JPEE 2022

Lisboa • LNEC • 9 a 11 de novembro de 2022

6as Jornadas Portuguesas de Engenharia de Estruturas
Encontro Nacional de Betão Estrutural 2022
12º Congresso Nacional de Sismologia e Engenharia Sísmica

LABORATÓRIO NACIONAL DE ENGENHARIA CIVIL

APEE Associação Portuguesa de Engenharia de Estruturas

GPBE Grupo Português de Betão Estrutural

SOCIEDADE PORTUGUESA DE ENGENHARIA SÍSMICA

TAGUS RIVER BRIDGE STRINGER BEARING REPLACEMENT AND STRUCTURAL STRENGTHENING

Tom Spoth, PE - PARSONS

Outline

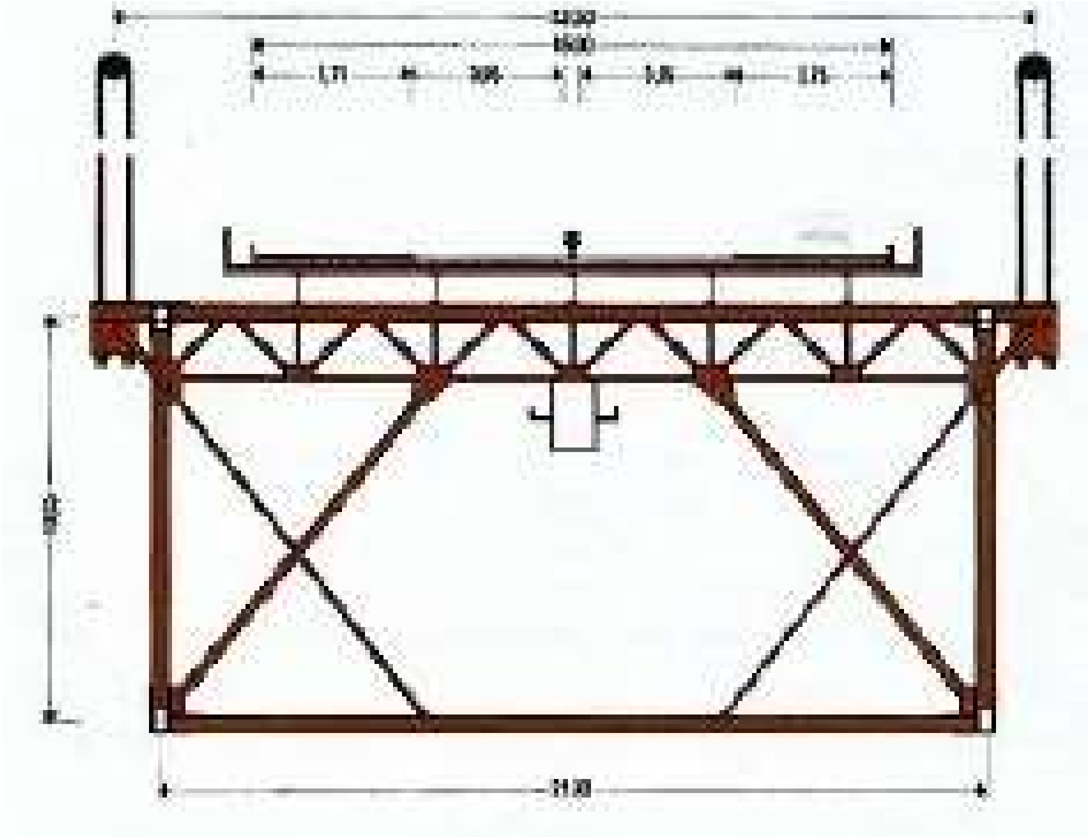
- Brief History of Bridge Modifications
- Background
- Study of Existing Conditions
- Similar Bridges, Similar Problems
- Final Design Solution
- Conclusion

Brief History of Bridge Modifications

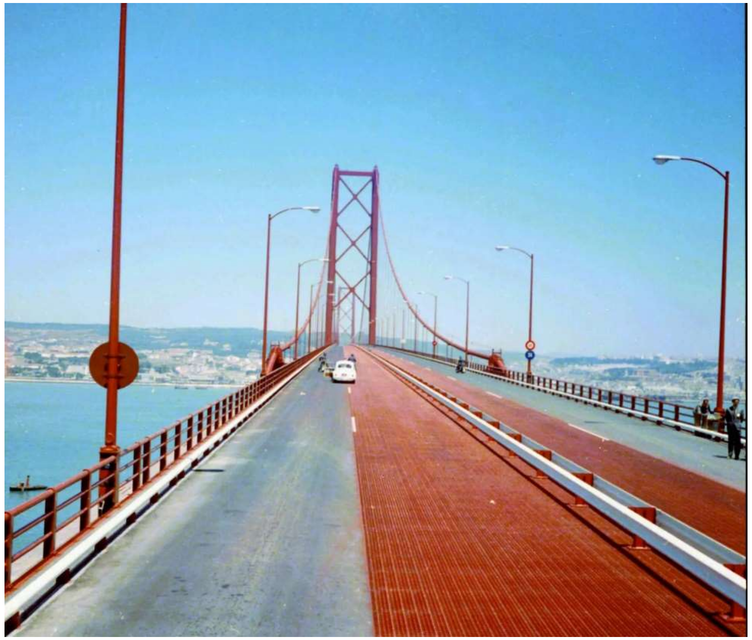
Original Construction

- Year Built:
  - 1966 by American Bridge Division of U.S. Steel Corporation based. on Design Engineer: Steinman, Boynton Gronquist and London.
- Notables:
  - Main span: 1,013m
  - Second longest span designed for rail loading
  - Total length between anchorages: 2,278m
  - World's longest continuous truss
  - World's deepest bridge foundation: South Tower caisson 83m below water level

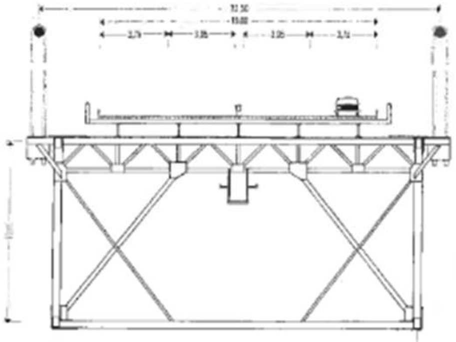
Original Cross section (1969-1990)

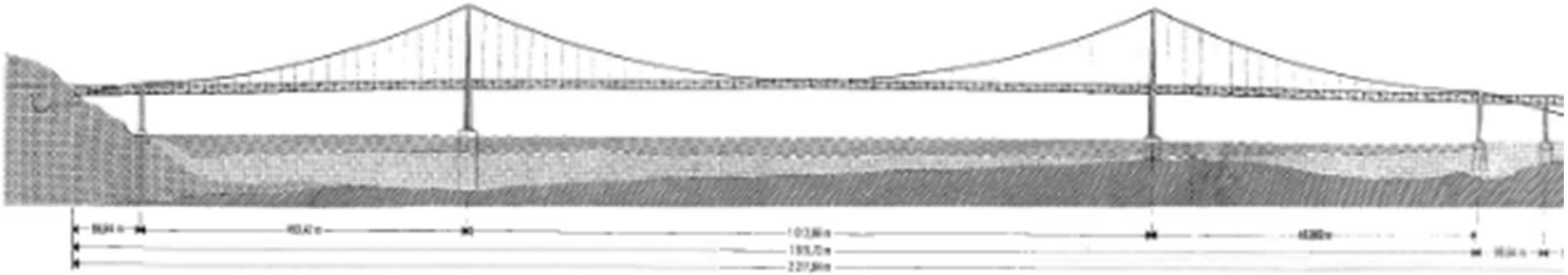


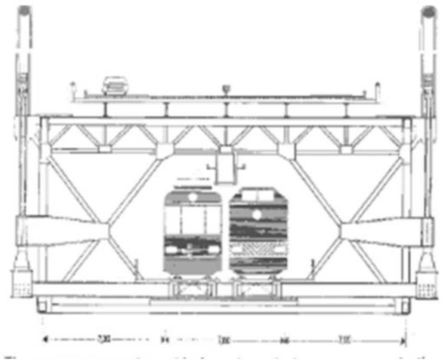
- 4 Vehicular Traffic Lanes
- Lower Lateral Bracing
- Suspenders at Even Number Panel Points

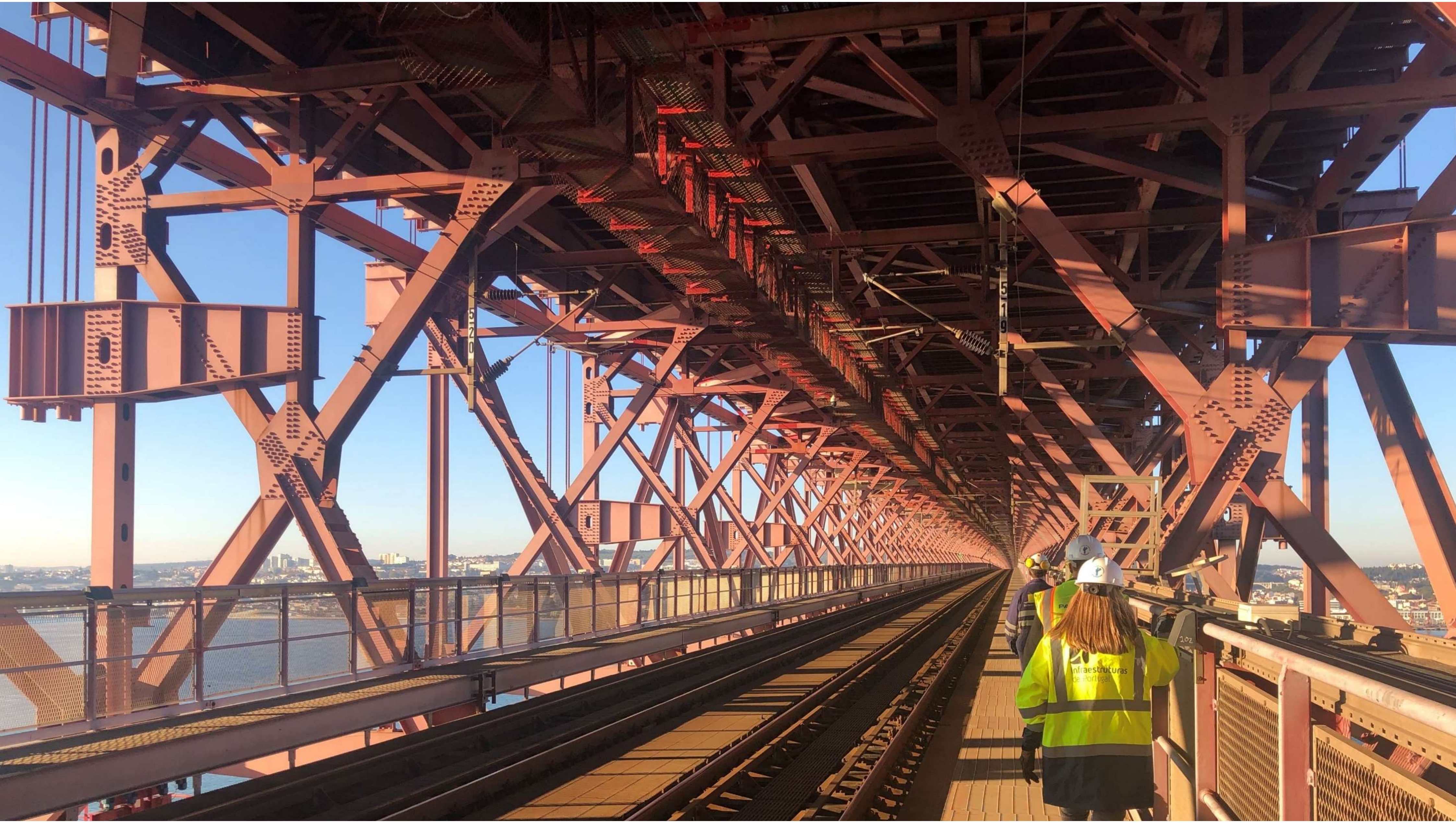


Original Plan to Accommodate Future Transit

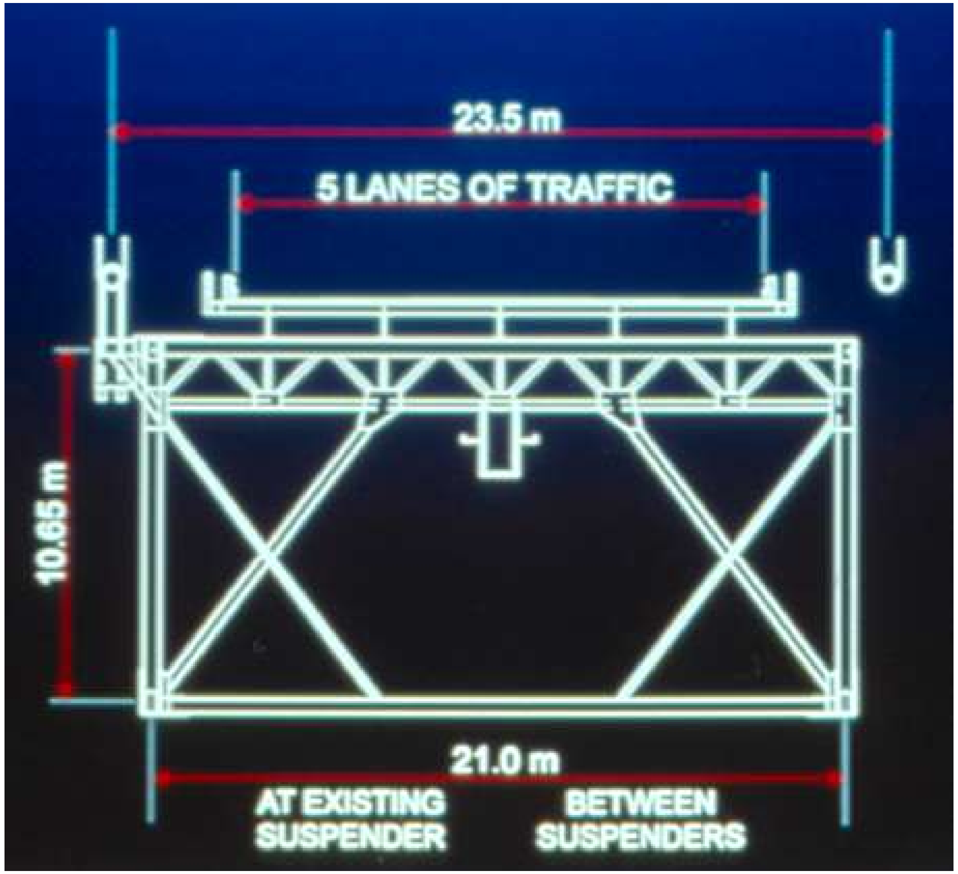






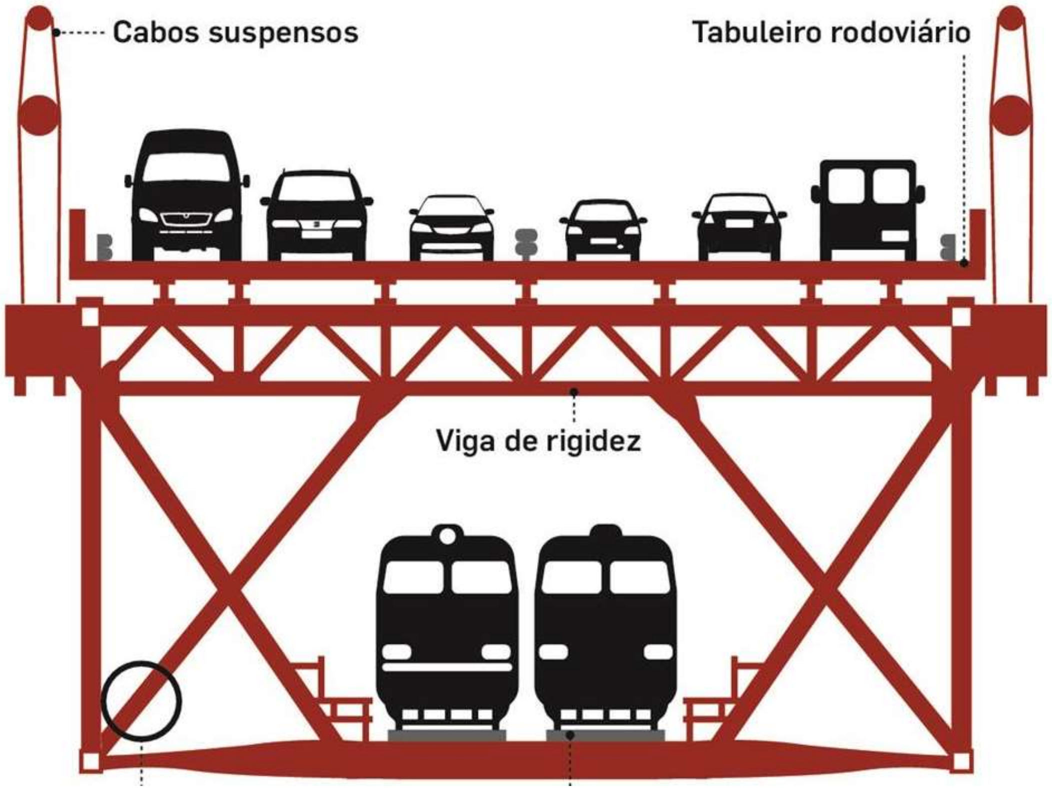

Infraestruturas
de Portugal

1990-1998 Cross section with Modified Roadway



4 Lanes + 1 Central Bi-Directional Lane

1999 Construction of Lower Rail Deck



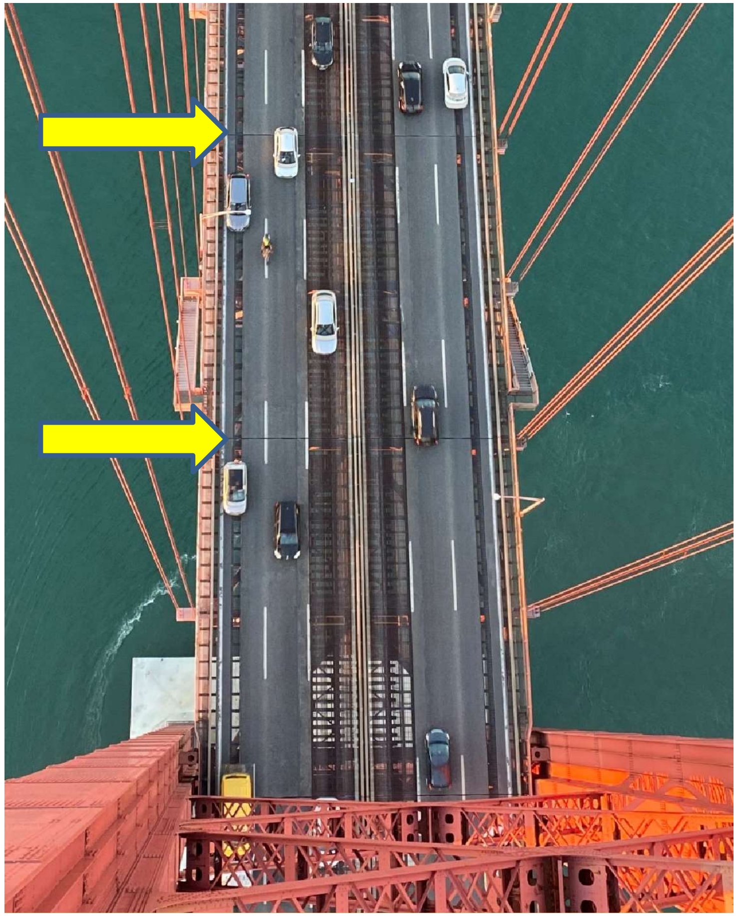
- Expand upper deck from 5 lanes to 6
- Convert lower level to two-lines of rail
- Add secondary suspension system including new anchorages

Expansion to 6 lanes


fertagus
fertagus
5

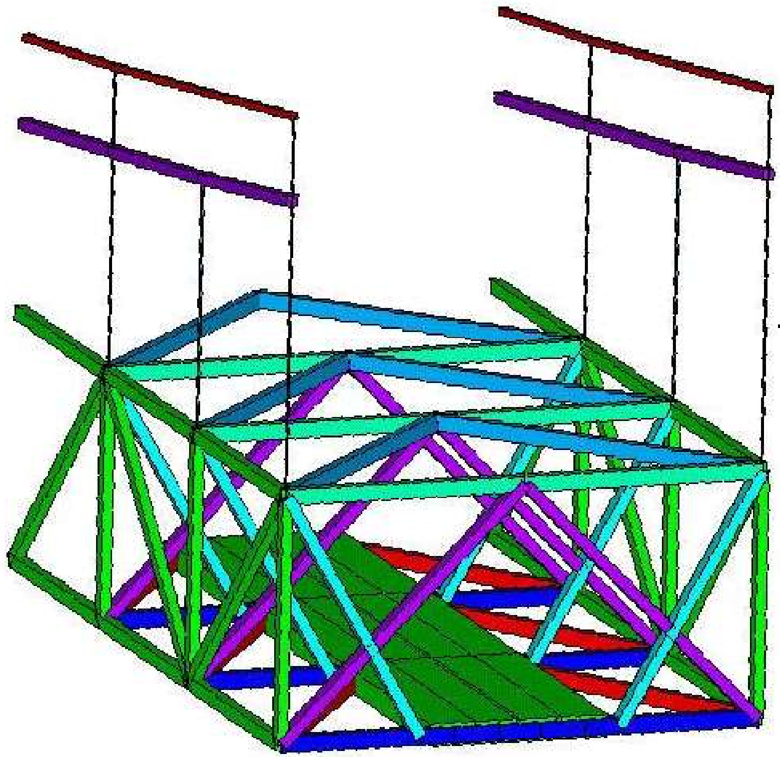
Background

Global and Local Element Structural System

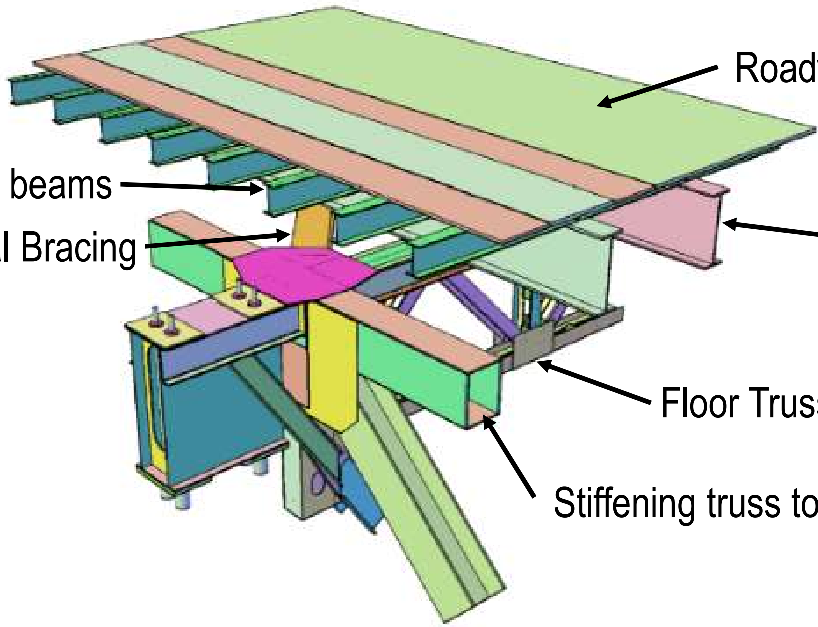


- Classic truss-stiffened suspension bridge
- Stringer-crossbeam deck framing
- Relief joints at even numbered panel points
- Stringer bearings on floor trusses at relief joints

Global and Local Element Structural System

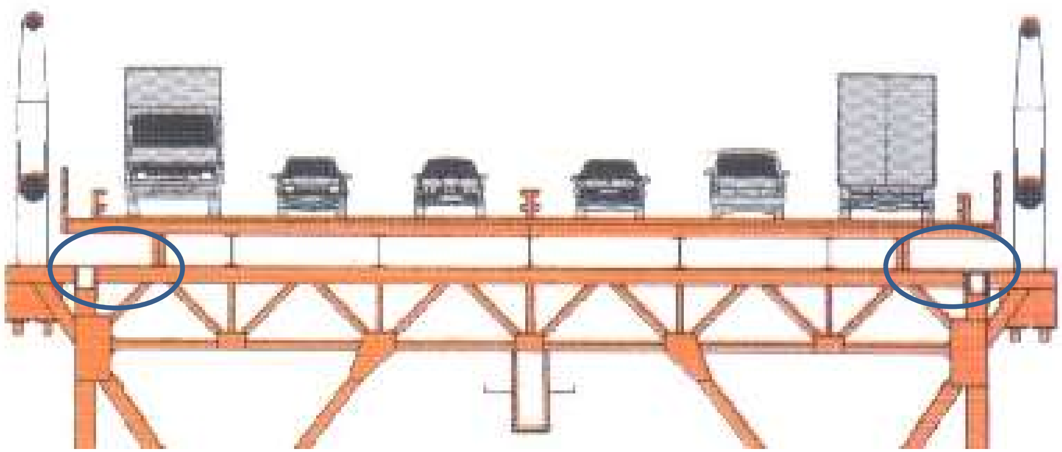


Stiffening Truss Framing



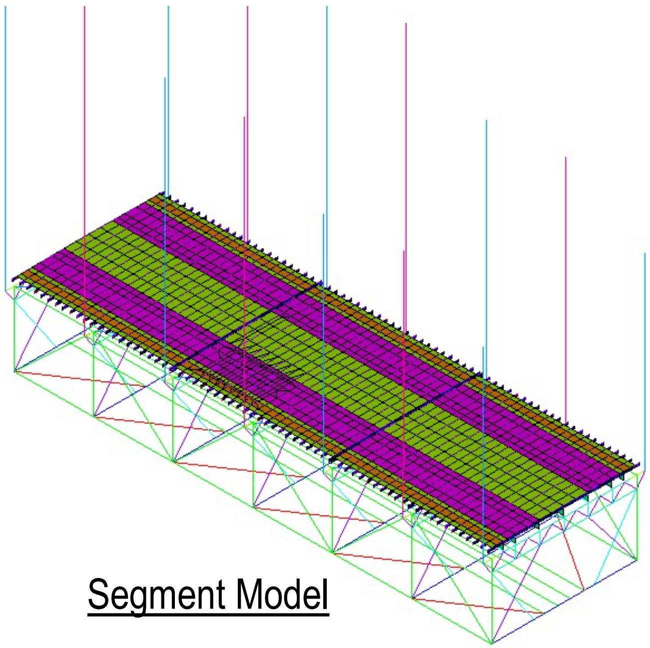
Framing at Even Number Panel Points

Floor Truss Cracking

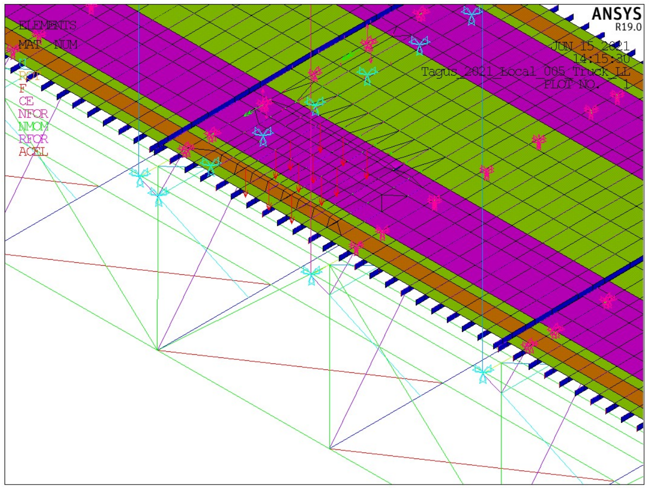


Study of Existing Conditions

Computer Modeling and Structural Strengthening Design

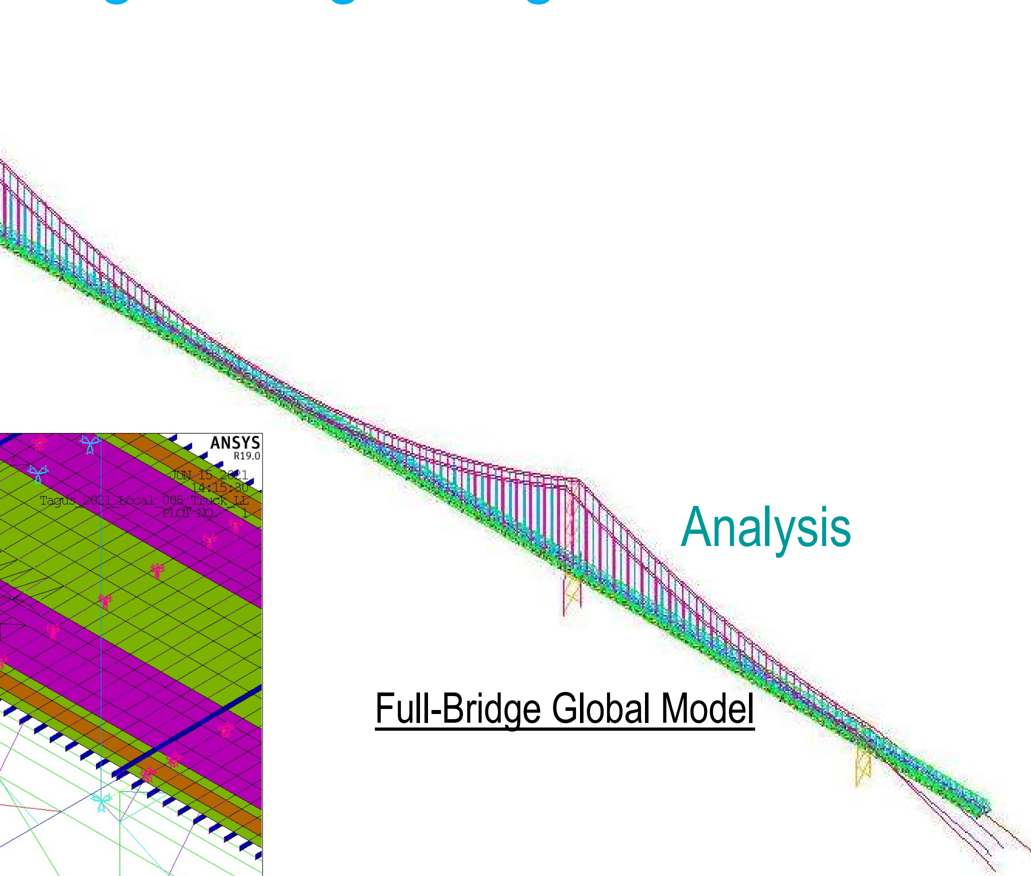


Segment Model



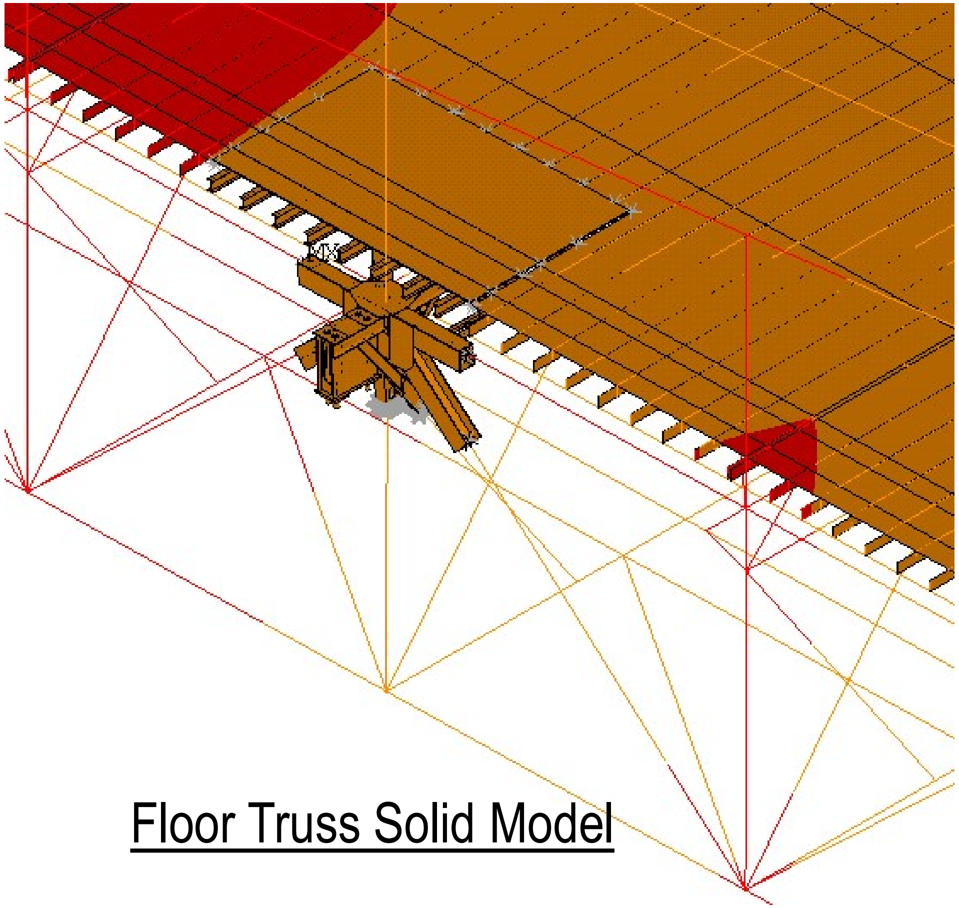
Detail of Segment Model at Relief Joints

Analysis

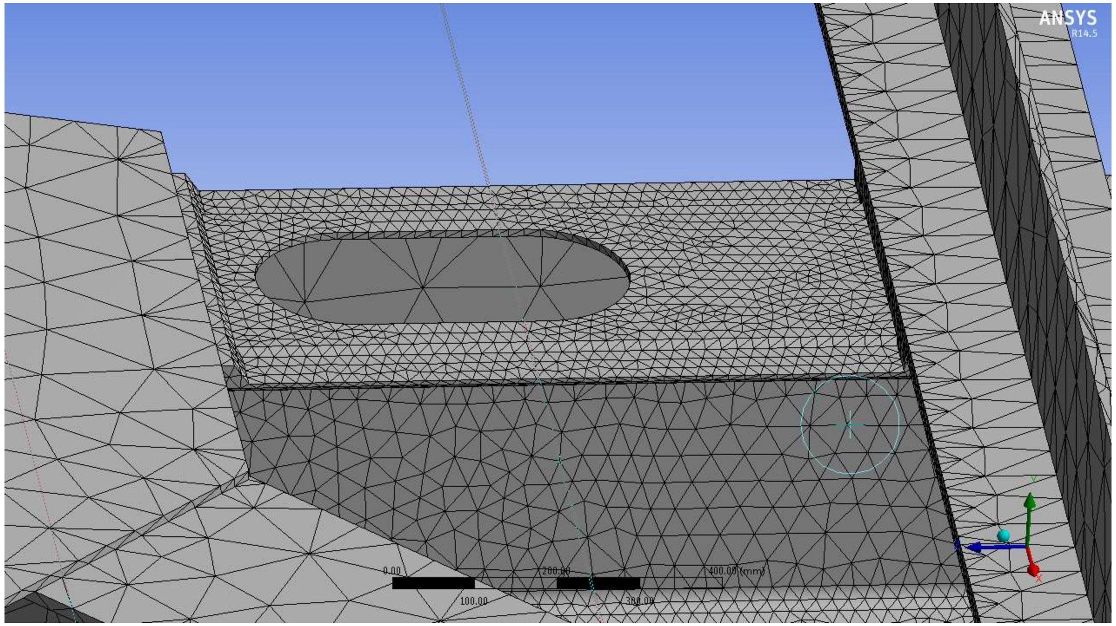


Full-Bridge Global Model

Analysis

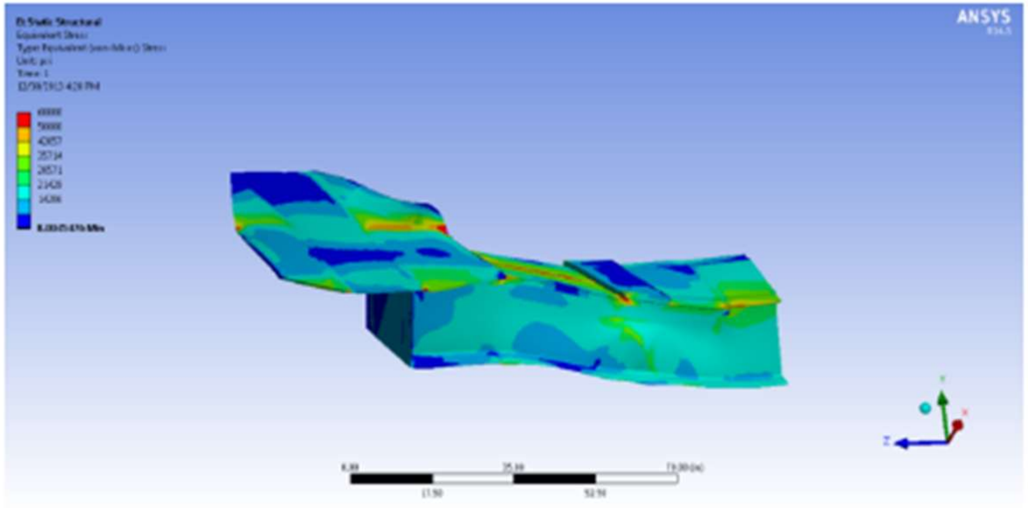


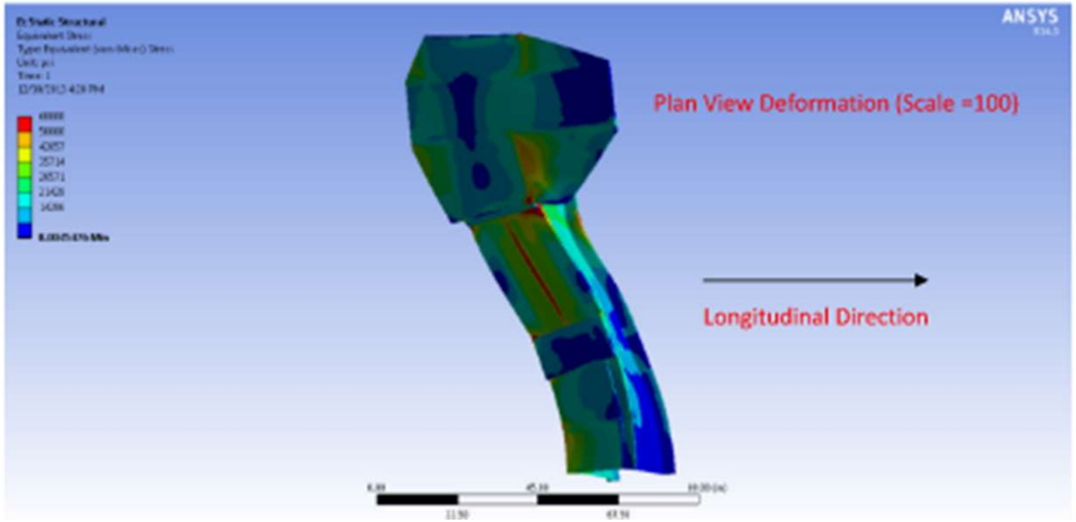
Floor Truss Solid Model



Solid model fine mesh near the floor truss chord hand hole cut-out

Local Stress Condition at Floor Truss Hand-Hole Cut-Out





As-Designed	My= 13 KN-m (9.80 kip-ft) σ_t = 6.3 MPa (0.91 ksi)	Mz= -15 KN-m (-11.08 kip-ft) σ_c = −39 MPa (−5.68 ksi)
Bearings Seized	My=-605 KN-m (-446.36 kip-ft), σ_t = 283 MPa (41.09 ksi)	Mz=-76 KN-m (-56.40 kip-ft) σ_c = −392 MPa (−56.83 ksi)

Similar Bridges, Similar Problems

Manhattan Bridge, New York City

wikipedia

Manhattan Bridge, NYC

According to the 1955 report entitled "Manhattan Bridge-Investigation of Structural Condition" by the Consulting Engineering firm of D.B. Steinman, and to one of the earlier studies made by Leon S. Moisseiff and Holton D. Robinson, in 1936, torsional stresses due to twisting of the suspended structure had been responsible for the cracks in the upper floorbeams and stringers and for the cracks in the lower floorbeam splice angles and webs.

New upper floor systems were installed in 1959. They were built in such manner as to permit motion between the stringers and floorbeams to minimize structural damage from the unsymmetrical loading.

THE CITY OF NEW YORK
TRANSPORTATION ADMINISTRA
DEPARTMENT OF HIGHWAYS
VINCENT J. GIBNEY
COMMISSIONER

CAPITAL PROJECT No. P.
MANHATTAN BRIDGE
OVER EAST RIVER
BETWEEN BOROUGHS OF MANHATTAN AN

REPORT

STUDY AND RECOMMENDATIONS FOR REDUCTION OF TORSIONAL DEFLECTIONS IN THE SUSPENDED SPANS

APRIL 1971

STEINMAN, BOYNTON, GRONQUIST & LONDON
CONSULTING ENGINEERS
NEW YORK, N.Y.

the outer trusses. This resulted from an attempt, in the original construction of the bridge, to distribute dead load equally to all four cables, which could only be done by producing dead load moments in the floorbeams. The new suspenders were adjusted in such a manner as to reduce these moments.

According to the 1955 report entitled "Manhattan Bridge-Investigation of Structural Condition" by the Consulting Engineering firm of D.B. Steinman, and to one of the earlier studies made by Leon S. Moisseiff and Holton D. Robinson, in 1936, torsional stresses due to twisting of the suspended structure had been responsible for the cracks in the upper floorbeams and stringers and for the cracks in the lower floorbeam splice angles and webs.

New upper floor systems were installed in 1959. They were built in such manner as to permit motion between the stringers and floorbeams to minimize structural damage from the unsymmetrical loading.

In 1965 new abutment rockers and tower hangers were installed to accommodate a new design of the pins.

–5–

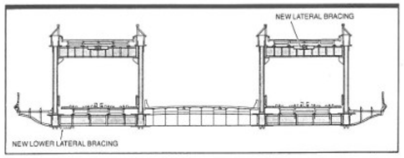
Manhattan Bridge, NYC

REPRINTED FROM
ENR Engineering News-Record
July 5, 1984

Boxing out distortion

By transforming stacked bridge decks into torque tubes, consultants think they have solved a severe cracking problem on New York City's aged Manhattan Bridge, across the East River. A 100-ft test section has performed admirably. Bids for the retrofit project on the bridge's side spans will be called this October, according to consultants.

Manhattan Bridge will be stiffened by turning outer decks into torque tubes (shaded).



The bridge was designed to handle heavy vertical loads—which it does very well, says Herbert B. Rothman, partner at Weidlinger Associates, New York City. Weidlinger is a subconsultant to Edwards and Kelcey Engineers, Inc., New York City, primary consultant to the city on the bridge.

The designers didn't anticipate the significant twisting and longitudinal distortion that would result when trains, running on two tracks on each side of the bridge, caused the deck to deflect. Lateral braces under the upper roadways, which run over the rail lines, were too weak to fight the twisting and had to be removed. It was eventually decided to let the bridge flex as needed.

But most upper-roadway and many floor beams under the lower roadway and tracks show significant fatigue cracking because of this flexing. By installing much stronger lateral braces, E&K and Weidlinger hope to create a torque tube, or box, that will not twist or distort longitudinally.

Stringers contribute to stress. During computer analysis of the stresses in the bridge, they also found that because bearing plates under the stringers had seized, any distortion was being focused on the section of the floor beams between the outer stringers and the stiffening trusses. The consultants installed neoprene pads to ensure the stringers would slide, even if the proposed box section would flex very little.

In the current test section, 25-ft beams, fabricated from 1-in.-thick steel, form 50-ft diagonals between the trusses under the upper roadway sections. These lock into the stiffening trusses, which tie into existing cross braces under the rail lines. Heavy gusset plate connections ensure that the box won't collapse into a nonrectangular shape.

Strain gage tests conducted after installation showed that the box concept worked. Not only did it resist distortion, but it promised some strain relief for the numerous fatigue cracks infecting the structure—buying the bridge 50 more years of life, says Rothman. In fact, the tubes were so stiff that they were creating excessive stresses at the transition points with the original structure, and connections in the test section were released after the test.

Side spans most important. Bids will be called this October for the first contract—installation on the side spans of the diagonal bracing and the neoprene stringer bearings. A second contract, for similar work on the center span, won't be let for several years. The roadway will be replaced in a still later contract, using prefabricated panels already placed in the current test section to show their feasibility.

Because there is enough of a gap between the side and center spans, the stiffened side spans will not overly stress the center span. In fact, says Rothman, since deflections in the side spans cause most movements on the bridge, stiffening them will significantly reduce stress on the center span. ■

Stringers contribute to stress. During computer analysis of the stresses in the bridge, they also found that because bearing plates under the stringers had seized, any distortion was being focused on the section of the floor beams between the outer stringers and the stiffening trusses.

Manhattan Bridge, NYC

The Overall Retrofit Scheme

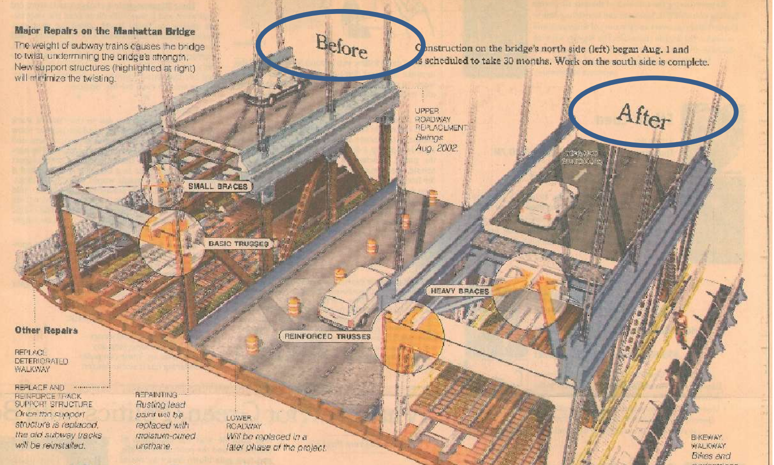
New Stringer Bearings

Heavy Bracing

Reinforced Truss

The New York Times

December 3, 2001



On the East River, A Big Fixer-Upper

Repair Work Is Monumental On an Oddly Designed Bridge

By RANDY KENNEDY

It is hard not to feel sorry for the Manhattan Bridge.

It has never had a Hart Crane to sing of its steel strings or a Joseph Stella to paint them. It doesn't have a River Café beneath it or an American flag waving above it. One architectural history book called it "perhaps the least inspiring design of any of the city's suspension bridges."

In fact, the only distinction the big ungainly bridge has really ever had — besides that of being the last span to open over the East River — is the enduring mystery attached to it: why did Leon Solomon Moisseiff build it that way?

Mr. Moisseiff was a well-known engineer and bridge-design theorist with many impressive bridges to his name — the Benjamin Franklin in Philadelphia, for example, once the longest suspension bridge in the world, and the Golden Gate, on which he was a consultant.

But two other bridges on his résumé did not fare so well. The Tacoma Narrows Bridge, which became known as Galloping Gertie because it twisted in the wind, so badly one morning in 1940 that it collapsed into the water.

Then there is the beleaguered Manhattan Bridge. It has never been in danger of falling into the water. But almost since the day it opened in 1909, it has also twisted, torturously, because of Mr. Moisseiff's decision, for reasons that no one has been able to explain, to build it with subway train tracks running along the outside of the span, instead of in the middle.

The effects of that design have reached far beyond engineering classes. They have been felt by millions of frustrated New Yorkers for at least the last 15 years, which is how long parts of the bridge have been closed and under repair, snarling subway lines, tying up traffic in two boroughs, costing the city untold millions and engendering endless delays. After Sept. 11, it has been easy to forget that any of the city's massive, seemingly endless, infrastructure projects, such as the Third Water Tunnel and the

Continued on Page F4

A worker hauls metal platforms across the subway tracks along the outside of the Manhattan Bridge, an unusual place for such tracks. Most major bridges have them on the inside.

On the East River, a Big Fixer-Upper

Continued From Page F1

Williamsburg and Manhattan Bridge reconstructions, are still underway. But they are, and surprisingly, officials say, they have been little slowed by the terror attacks. In fact, city officials say that while the Manhattan Bridge was completely closed, even to workers, for six days after the attack, that lost time has been nearly recovered.

The final deadline for the project, in January 2004, has not been moved. And the bonuses and penalties built into the contract will remain — $50,000 a day extra to the contractor for each day ahead of time that the project is finished; $50,000 a day in penalties for each day over the deadline. City engineers say that the bridge, approaching its 93rd year, probably would have needed a facelift by now, even if it had been built perfectly. But the way that Mr. Moisseiff built it has made the facelift much more expensive, complicated and urgent.

Nearly all other major bridges with train tracks — the Williamsburg is one example — have the tracks in the middle and the road lanes on the outside, on the theory that too much weight on the outside can cause a suspension bridge to twist.

Even with heavy traffic, cars and trucks are collectively much lighter than subway trains. Cars and trucks also provide a much more even load, with some on one side of the bridge and some on the other.

And what happens when a train crosses on one side, with no counterbalance on the other side, was starkly demonstrated one recent sunny morning, when Henry Perahia, the city's chief bridge engineer, escorted an observer out to the middle to watch. A W train rattled by. After its last car passed, the south side of the bridge could be seen slowly rising about three or four feet, its millions of tons of girders and cables wrenching themselves back into place after sagging under the weight.

"I call that the 'Bridge Over the River Kwai' effect," said Mr. Perahia, who is given to dark engineering humor.

Even one train, he said, causes enough contortion to open tiny cracks in the bridge's steel. And even one train causes the thick vertical suspension cables to shift up to six inches, forcing them to scrape against the vertical steel columns, wearing down both the cables and the columns.

While Mr. Moisseiff's design is the biggest factor in the bridge's problems, Mr. Perahia explained that another reason it has turned into one of the city's longest and most costly repair jobs is that for nearly two decades, beginning with the fiscal crisis in the 1970's, the bridge, like most in the city, was nearly completely ignored.

It was not repainted. Columns that had been rammed by trucks were left badly bent. Highly acidic pigeon-droppings were not cleaned and they piled up several feet deep in some corners, over time eating away at the steel as effectively as a blowtorch.

Most damaging was the rust that caused what engineers call section loss, a technical way of explaining how three-inch thick metal plates slim down to an inch or less.

Out on the bridge, Mr. Perahia was asked: What's the worst section loss? He pointed down at a tennis-ball-size hole in a horizontal beam, through which the East River could be seen clearly, coursing by.

Pity the bridge seemingly forever in need of repair.

"The worst section loss is zero," he said. The good news is that, after $260 million spent on the south side and on the 322-foot-tall towers, the holes on that side have been patched and the dip caused by the subway, though still shocking to any observer, is not as deep as it used to be.

And when the repairs on the north side are completed, at a cost of an additional $175 million, the twisting will be reduced even more, to levels that will still require heavy maintenance and oiling but that will be acceptable, officials say. (The total price tag will approach $500 million. The whole bridge cost $31 million to build in 1909.)

The repair work is prosaic in its details but huge and painstaking in its scope.

Think of a corridor in a carnival fun house, where the floor pitches and the walls sway. The bulk of the repair work will strengthen the four corners of the ceiling of this corridor by putting much bigger X-shaped cross braces across them. The project will also add huge steel arches that will stiffen the walls and help them maintain their right angles to the ceiling and floor.

Finally, like quilters, the workers will patch the rusted and deteriorated steel with plates and thousands of new rivets. These rivets have made the girders on the already-repaired south side of the bridge resemble cottage cheese, with seemingly more fasteners than material being fastened.

All of this work would be complicated enough without an additional headache: somewhere within the layers and layers of paint on the bridge there is lead paint, which can be harmful to the developing nervous systems of fetuses and young children if it is blasted off and ends up in soil and water.

So before any work on the steel is done, workers must carefully cordon off areas of several hundred square feet and build virtually airtight polyester tents around them, so that the dust and chips from the paint are contained when they are blasted.

Not only has an environmental inspection company been hired to keep watch over the process, but city officials have also been assigned to keep watch over that company.

Inside the tents, the paint removers wear masks, protective suits and air tanks. Snaking away from the tents are giant air hoses that look like something from a science fiction movie. The air pressure inside the tent is kept lower than it is outside, so that if the polyester walls tear, dust stays inside instead of spewing out.

"Nothing goes in, nothing comes out," said Reza Lotfi, the city's engineer in charge of the Manhattan Bridge.

In the end, all the dust is sucked into a huge orange vacuum cleaner the size of a bus that costs $200,000 and was trucked in for the job from Wisconsin. "I've got one just like it at home," joked one worker.

The gargantuan repair job raises one last troubling question: By the time it is done, will the parts that were repaired first need to be repaired again?

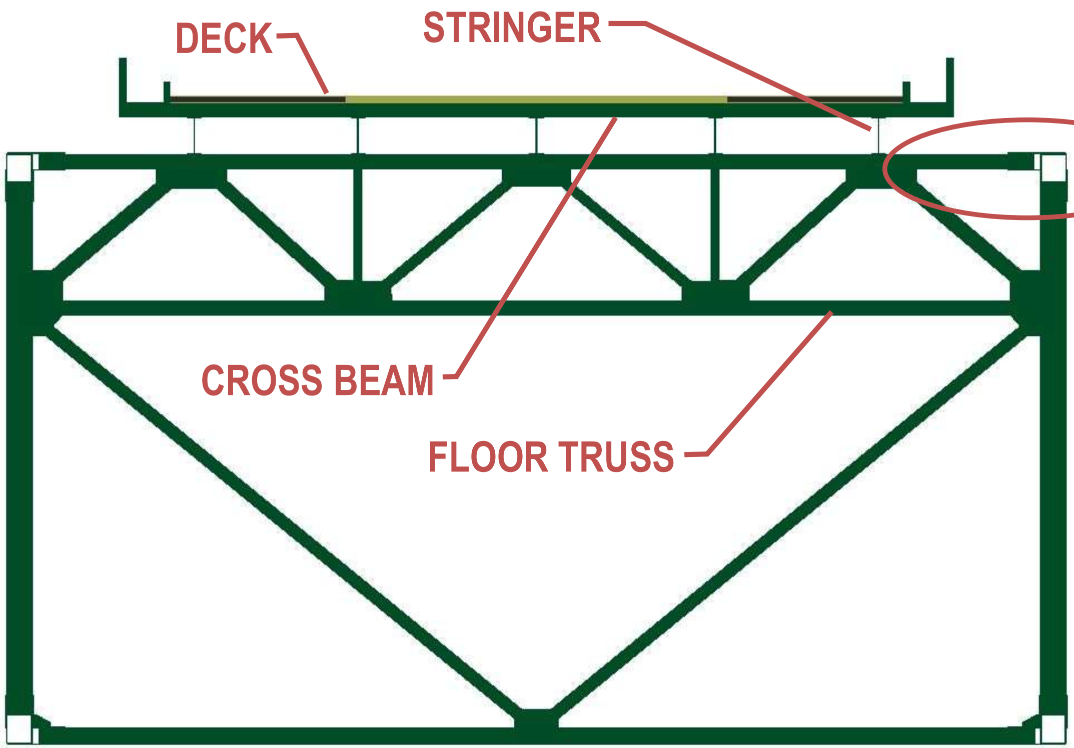
Mr. Perahia says no and adds, as if to himself, "Will it ever have to go through this kind of work again?"

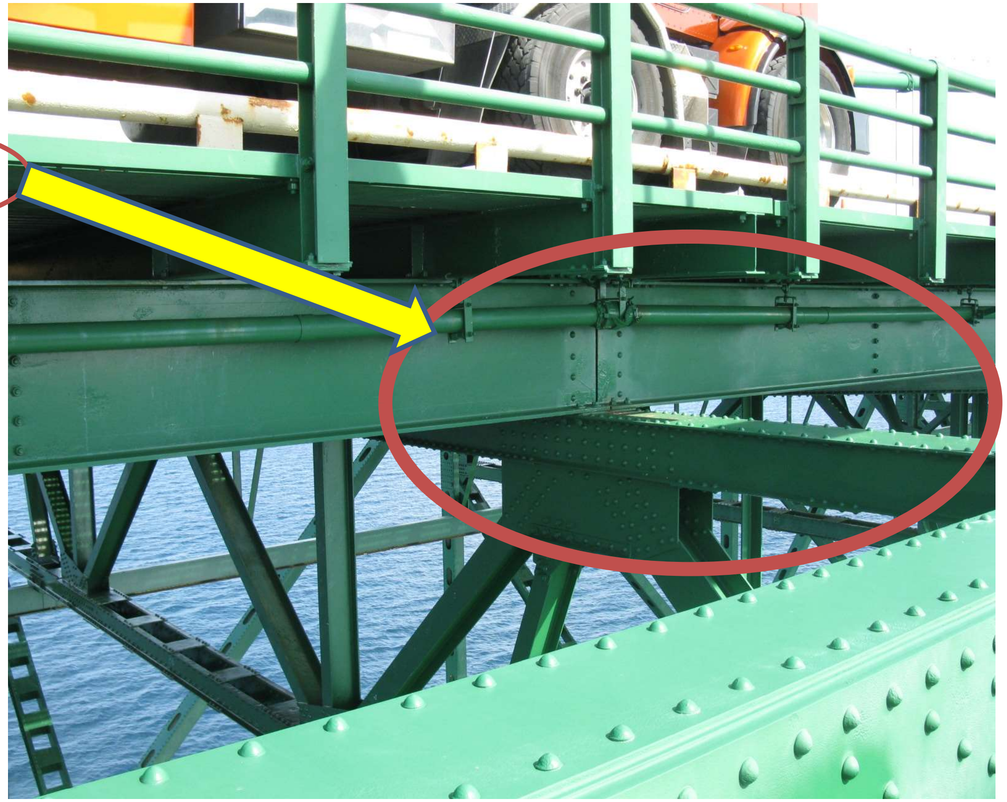
"Probably," he admits. "But I am here to say that my children won't be doing it. Or my grandchildren. Or most likely my great-grandchildren."

Mackinac Bridge, MI

Mackinac Bridge, MI

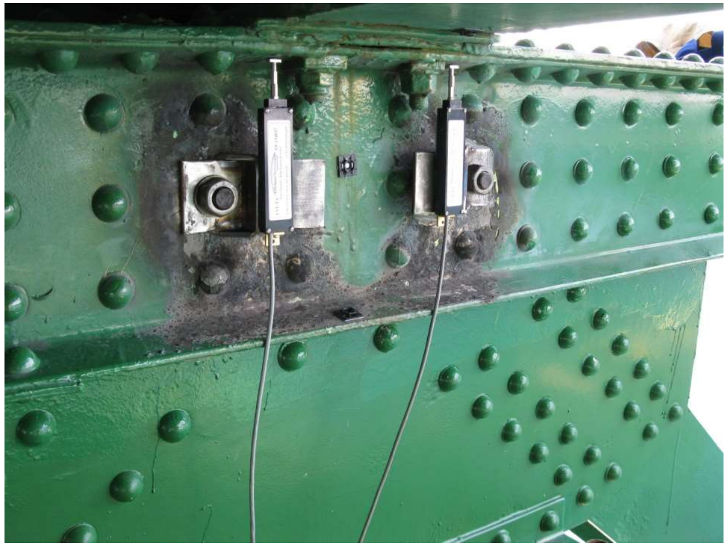
Typical Cross Section and Deck Framing

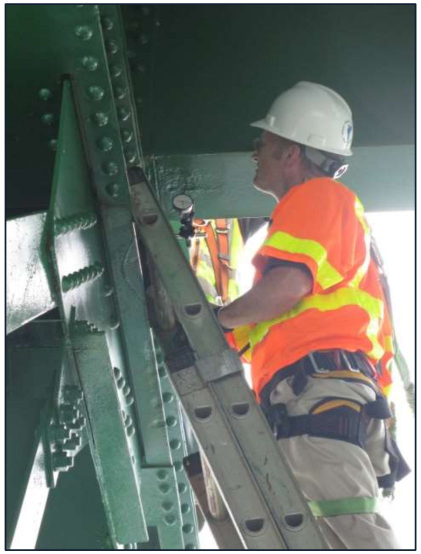


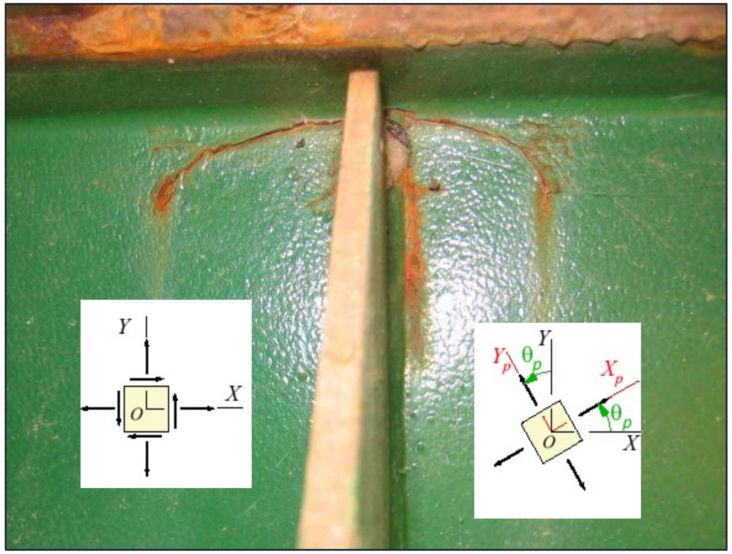


Mackinac Bridge, MI

Field Measurements and Element Cracking

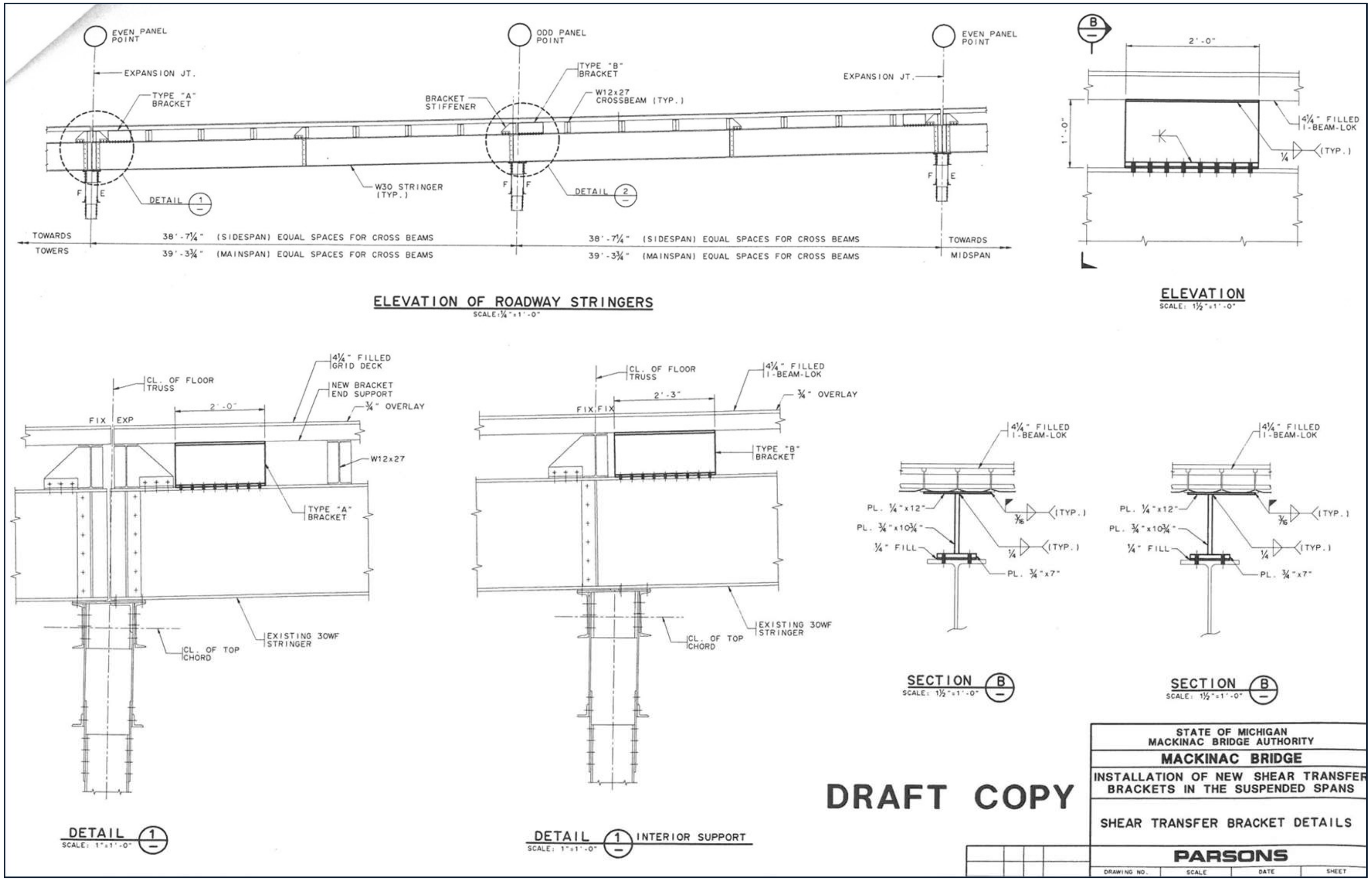






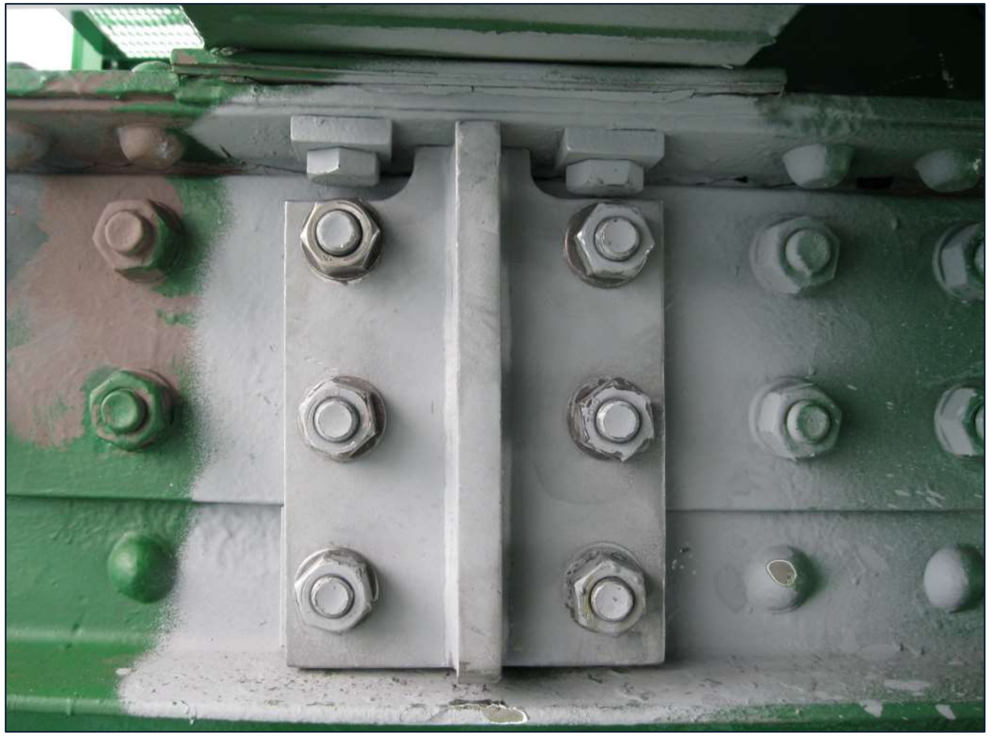
Mackinac Bridge, MI

Trial Installation of Shear Connectors



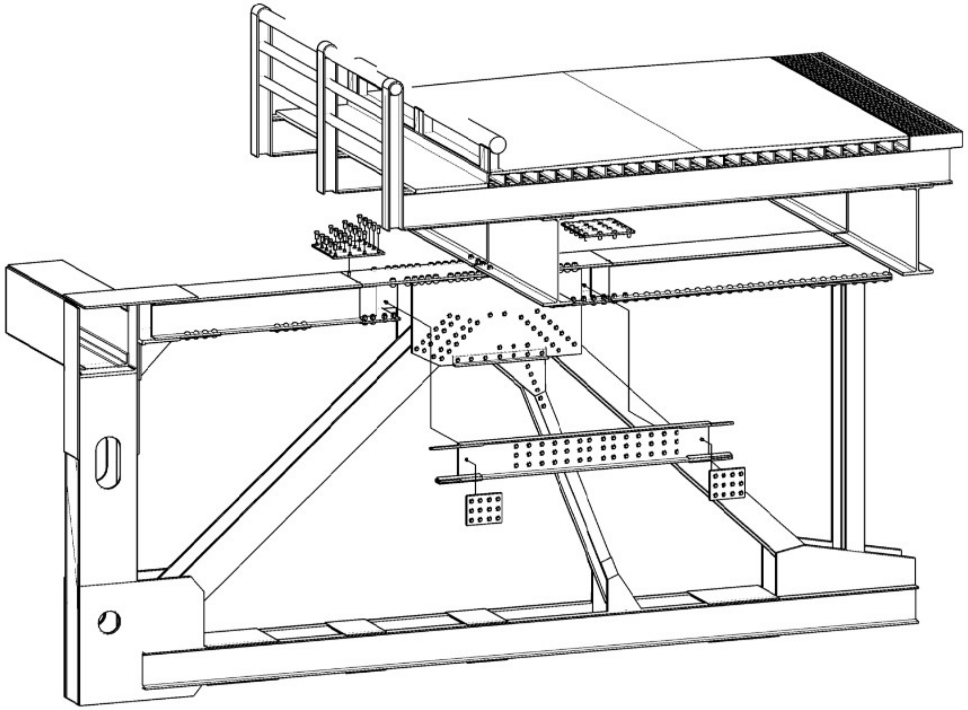
Mackinac Bridge, MI

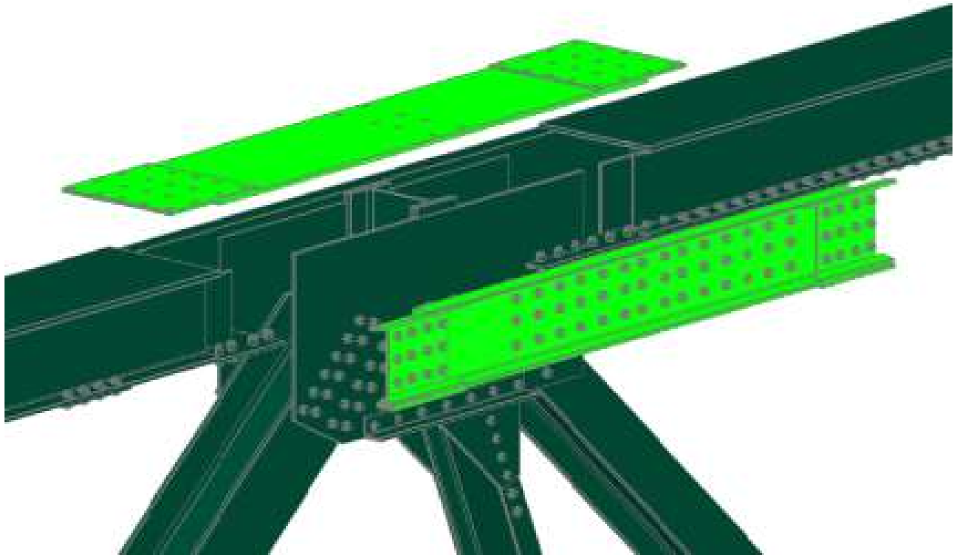
Interim Repairs



Mackinac Bridge, MI

Permanent Floor Truss Repairs

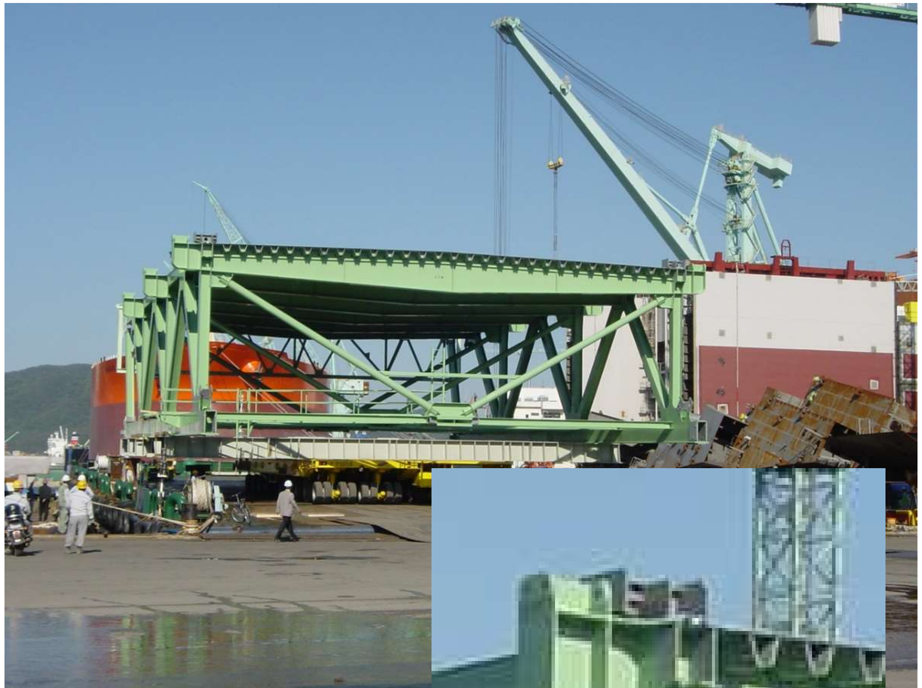


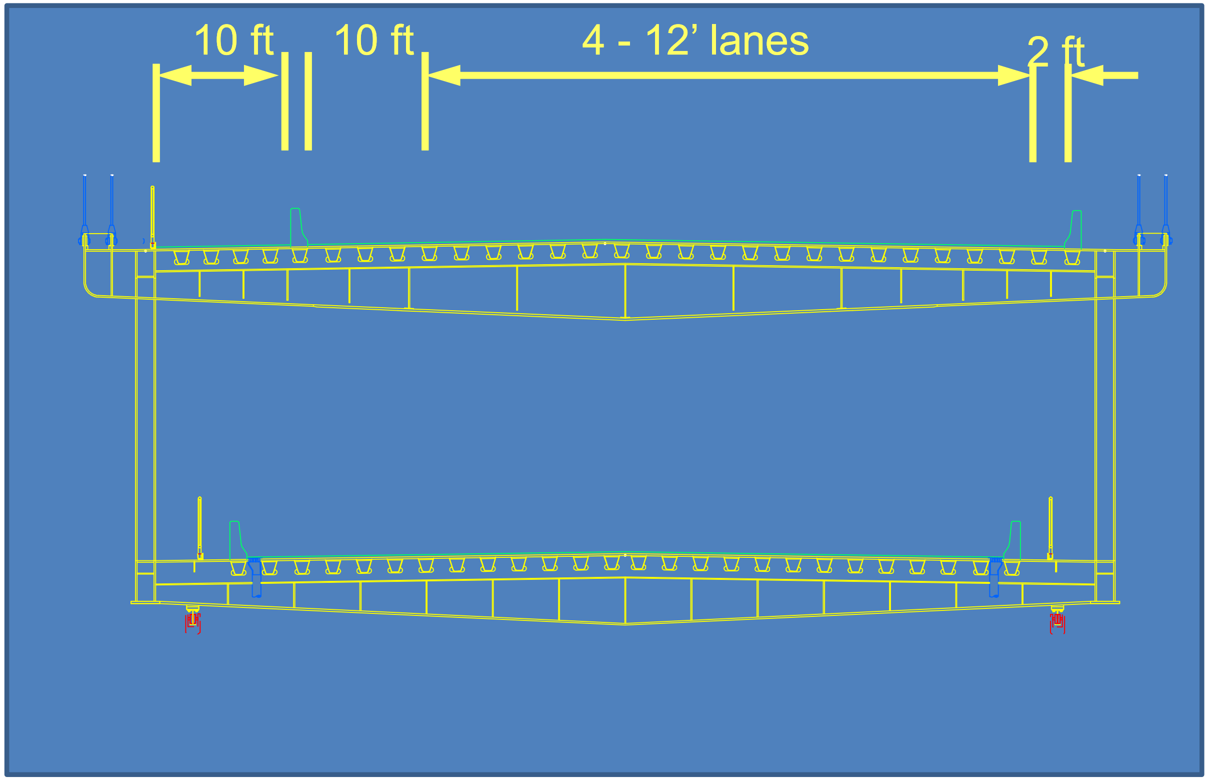



2007 Tacoma Narrows Bridge, WA

2007 Tacoma Narrows Bridge, WA

Initial and Future Build





Study of Potential Solutions and Final Design

Initial Options Investigated

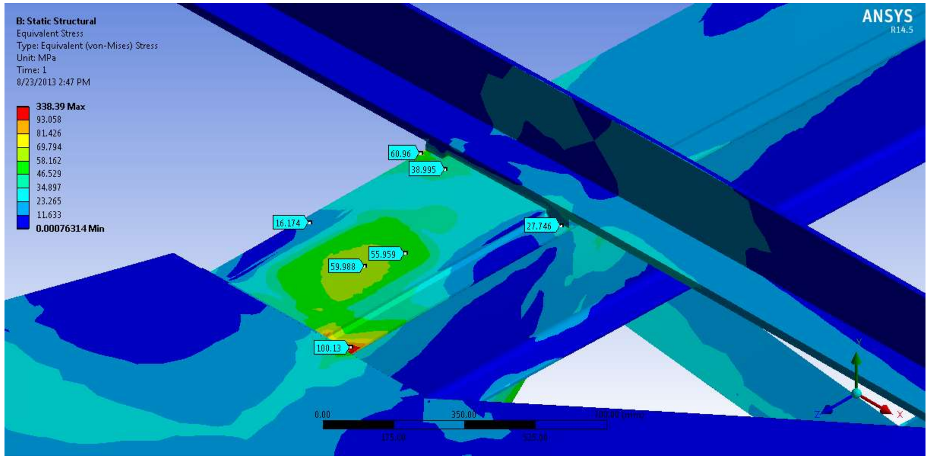
Option 1 – Reinforce floor truss top chord at problematic hand hole cut-out.

100 MPa (14.5 ksi) stress concentration.

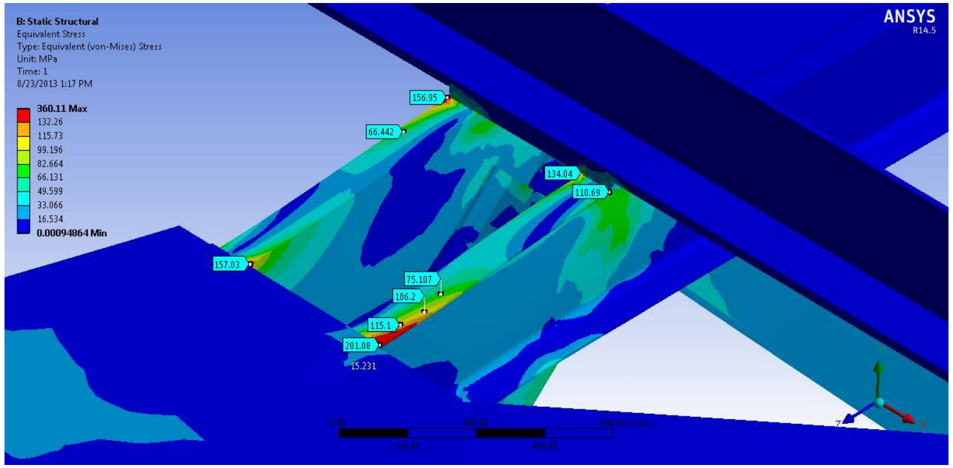
Option 2 – Remove the problematic floor truss top chord cover plate.

200 Mpa (29 ksi) stress concentration.

Option 1



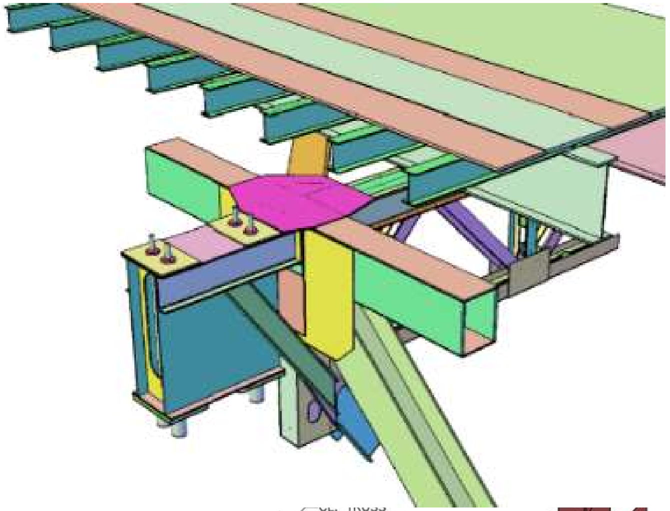
Option 2

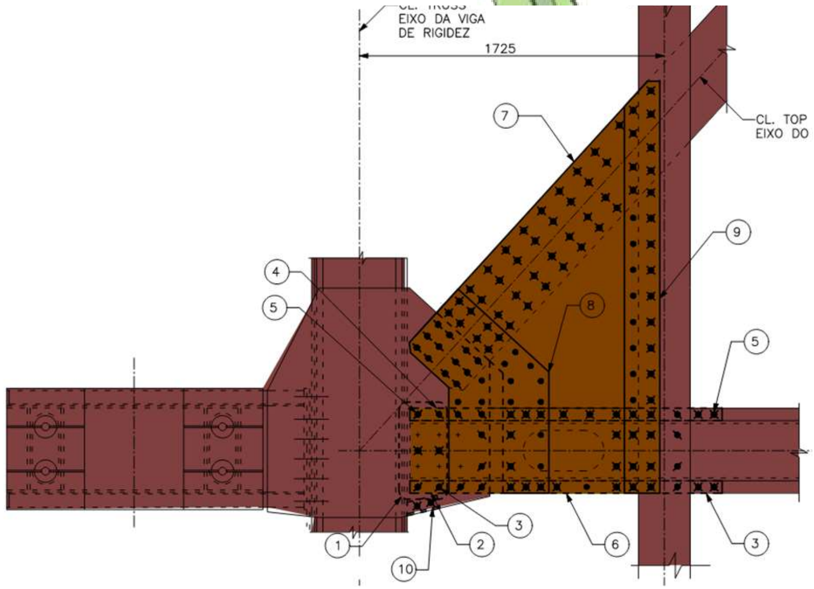


Design Solution

Introduce Strengthening Plates for Floor Truss Framing

- Strengthening plates at odd numbered panel points.
- Hand hole cut-outs completely plated over.
- New plates encompass entire node.
- Floor truss, exterior stringer and stiffening truss diagonal is integrated into single node.

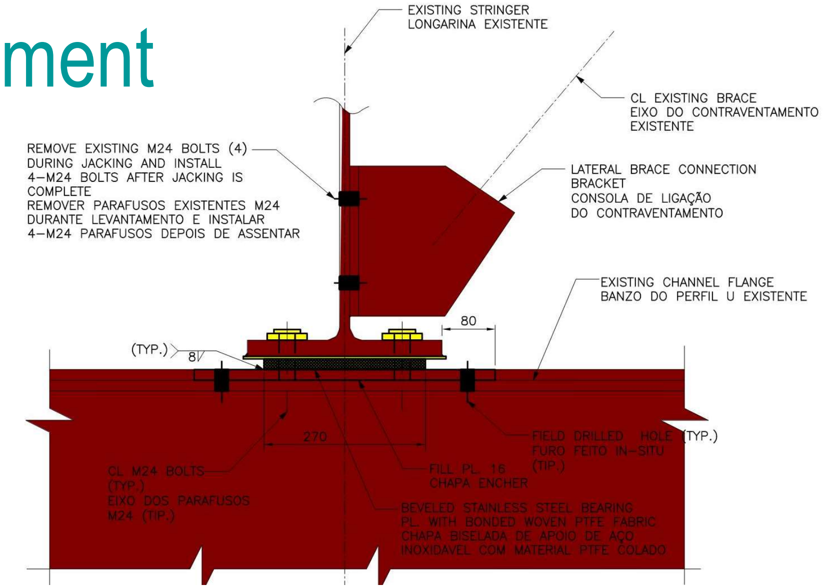




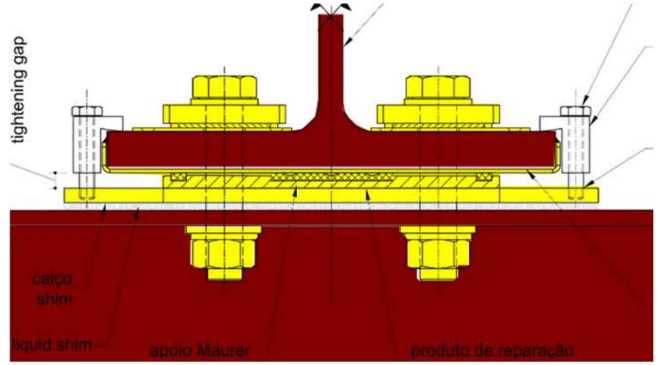
Stringer End Support Bearing Replacement

Floor truss bending situation can only be mitigated by:

- Introducing a series of rigid shear connectors between the deck and stiffening truss to achieve global composite action.
- Restoring the slinging stringer ends so they function as intended by design, i.e. maintaining the original structural system.

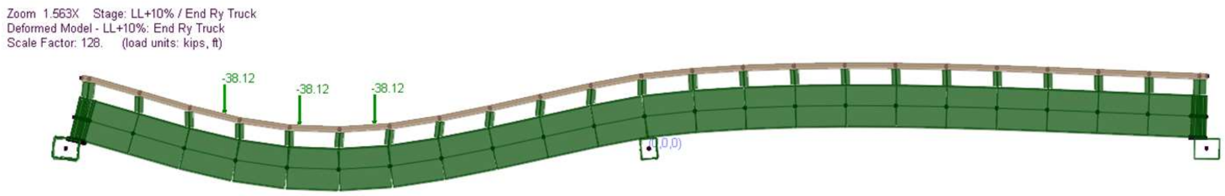


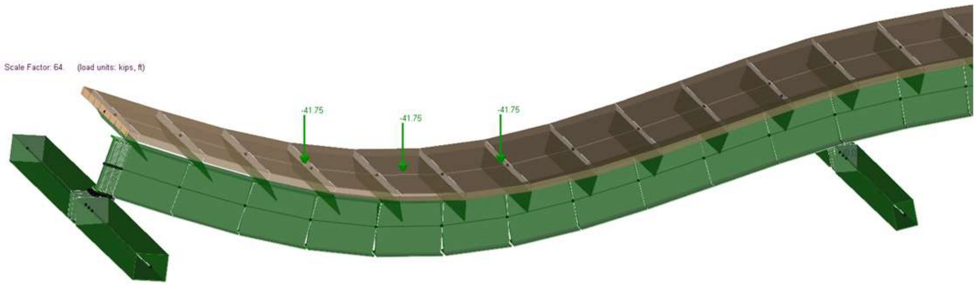
AS DESIGNED



CONTRACTOR MODIFIED

Analysis for Stringer Bearing Design at Even Numbered Panel Points





Stringer and Deck Strip Model

Conclusions

- Many Pre-1970 suspension bridges were designed with deliberate structural separation between the deck and floor framing by way of regularly spaced relief joints.
- If stringer bearing motion becomes inhibited, or seized, unintended composite action between the deck and suspended spans will develop, usually resulting in problematic stress conditions.
- Structural strengthening and/or stringer bearing replacement is necessary to maintain the original structural system.
- Retrofitting for complete composite action is possible for some bridge configurations, though costly and possibly entailing complete deck replacement.