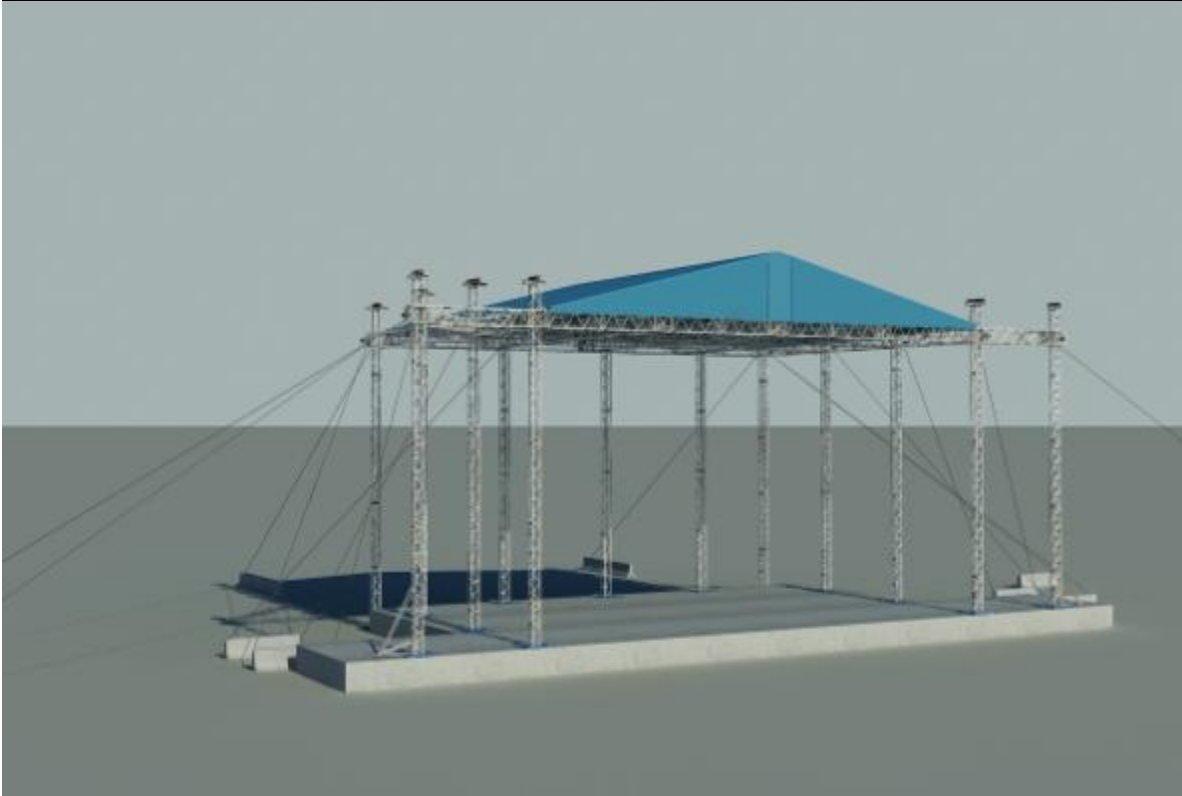
Tarp/Membrane:

3 sections:

East/West/Ridge

Connected at Perimeter

Components of the ISF Structure



Guy Lines/Ballast:

10 Jersey Barriers

14 Guy Lines

Wire Rope

Ratchet Straps

Components of the ISF Structure



PA Wings:

4 Banks of Speakers

Components of the ISF Structure



Entertainment Technology
Equipment:

Sugarland Set:

6 Lighting Trusses
LED Scrim

Components of the ISF Structure



Entertainment Technology
Equipment:

Sugarland Set:

- 6 Lighting Trusses
- LED Screen
- LED Scrim
- Chandeliers
- Vertical Trusses

Components of the ISF Structure

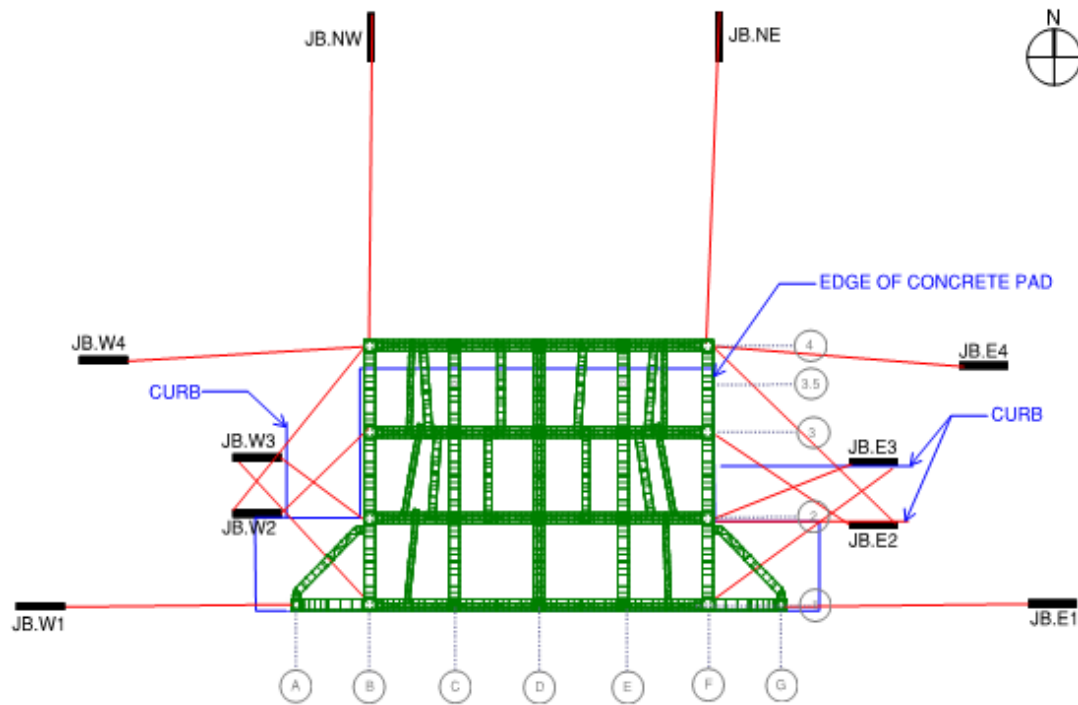


Jersey Barriers (K-Rails):

Reinforced Concrete

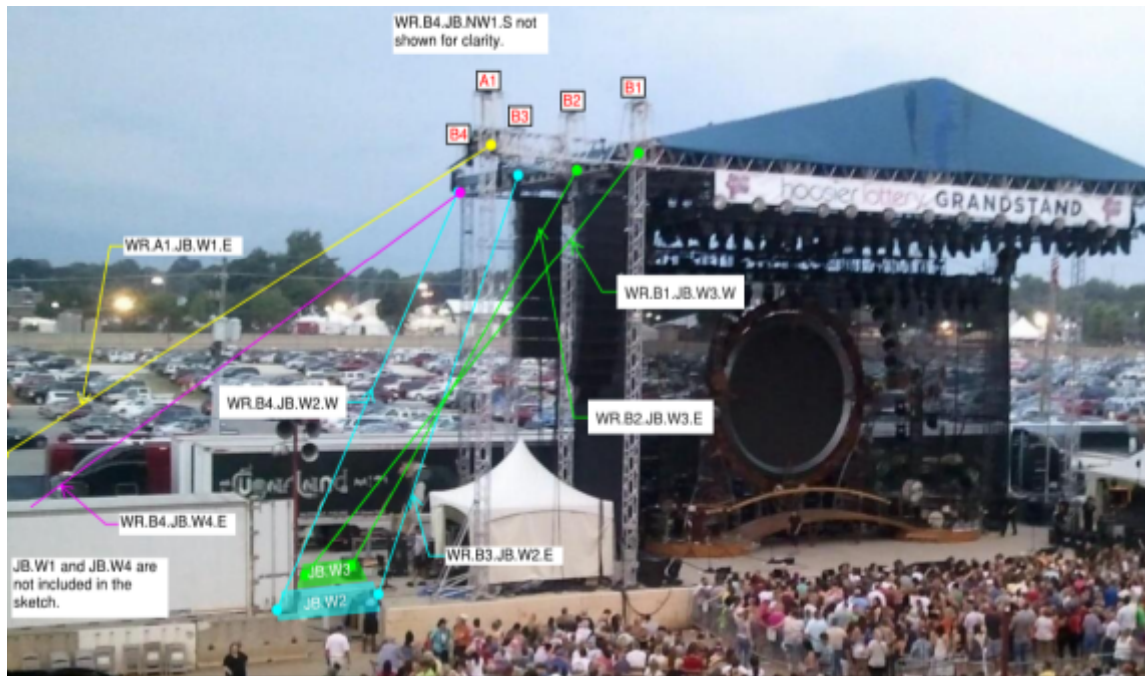
4100 – 4300 pounds

Components of the ISF Structure



Jersey Barriers – Plan View

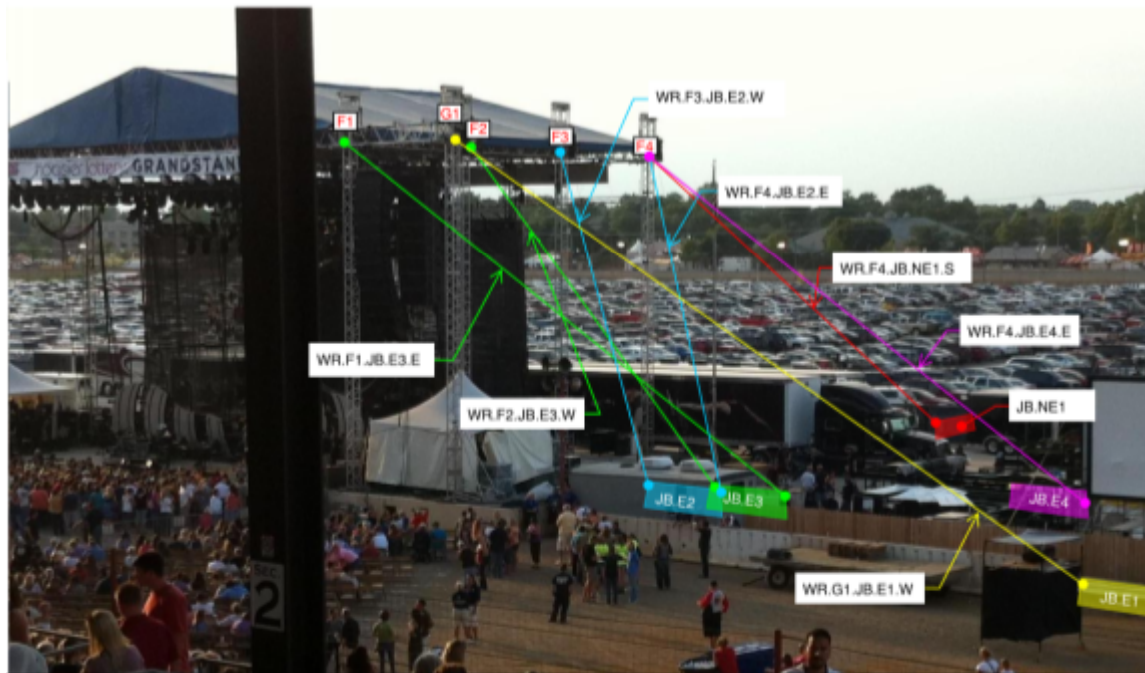
Components of the ISF Structure



Jersey Barriers – West:

4 Barriers

Components of the ISF Structure



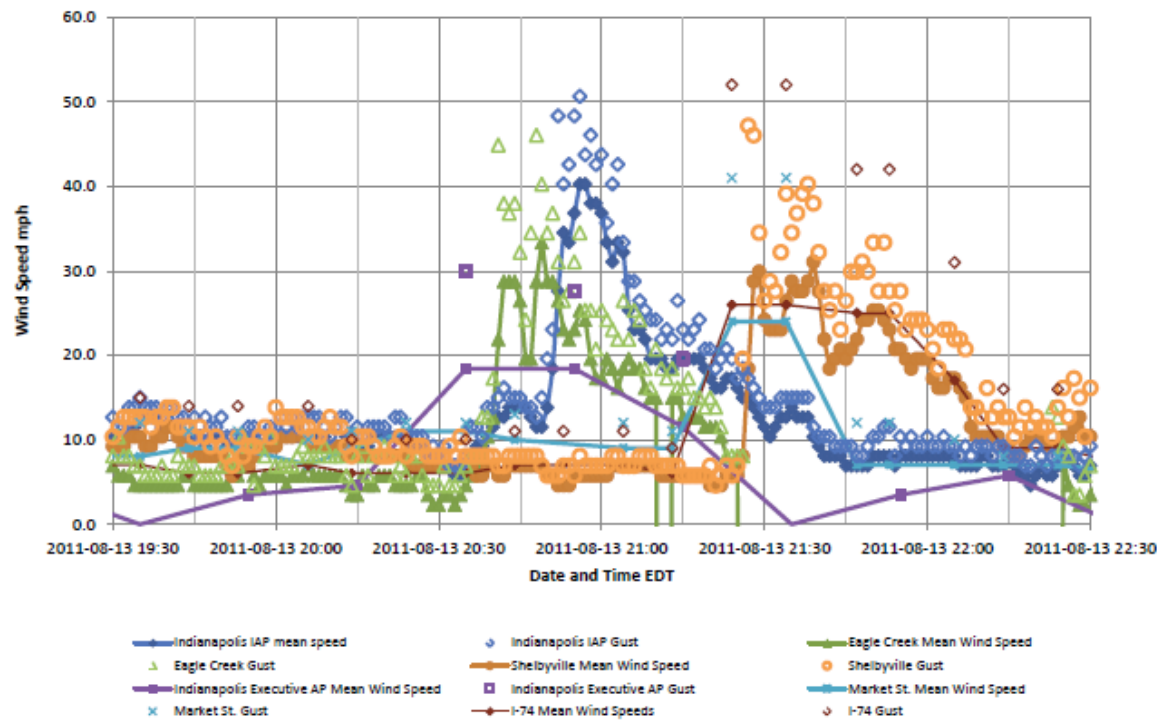
Jersey Barriers – East:

4 Barriers

Analysis



Wind Analysis

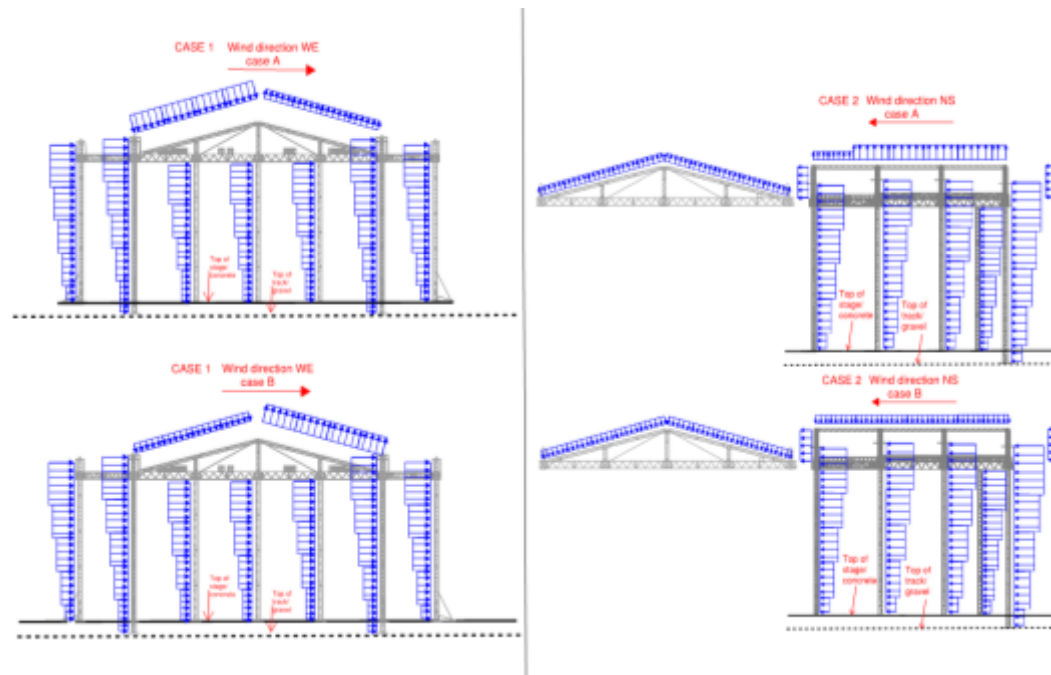


Maximum Gusts:

- > 51 mph
- > 46 mph
- > 30 mph
- > 47 mph
- > 41 mph
- > 52 mph

Data review and analysis for local conditions: 59 mile per hour gust

Wind Analysis



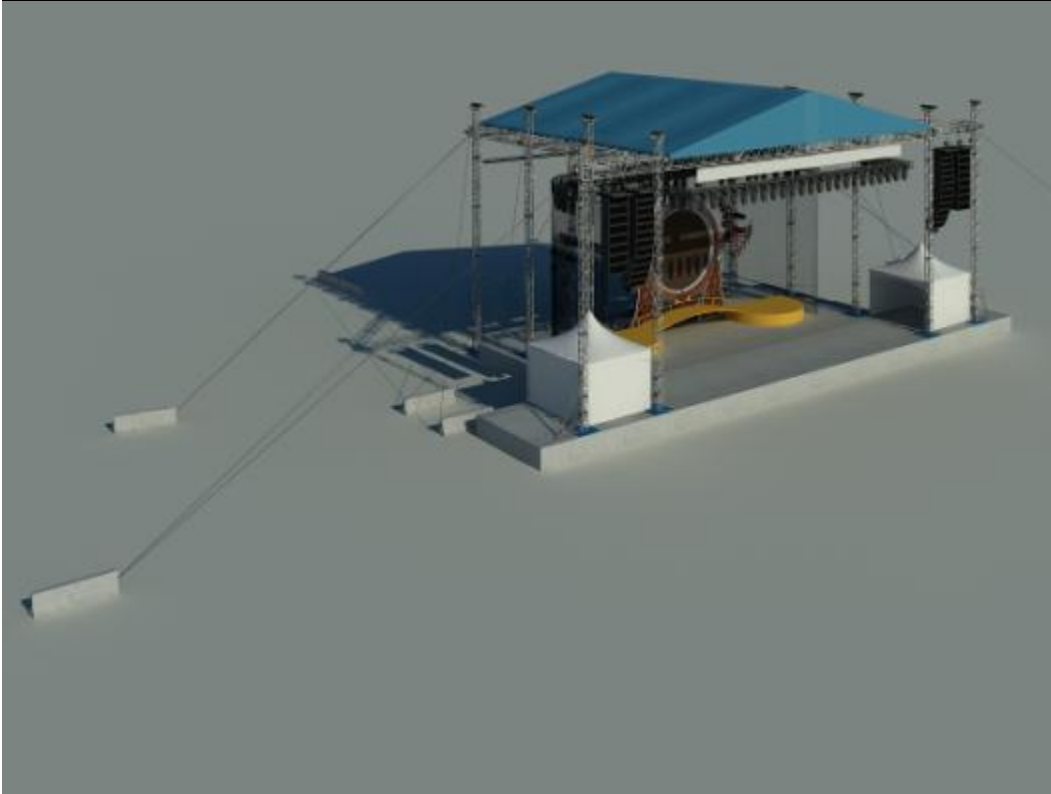
Wind Loading:

West Wind Case

North Wind Case

NW Wind Case

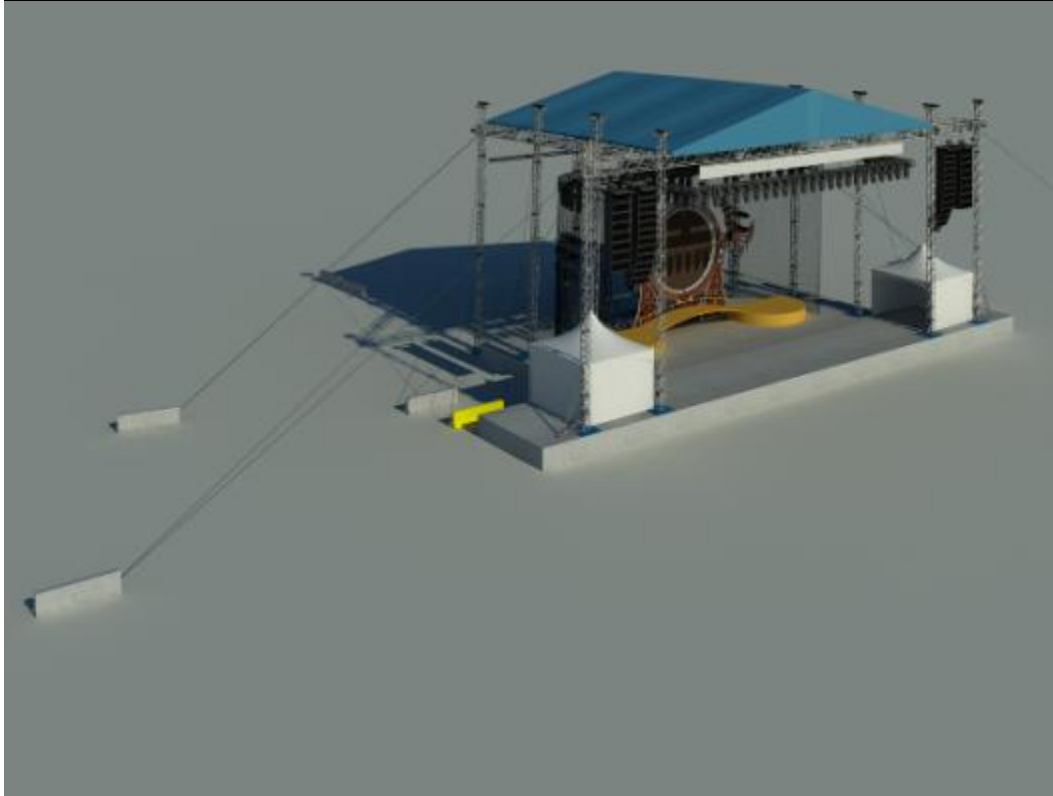
Failure Sequence



ISF Structure as
Erected

Note: Displacements exaggerated for visual clarity

Failure Sequence

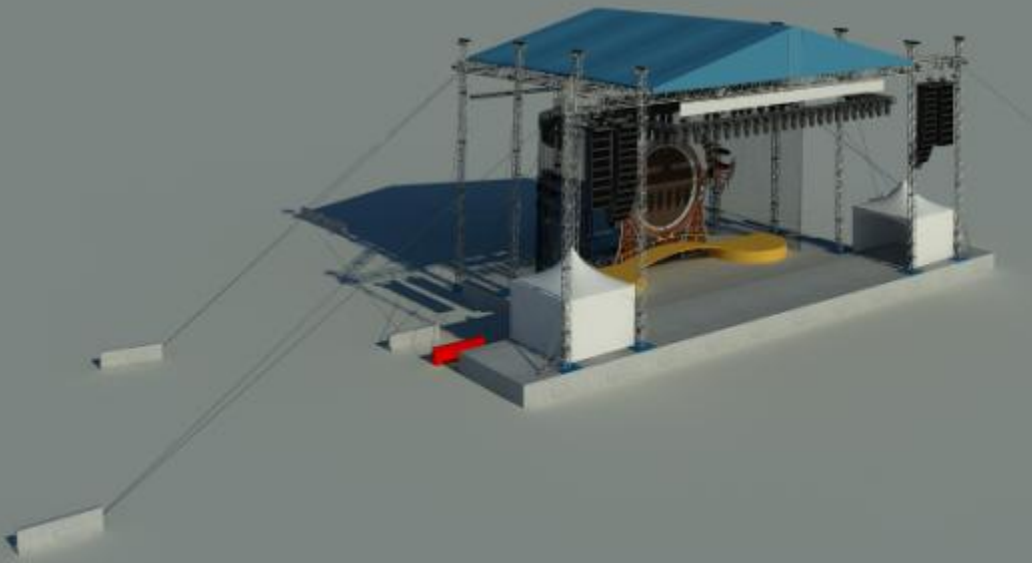


Sequence Step 1:

JBW2 Slides

33 Miles Per Hour

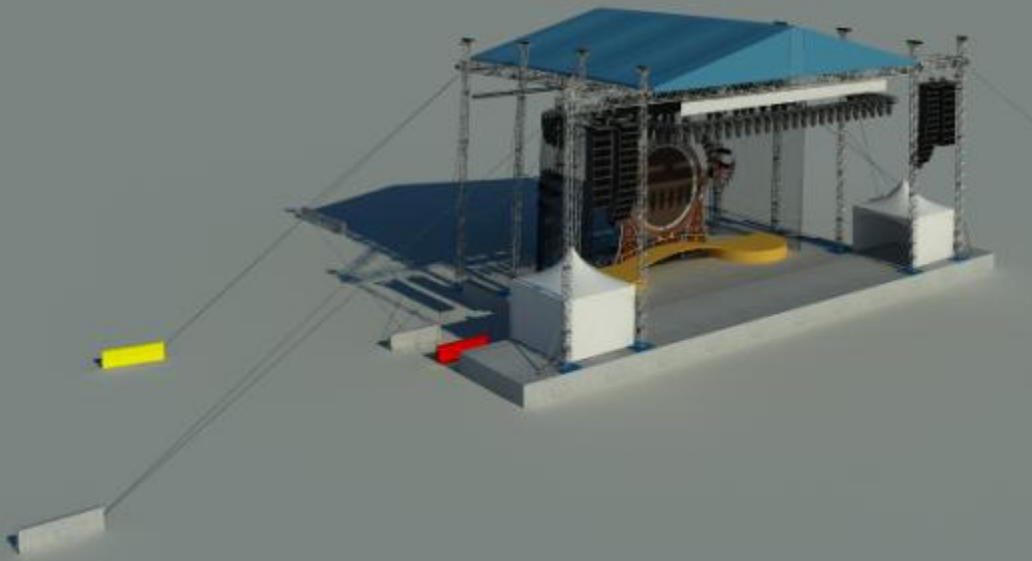
Failure Sequence



Sequence Step 2:

JBW2 Fails

Failure Sequence



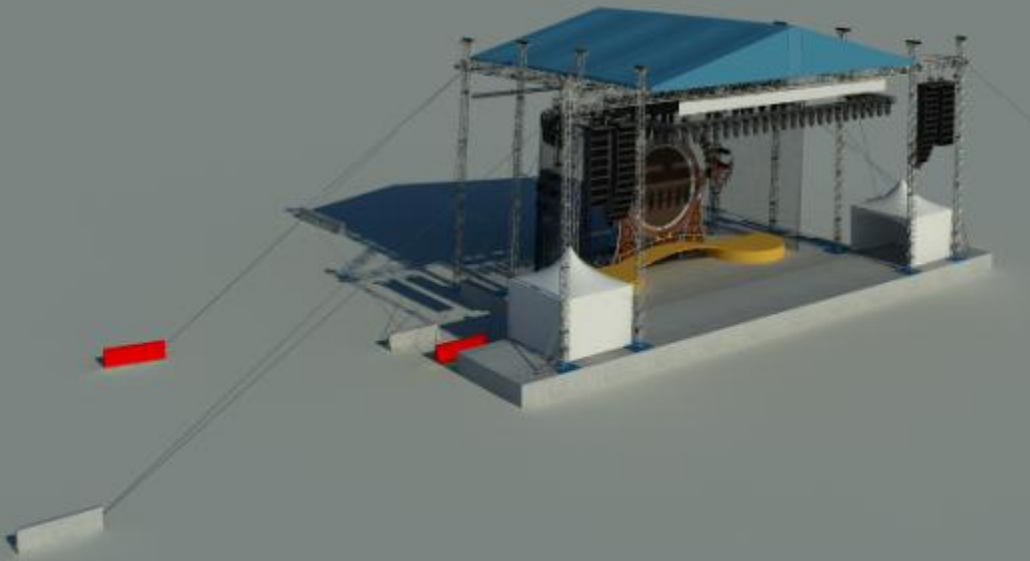
Sequence Step 3:

JBW2 Failed

JBW4 Slides

41 Miles Per Hour

Failure Sequence

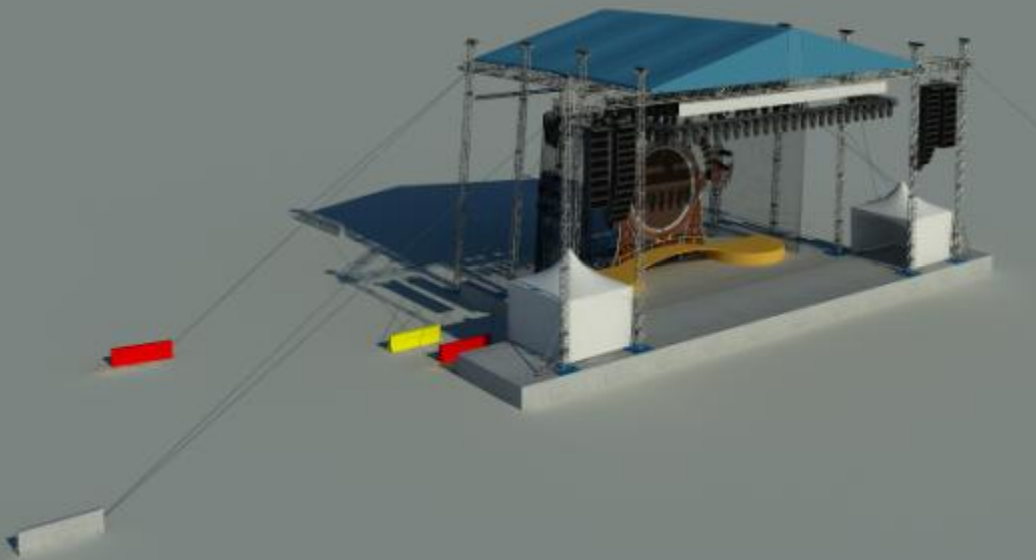


Sequence Step 4:

JBW2 Failed

JBW4 Fails

Failure Sequence



Sequence Step 5:

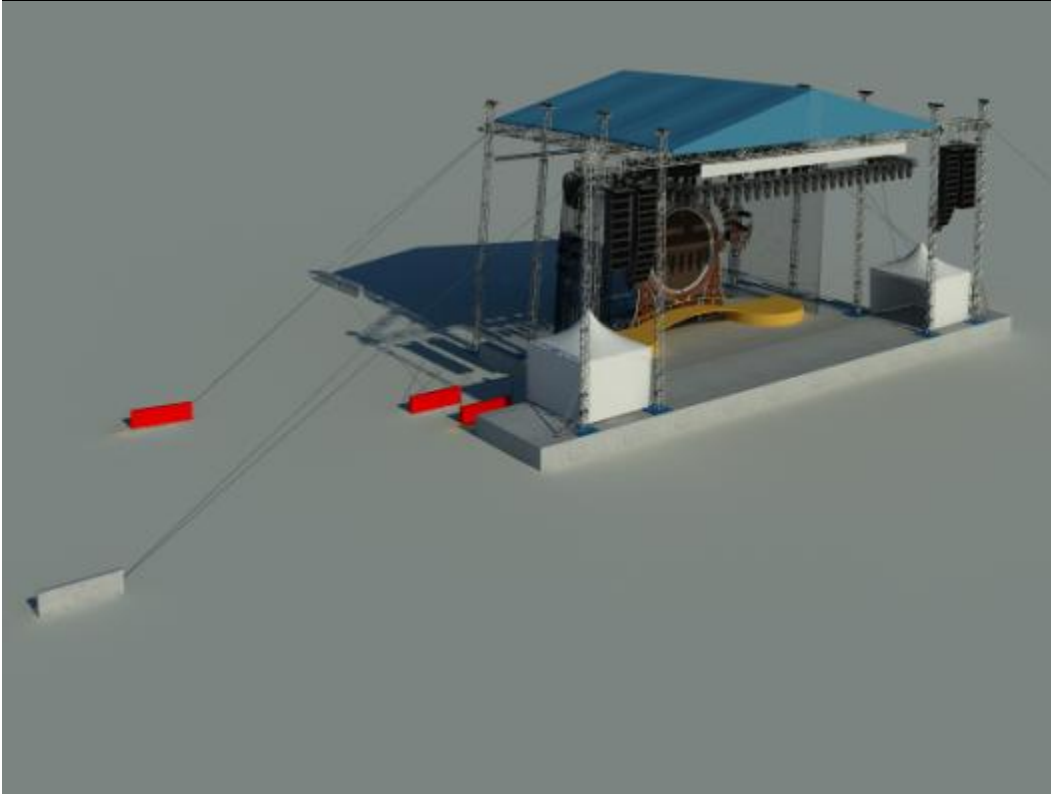
JBW2 Failed

JBW4 Failed

JBW3 Slides

43 Miles Per Hour

Failure Sequence



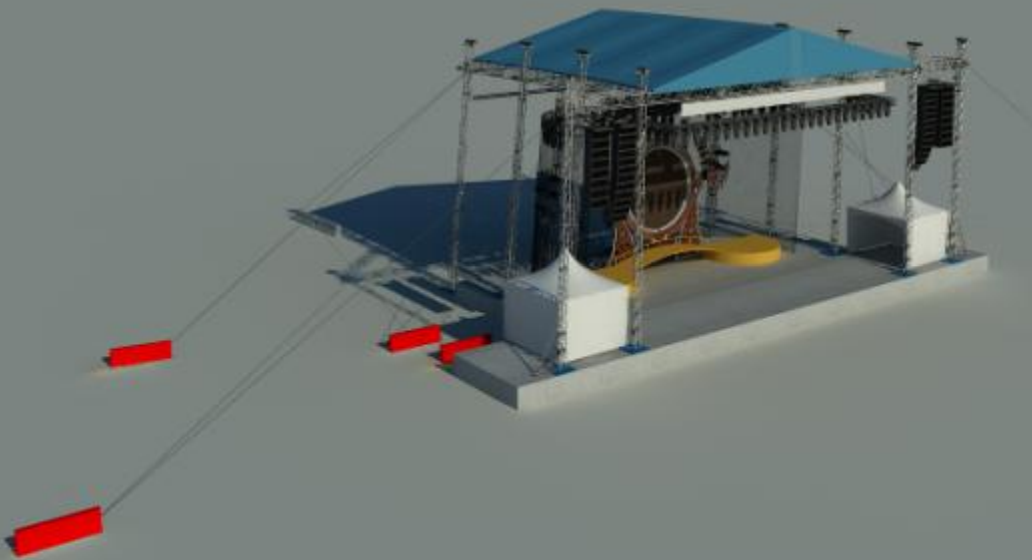
Sequence Step 6:

JBW2 Failed

JBW4 Failed

JBW3 Fails

Failure Sequence



Sequence Step 7:

JBW2 Failed

JBW4 Failed

JBW3 Failed

JBW1 Fails

43 Miles Per Hour

Failure Sequence

Subsequent Failure as a Result of Second Order Effects (P-Delta)

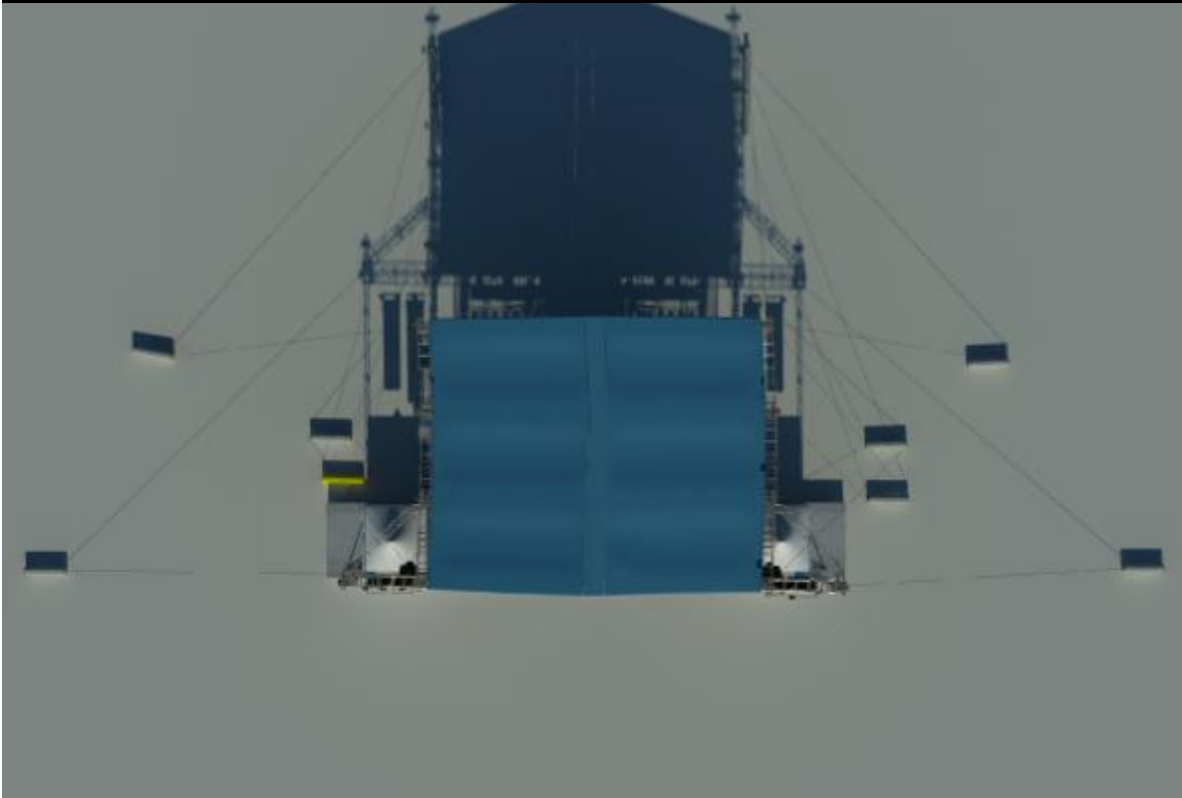
43 Miles Per Hour

Failure Sequence



ISF Structure as
Erected

Failure Sequence

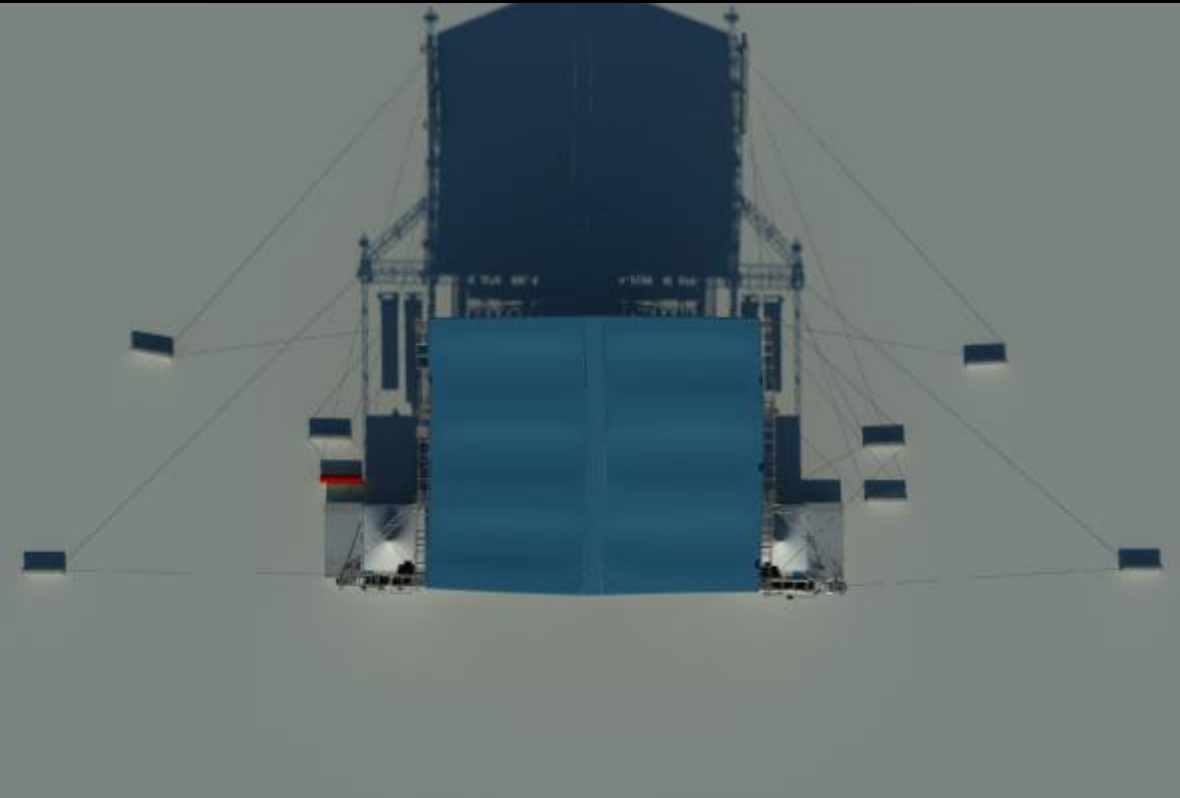


Sequence Step 1:

JBW2 Slides

33 Miles Per Hour

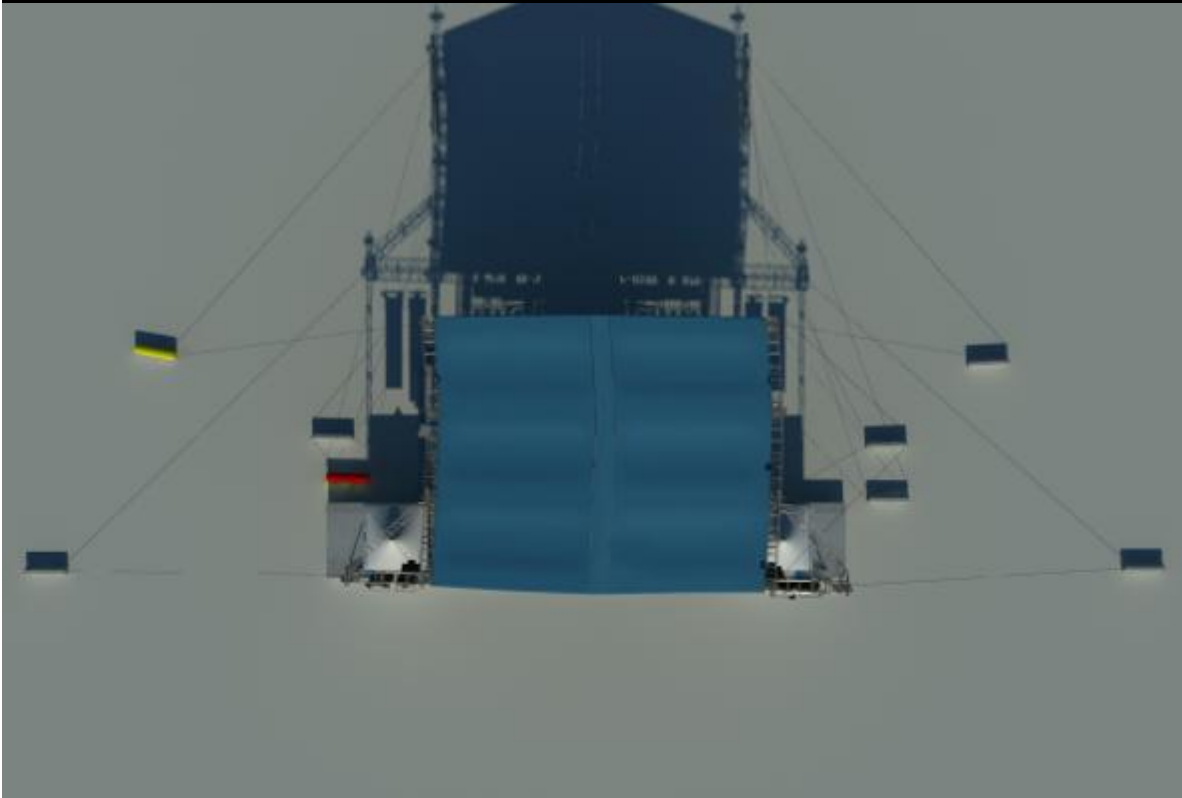
Failure Sequence



Sequence Step 2:

JBW2 Fails

Failure Sequence



Sequence Step 3:

JBW2 Failed

JBW4 Slides

41 Miles Per Hour

Failure Sequence

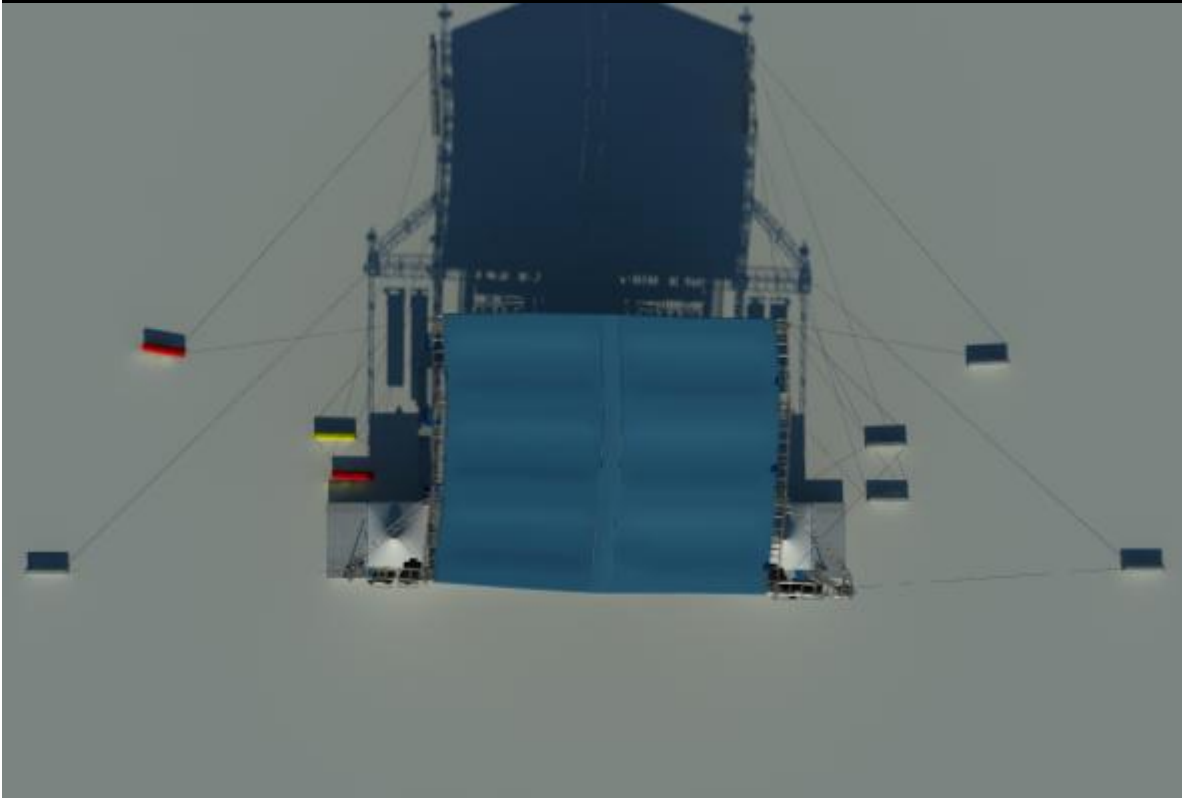


Sequence Step 4:

JBW2 Failed

JBW4 Fails

Failure Sequence



Sequence Step 5:

JBW2 Failed

JBW4 Failed

JBW3 Slides

43 Miles Per Hour

Failure Sequence



Sequence Step 6:

JBW2 Failed

JBW4 Failed

JBW3 Fails

Failure Sequence



Sequence Step 7:

JBW2 Failed

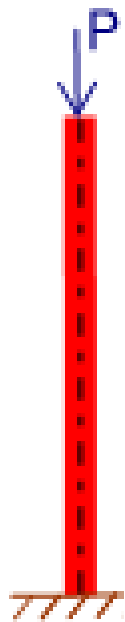
JBW4 Failed

JBW3 Failed

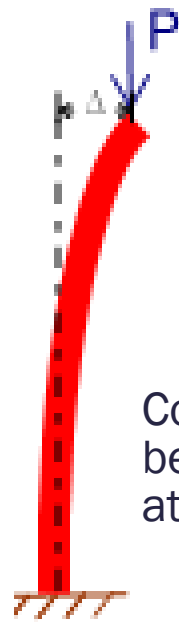
JBW1 Fails

43 Miles Per Hour

Failure Sequence



Column under axial load



Column under axial load with bending due to displacement at top of column

P-Δ (Delta) Effects:

After a defined displacement, the Structure retains no ability to self-support.

Key Findings



Finding #1:

Inadequate Lateral System

- > The ISF Structure failure was due to the inadequate capacity of the lateral load resisting system, which was comprised of guy lines connected to concrete “Jersey barrier” ballast.

Finding #2:

Failure to Meet Code Requirements

- > The ISF Structure was shown to fail at wind speeds lower than those specified under even the most liberal provisions of applicable building codes and reference standards.

Finding #3:

Limited Lateral System Capacity

- > Based on testing and calculation, it was determined the lateral load resisting system of the ISF Structure as rigged on August 13, 2011 was capable of resisting winds speeds ranging from 25 miles per hour to 43 miles per hour (depending on wind direction).

With LED Scrim / LED Screen:

North: 25 mph

Northwest: 28 mph

West: 43 mph

Without LED Scrim / LED Screen:

North: 38 mph

Northwest : 40 mph

West: 53 mph

Note: Winds speeds are at ultimate capacity, not *initial* failure of an element

Finding #4:

Failure to meet Required Lateral System Capacity

- > Calculations and in-situ physical testing determined the Jersey barrier ballast system had grossly inadequate capacity to resist both the minimum code-specified wind speed and the actual wind speed that was present at the time of the failure.

• Full code wind speed (ASCE 7):	90 miles per hour
• Temporary Structure Reduction (ASCE 37):	68 miles per hour
• August 13, 2011 Wind Speed:	59 miles per hour

Finding #5:

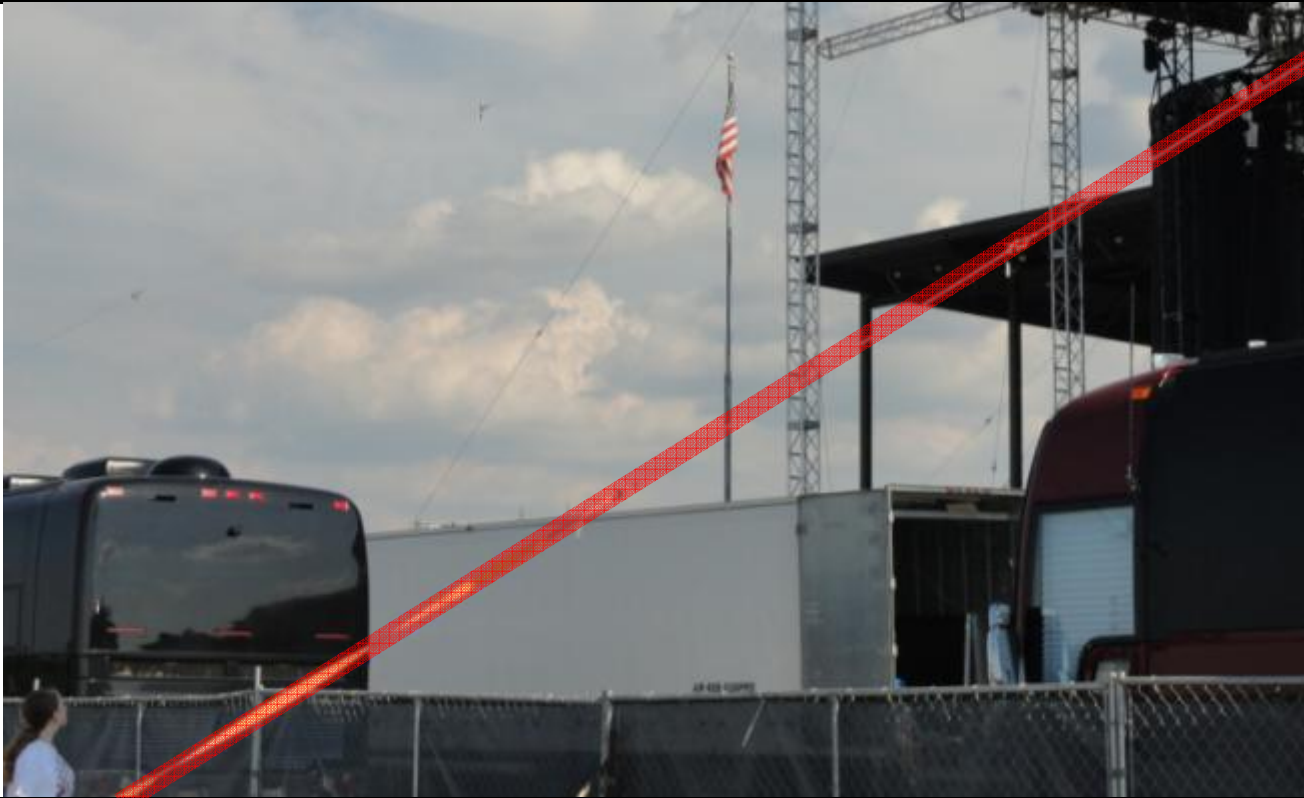
Inadequate Guy Line Capacity

- > Even if the ballast system had provided sufficient resistance, the synthetic webbing ratchet straps and wire rope guy lines used did not have sufficient strength to resist forces resulting from the North wind case under the wind loads of August 13, 2011 that were of a smaller magnitude than the code-specified requirements.
 - At 59 mph:
 - Wire Rope Capacity (13,000 lbs ultimate) exceeded at F4, B4 @ 92%
 - Ratchet Strap Capacity (10,000 lbs ultimate) exceeded at F4, B4
 - For NW wind ratchet strap capacity at F4 exceeded.
 - Note, all values are below the “allowable” capacity of components

Finding #5:

Inadequate Guy Line Capacity

Thornton Tomasetti



Finding #5:

Inadequate Guy Line Capacity



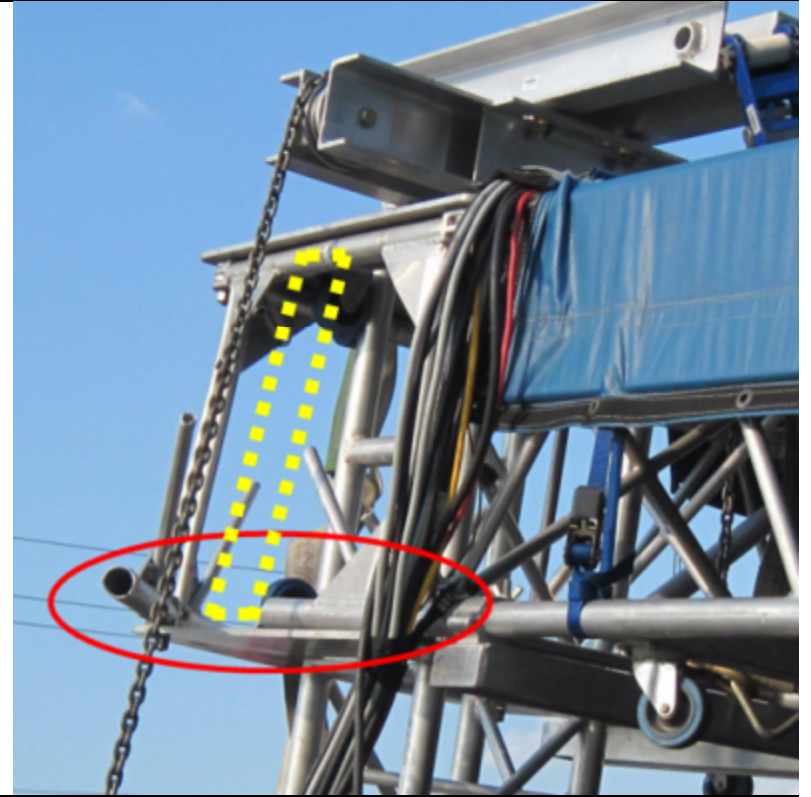
Finding #6:

Inadequate Structure Connection Capacity

- > Even if the ballast system and guy line system had provided sufficient strength to resist the wind loads, the “fin plate” connections to the structure did not have sufficient strength to resist forces resulting from the North, West and Northwest wind cases under the wind loads of August 13, 2011 that were of a smaller magnitude than the code-specified requirements.

Finding #6:

Inadequate Structure Connection Capacity



Finding #6:

Inadequate Structure Connection Capacity

- > Even if the ballast system and guy line system had provided sufficient strength to resist the wind loads, the “fin plate” connections to the structure did not have sufficient strength...

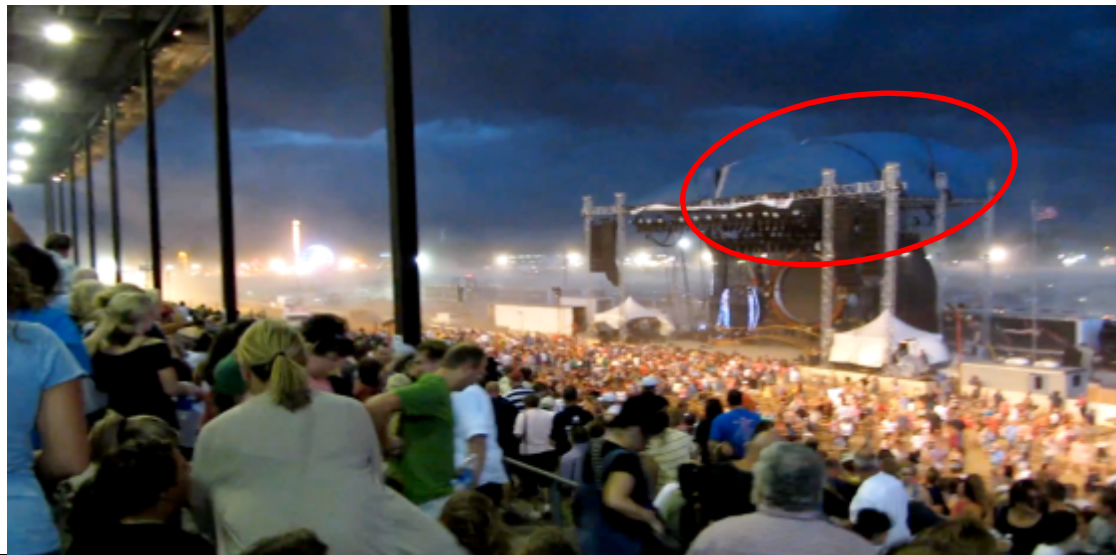
Load Case	Node	DCR	Node	DCR	Node	DCR	Node	DCR
North Case A	F2	1.53	B4-N	1.23	F4-N	1.66		
North Case B	B2	1.15	F2	1.7	B4-N	1.31	F4-N	1.81
West Case A	B4-W	2.66	B3	1.23	B2	1.02		
West Case B	B4-W	2.5	B3	1.13				
Northwest Case A	B4 -W	2.57	B2	1.5	B4 -N	2.25	F4-N	3.28
Northwest Case B	B4 -W	2.47	B2	1.22	B4-N	2.15	F4-N	3.14

Table 2: Demand-capacity ratios (DCR) of fin plates under 59 mph wind load cases

Finding #7:

Roof Tarp Did Not Cause Failure

- > The ISF Structure was shown to fail at the August 13, 2011 wind speed without the addition of loading caused by the roof tarp displacement.



Finding #8:

Roof Ridge Panel Release Was Insignificant

- > Timing of the roof tarp ridge panel release would not have had an effect on maintaining stability of the ISF Structure.



Finding #9:

Unclear Intent of Catalog Data

- > The technical information presented in the James Thomas Engineering catalog is insufficient to adequately design a structure such as the ISF Structure, yet there is no explicit direction to engage the services of a licensed design professional to analyze complex loading configurations or conditions.

Finding #10:

Inadequate Engineering Review by Manufacturer

- > Structural analysis performed by James Thomas Engineering's structural engineer falls short of adequately addressing the actual loading conditions of the Sugarland set and suspended entertainment technology equipment for the 2010 show (for which the structure was analyzed) or the code-defined environmental loading conditions to which the ISF Structure could be subjected.
 - No review of wind load on LED scrim or LED screen.
 - Improper use of code provisions for Pressure Coefficients, Uplift.
 - No defined load path for lateral system (ballast or ground anchor).
 - Unrealistic contingency plans (lowering of grid).

Finding #11:

Lack of Engineering Review in 2011

- > There is no evidence of an engineering review of the “2011 Sugarland Rigging Plot” by a licensed design professional prior to August 13, 2011.

Finding #12:

Non-compliant Installation

- > Regardless of the inadequacy of the directions of James Thomas Engineering's structural engineer, Mid America Sound Corporation's installation of the ISF Structure deviated from the directions provided in the calculations performed by that structural engineer with regard to the lateral load resisting system.
 - 1/2" Diameter Wire Rope Guy Lines
 - Braced at 4 corners, at 45 degrees in plan
 - Supplemental Columns – various configurations

Finding #13:

No Engineering Review of Installation

- > Mid America Sound Corporation's configuration and erection of the ISF Structure did not include a review by a licensed design professional to determine the capacities or limitations of the ISF Structure.

Finding #14:

State Code Exemptions

- > The current interpretation of governing code language in the State of Indiana waives requirements for the appropriate design, review, permitting or inspection of structures such as the ISF Structure, despite the fact that these are highly complex constructions erected in the vicinity of high population densities.

Finding #15:

Lack of On-site Technical Information

- > The Indiana State Fair Commission staff has no records, documentation, plans, engineering reports or related technical data regarding the ISF Structure that is erected at the Fairgrounds on an annual basis.

Finding #16:

Lack of On-site Technical Knowledge

- > The Indiana State Fair Commission staff does not have knowledge regarding the wind limitations of the ISF Structure sufficient to establish an appropriate risk mitigation plan for the Grandstand Stage site.

Key Recommendations



Recommendation #1:

Design by Licensed Design Professional

- > Entertainment structures should be designed by a licensed design professional with experience in the design and evaluation of temporary entertainment structures with complex loading configurations. Analysis should be performed for the engineered structure and for the establishment of highly specific rigging rules and limitations for its use. For productions that do not conform to the resulting “pre-approved” rigging configurations, a separate engineering analysis should be performed.

Recommendation #2a:

Code & Permitting as Class 1 Structures

- > The design referenced above should be subject to all code and permitting requirements of Class 1 structures...

IC 22-12-1-4

"Class 1 structure"

Sec. 4. (a) "Class 1 structure" means any part of the following:

(1) A building or structure that is intended to be or is occupied or otherwise used in any part by any of the following:

(A) The public.

(B) Three (3) or more tenants.

(C) One (1) or more persons who act as the employees of another.

Recommendation #2b:

Code & Permitting as Class 1 Structures

- > ...in addition to a third-party peer review if the authority having jurisdiction (AHJ) does not have adequate capability to perform the plan review...

Recommendation #2c:

Code & Permitting as Class 1 Structures

- > ...This review should be performed for the engineered structure and for the established rigging rules and limitations for its use. For productions that do not conform to the “pre-approved” rigging configurations, a separate review should be performed.

Recommendation #3:

Inspection of Erected Structure

- > A Special Inspection of the completed structure should be completed by an independent licensed design professional with experience in the design and/or evaluation of temporary structures.

Recommendation #4:

Realistic Operational Limitations & Controls

- > Operational controls implemented or considered in the design and use of entertainment structures should reflect the complexity of modern productions, including the limited ability to rapidly reduce loads by removing the suspended entertainment technology used in these productions. Systems should be designed for the appropriate code-prescribed wind speeds, and operational contingency plans should also be developed to address extreme events such as high winds.

Recommendation #5:

Site-Specific Design

- > Environmental and site-specific loading conditions should be analyzed for the specific structure to be erected and the suspended entertainment technology equipment to be suspended.
 - Based on the full details of proposed Entertainment Technology Eqpt.
 - Based on the restrictions of the site (anchor locations, obstructions, etc.)

Recommendation #6:

Appropriate Code-Based Classification

- > Structure Class and Occupancy classifications of entertainment structures should be based on both the risk and hazards associated with their failure and on their cumulative exposure to risk from wind loads and varying rigging loads, rather than their exposure in an individual season of use.
 - Balance of statistical risk of recurrence intervals and actual time
 - Occupancy based on number of persons adjacent to structure, not just those that are 'within' the structure.

Recommendation #7:

Appropriate Local Code Amendments

- > Modifications to model codes and reference standards should not alter the intent of the original code language with regard to life-safety, nor should local amendments partially delete model provisions that are not properly addressed elsewhere in those local amendments.

BUILDING CODES

*Indicates those counties with extreme variation and shall require investigation by the design professional, or owner when a design professional is not required, to determine the actual minimum ground snow load at each site; however, the determined minimum snow load (p_g) shall be at least thirty (30) pounds per square foot. Ground snow load determination for such counties shall be based on an extreme value statistical analysis of data available in the vicinity of the site using a value with a two percent annual probability of being exceeded (50-year mean recurrence interval).

3. Foundation is the minimum foundation depth to bottom of footing from the top of the grade above the footing in inches.

(8) Amend Section 1609.1.1, Determination of wind loads, by deleting the text and substituting to read as follows: Wind loads on every building or structure shall be determined in accordance with Table 1608.2.

(9) Delete Section 1609.1.2, Protection of openings, without substitution.

675 IAC 13-2.5-17: Note 8 deletes Section 1609.1.1 of IBC-2006

Recommendation #8:

Require Mechanical Anchors for Guy Lines

- > Guy line anchor systems for entertainment structures should utilize fixed, mechanical anchors whenever possible.

Recommendation #9:

Engineering-Based Design Guide

- > The entertainment industry would benefit from the development of comprehensive engineering-based documents related to the design, construction and use of entertainment structures.

Thornton Tomasetti

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