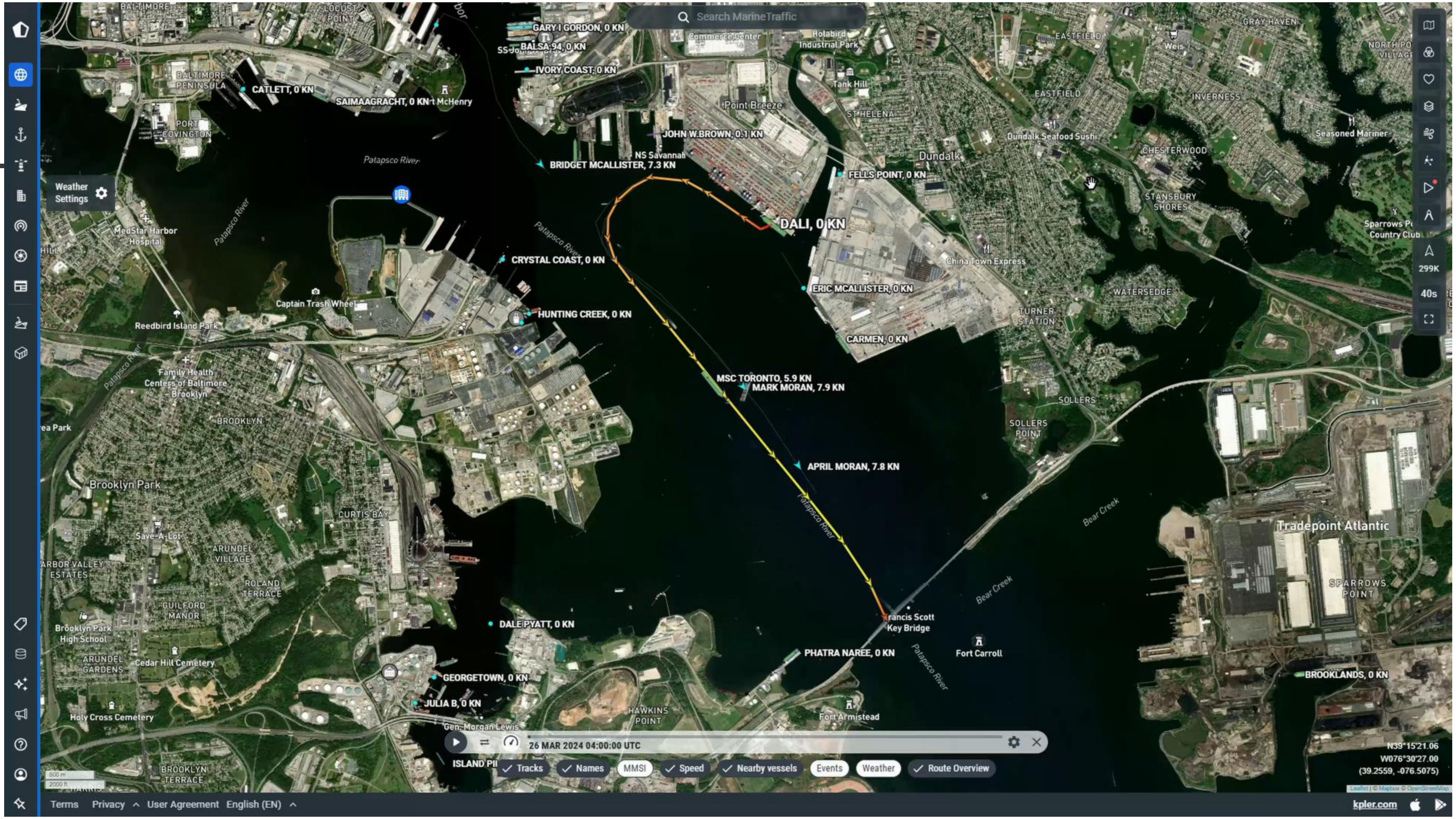
CITY COLLEGE IS CUNY

Complex Simulation of Large Ship Impacts on Bridges

Anil K. Agrawal, Ph.D., P.E.
Dist. Member (ASCE)
Herbert G. Kayser Professor of Structural Engineering
The City College of New York, New York, NY

Outline

- Complex Simulation of Large Ship Impacts on Bridges
  - Collapse of the Frances Key Bridge
  - Current AASHTO Guidelines
  - Computational Simulation of Large Ship Impacts on Bridge Piers


Search MarineTraffic
Weather Settings
GARY I GORDON, 0 KN
BALSA 94, 0 KN
IVORY COAST, 0 KN
CATLETT, 0 KN
SAIMAAGRACHT, 0 KN
JOHN W.BROWN, 0.1 KN
NS Savannah
BRIDGET MCALLISTER, 7.3 KN
FELLS POINT, 0 KN
DALI, 0 KN
CRYSTAL COAST, 0 KN
ERIC MCALLISTER, 0 KN
HUNTING CREEK, 0 KN
CARMEN, 0 KN
MSC TORONTO, 5.9 KN
MARK MORAN, 7.9 KN
APRIL MORAN, 7.8 KN
DALE PYATT, 0 KN
PHATRA NAREE, 0 KN
GEORGETOWN, 0 KN
JULIA B, 0 KN
BROOKLANDS, 0 KN
Patapsco River
Dundalk
Point Breeze
Brooklyn Park
Curtis Bay
Tradepoint Atlantic
Sparrows Point
Fort Carroll
Fort Armistead
Hawkins Point
Bear Creek
Sollers Point
Captain Trash Wheel
Reedbird Island Park
MedStar Harbor Hospital
Baltimore Peninsula
Port Covington
Dundalk Seafood Sushi
China Town Express
Seasoned Mariner
Holy Cross Cemetery
Cedar Hill Cemetery
Brooklyn Park High School
26 MAR 2024 04:00:00 UTC
Tracks
Names
MMSI
Speed
Nearby vessels
Events
Weather
Route Overview
N39°15'21.06
W076°30'27.00
(39.2559, -076.5075)
299K
40s
Terms
Privacy
User Agreement
English (EN)
kpler.com

Bridges Collapses because of Ship Impacts

- As per 2018 report by the World Association for Waterborne Transport Infrastructure, 35 major bridge collapsed worldwide that were caused by boat strikes between 1960 and 2015, killing a total of 342 people.

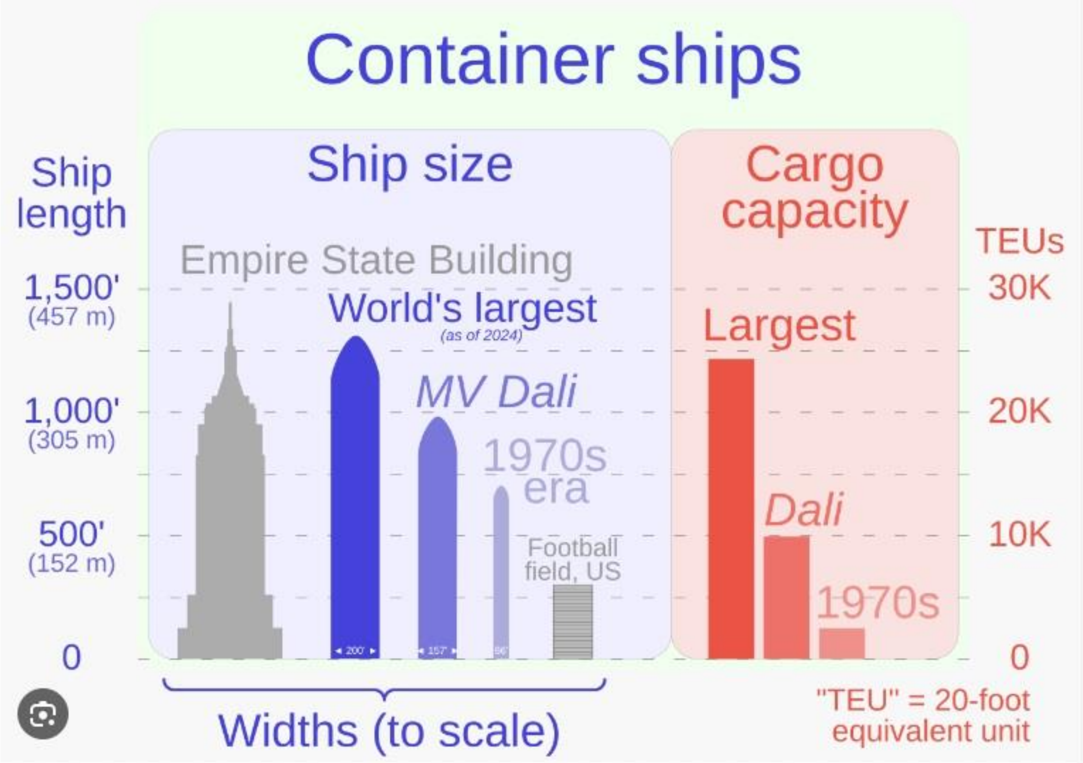
- Eighteen (51%) of those incidents happened in the United States.

Economic Impact on Francis Key Bridge Collapse

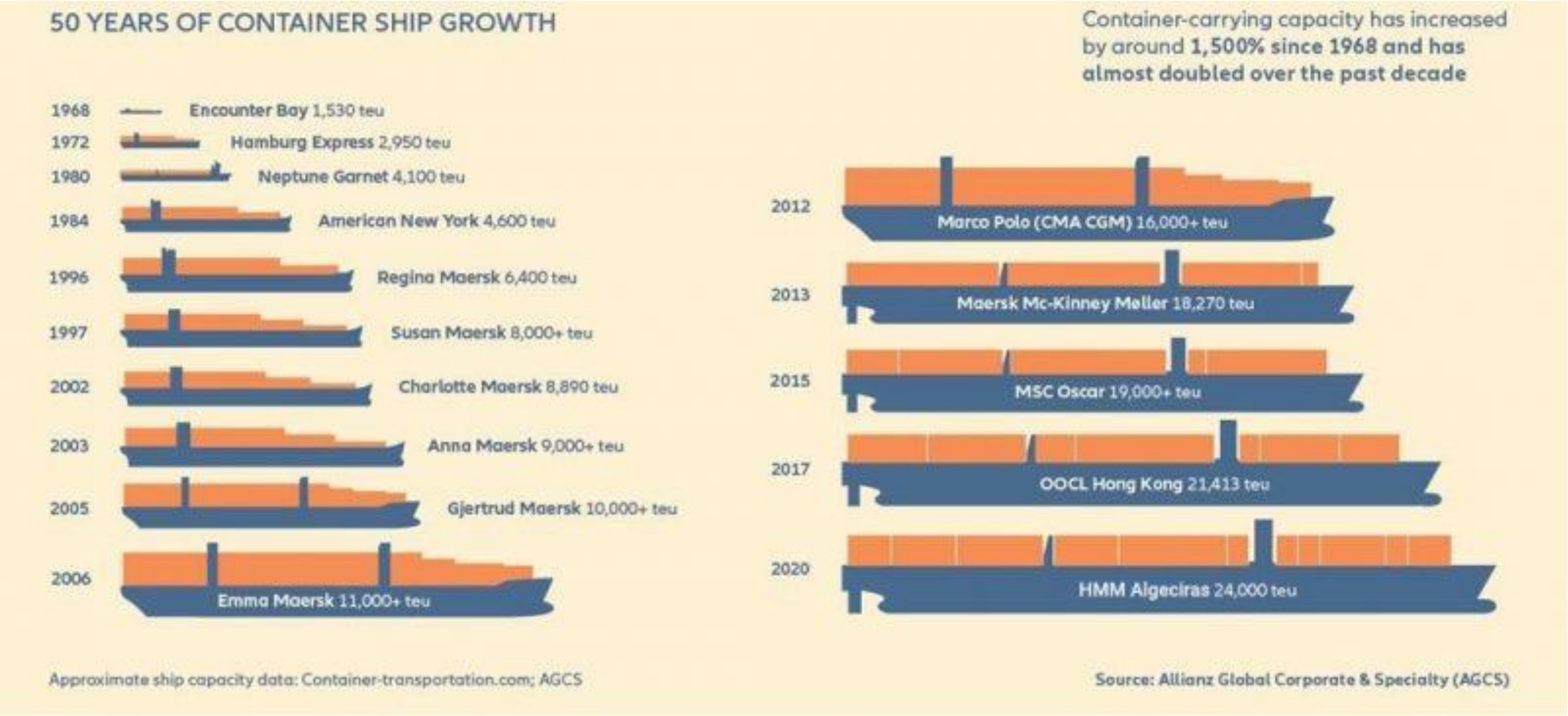
- **Total economic impact over 5 year: ~ $ 20 B**
  - $1.5B (Rebuilding Cost)
  - Economic loss over 5 years of rebuilding = 11.5M vehicles per year × 3 hour per vehicle detour (two to four times longer)× $50 per hour × 5 years = $8.63 B
  - 4,900 trucks / day, 30-mile detour for hazmat trucks.
  - Increased accidents, reduced mobility on other highways! Traffic crashes increased by 29% on alternative highways since the collapse.
  - Increased air pollution, wasted fuel and other environmental impacts.
  - Loss of use of port facilities, loss to local businesses!

DALI is not the largest ship!

Ships getting larger: size, weight and speed. Dali may not be the worst-case scenario.



DALI is not the largest ship!



Ship Impact on Zarate-Brazo Largo Bridge

- On January 29, 2024, ship EN MAY collided with piers of Zarate-Brazo Largo Bridge, a cable-stayed bridge, in Argentina.
- **Ship EN MAY**:
  - Length: 228 m
  - Width: 36 m
  - DWT: 85,000 tons

- **Ship Dali Details**:
  - Length: 299 m
  - Width: 48 m
  - DWT: 116,000 (Dali has unloaded cargo before the accident and was only 3/4th full)

Ship Impact on Zarate-Brazo Largo Bridge

Protection Measures at Zarate Bridge

Protection Measures at Zarate Bridge

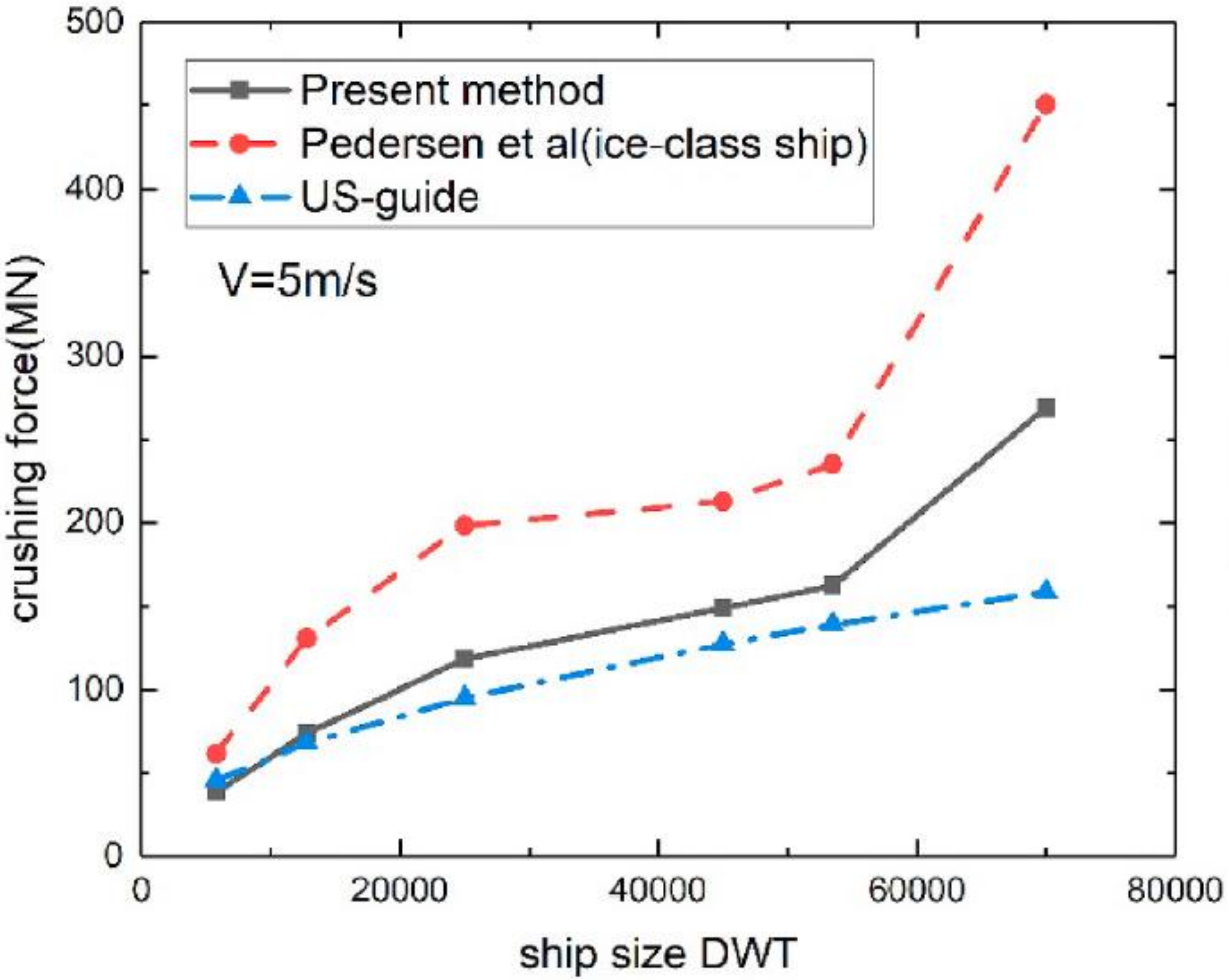
- Piers were protected on upstream side by concrete buttresses. Bridge was impacted from downstream side.
- No reported damage to the bridge. Detailed inspection of the bridge piers and foundation underway.
- This incident shows that the collapse of the **Key Bridge** could have been prevented if there was protection (such as pedestal) around the piers.

Sunshine Skyway Bridge Collapse (1980)

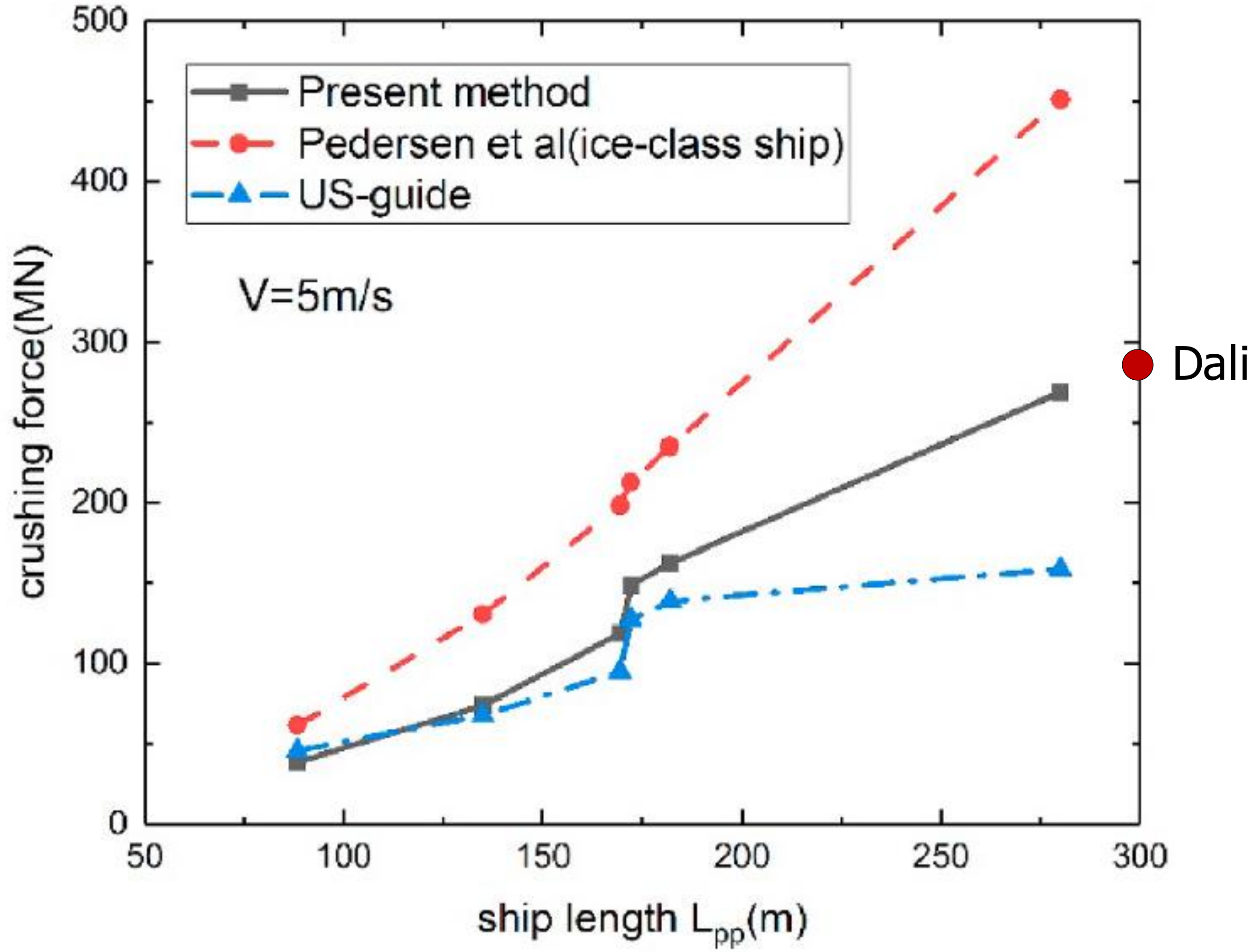
- Sunshine Skyway Bridge similar to the Maryland Key Bridge in look and construction.
- The Skyway bridge's central span was 22,373 ft (6,819 m) long with 864 ft (263 m) opening for a ship channel.
- Sunshine Skyway Bridge pier was impacted by a **33,000 tons** carrier, causing collapse of the bridge.
- The collapse of this bridge prompted AASHTO develop guidelines in 1991 and incorporate in AASHTO Bridge design specifications in 2007.

Freighter MV Summit Venture

Current AASHTO Guidelines versus Large Ship Impacts



Current AASHTO Guidelines versus Large Ship Impacts



Evaluation of the Probability of Collapse

- AASHTO Guidelines recommend calculating the probability of collapse through the following equation:

4.8.3 Annual Frequency of Collapse

The annual frequency of bridge element collapse shall be computed by:

$$AF = (N)(PA)(PG)(PC)(PF) \quad (4.8.3\text{-}1)$$

where:

AF = annual frequency of bridge element collapse due to vessel collision;

N = annual number of vessels classified by type, size, and loading condition which can strike the bridge element;

PA = probability of vessel aberrancy;

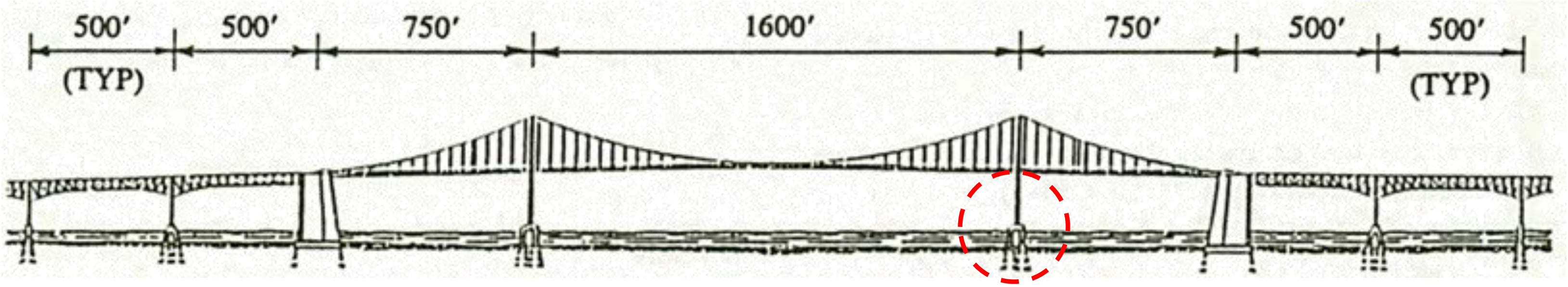
PG = geometric probability of a collision between an aberrant vessel and a bridge pier or span;

PC = probability of bridge collapse due to a collision with an aberrant vessel; and

PF = adjustment factor to account for potential protection of the piers from vessel collision due to upstream or down stream land masses, or other structures, that block the vessel.

AF shall be computed for each bridge element and vessel classification. The summation of all element AFs equals the annual frequency of collapse for the entire bridge structure.

Example: A long-span Suspension Bridge



No protection for the pier, PF =1.0.

Annual Frequency of A Main Pier Collapse (H_p=20,000 kip), **Dali Ship: ~ 7000 tons** kips

Ship (DWT)	N	PA	PG	PC	PF	AF	ΣAF
150,000	60	9.9E-05	0.1147	0.0737	1.0	0.000050	0.000050
100,000	100	9.9E-05	0.1095	0.0652	1.0	0.000071	0.000121
80,000	300	9.9E-05	0.0978	0.0598	1.0	0.000174	0.000294
60,000	100	9.9E-05	0.0907	0.0519	1.0	0.000047	0.000341
40,000	100	9.9E-05	0.0842	0.0386	1.0	0.000032	0.000373
20,000	2,000	9.9E-05	0.0790	0.0085	1.0	0.000133	0.000506
10,000	3,000	9.9E-05	0.0614	0.0000	1.0	0.000000	0.000506

For the main pier, ΣAF = 0.000506 > Allowable AF_P = 0.000025 (**Insufficient Protection)**

Example: A long-span Suspension Bridge

Annual Frequency of A Main Pier Collapse (H_p=20,000 kip)
(Assuming that much fewer ships of DWT greater than 20,000 tons)

Ship (DWT)	N	PA	PG	PC	PF	AF	ΣAF
150,000	1	9.9E-05	0.1147	0.0737	1.0	0.000001	0.000001
100,000	1	9.9E-05	0.1095	0.0652	1.0	0.000001	0.000002
80,000	5	9.9E-05	0.0978	0.0598	1.0	0.000003	0.000004
60,000	25	9.9E-05	0.0907	0.0519	1.0	0.000012	0.000016
40,000	20	9.9E-05	0.0842	0.0386	1.0	0.000006	0.000022
20,000	30	9.9E-05	0.0790	0.0085	1.0	0.000002	0.000024
10,000	3,000	9.9E-05	0.0614	0.0000	1.0	0.000000	0.000024

For the main pier, ΣAF = 0.000024 < Allowable AF_P = 0.000025, Good.

Annual Frequency of Collapse?

- Example shows AF for the bridge from ship collision dependent on N (ship traffic).
- It is possible that Dali type of ship came the first time, went adrift and impacted the bridge!
  - Ship traffic probabilistic, but the risk of collapse binary!
  - Risk of consequence: ~$20B

    Protection costs: ~ $60M

    Risk Cost / Mitigation cost = $20B/$60M > 6,000

Annual Frequency of Collapse?

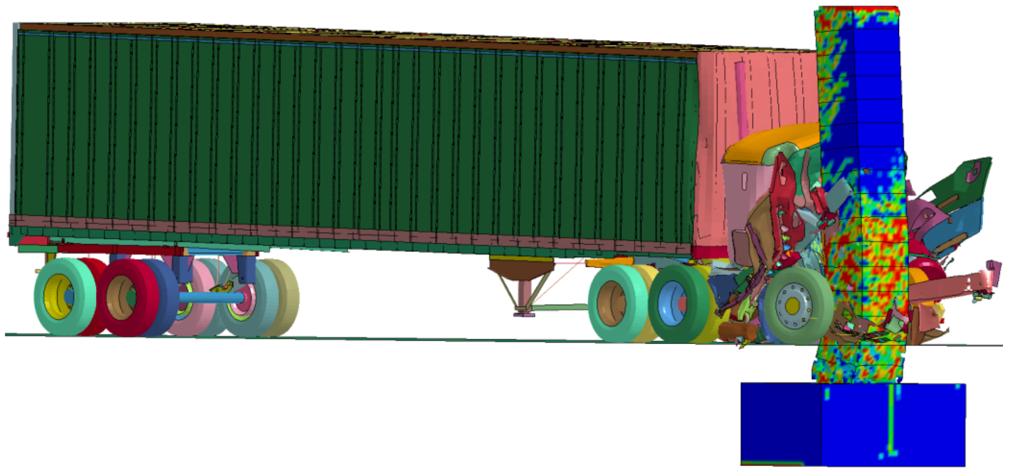
- Lateral impact load at 100,000 DWT = 41,300 kips

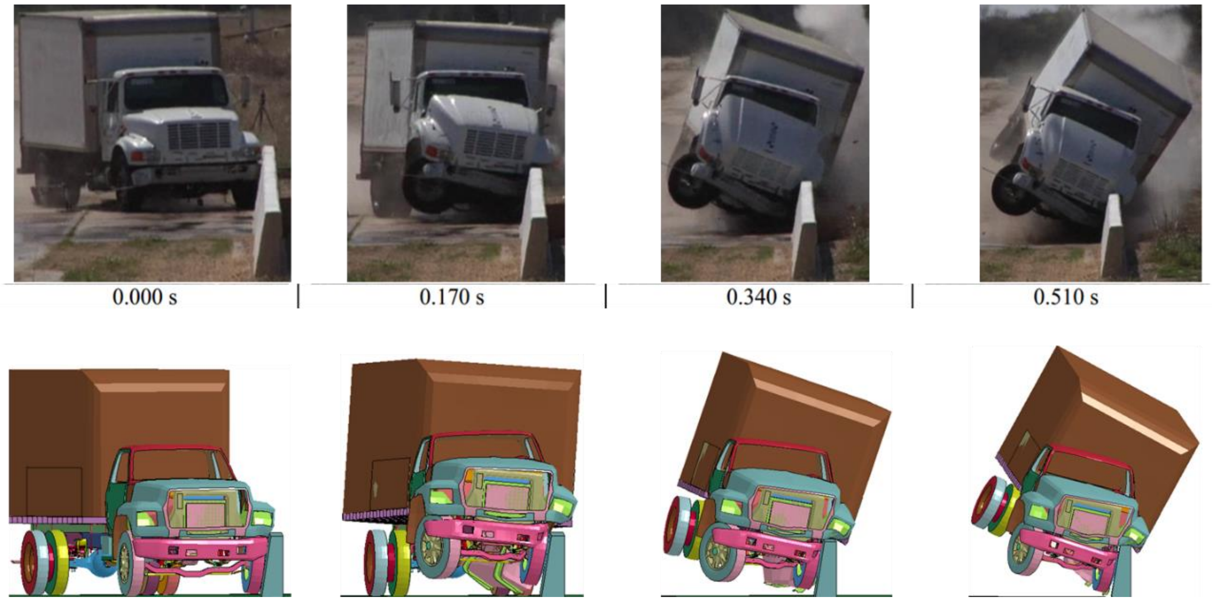
  Key Bridge Pier Capacity: ~7,000 kips

- Key bridge was impacted by a ship of 7,000 DWT in 1980, resulting in damage to concrete protection block around the pier.
  - Risk of collapse was well-known!
- Can we really rely on AASHTO risk calculations to ensure safety?

What Can We Do?

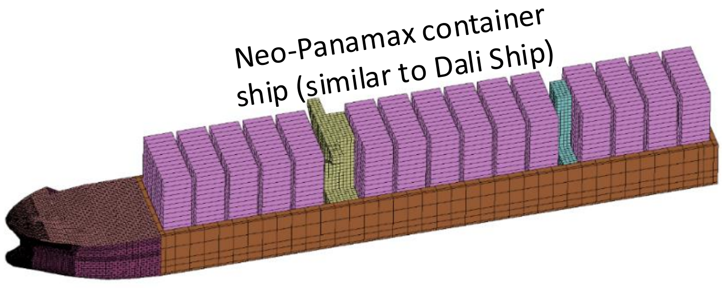
- For bridge barriers, we have been doing crash testing.
- Computational simulation of crash testing well established.
    - **PBD**: Can achieved desired performance of no collapse or reparable damage.

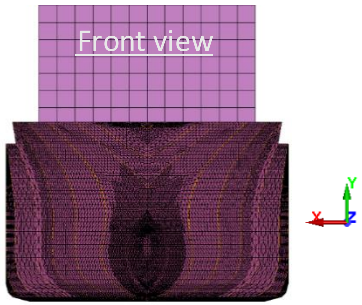


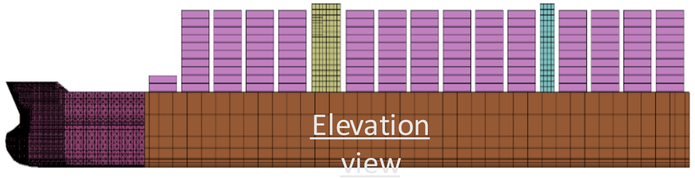


Finite Element Model of Large Container Ship

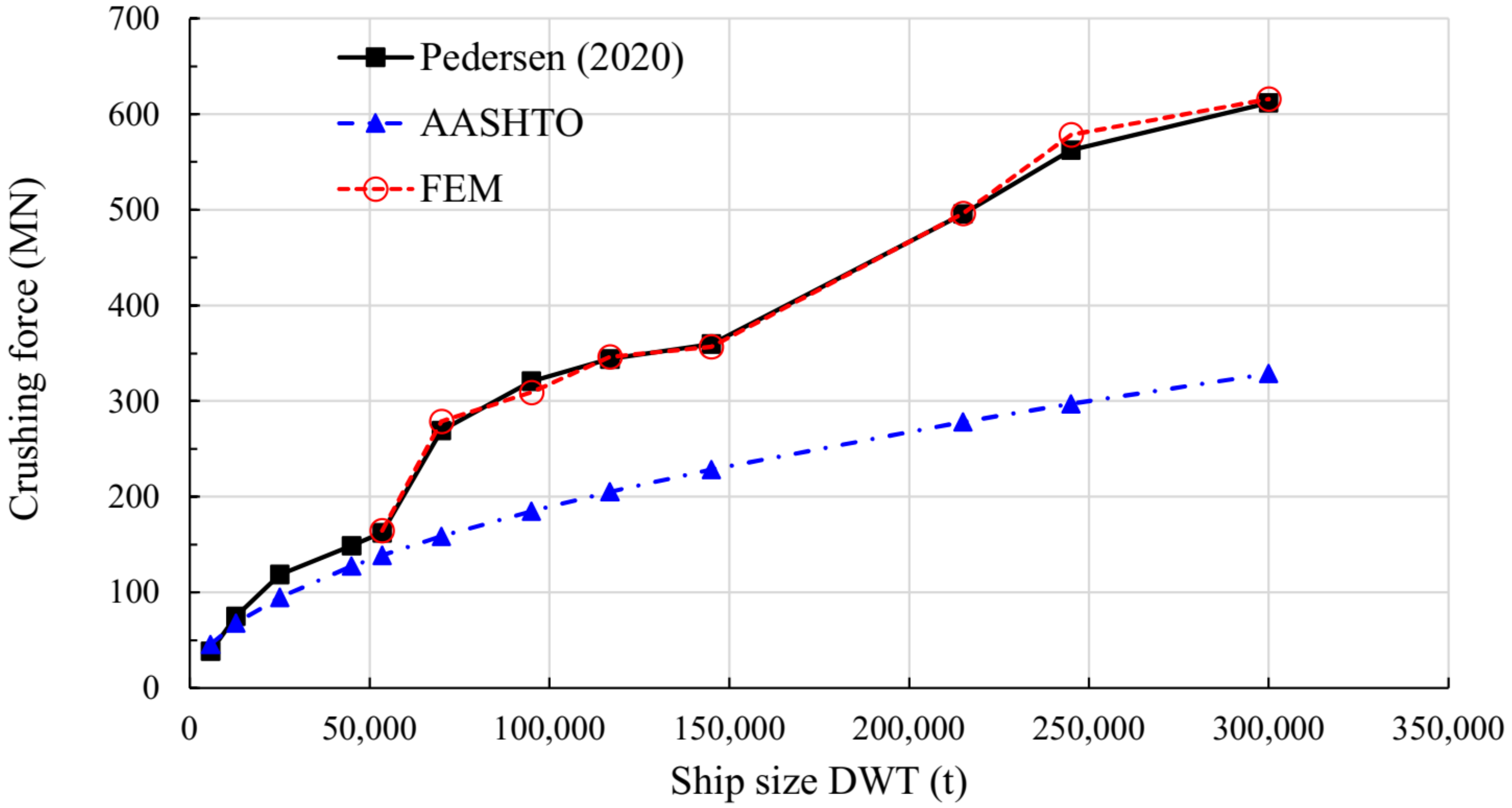
- Neo-Panamax Type container ship (the same class as Dali)
- FE Model based on actual drawings of a Neo-Panamax ship
- DWT (Deadweight Tonnage) = 116,851 t
- Displacement Tonnage (full load) = 148,984 t (Total weight, including self weight)
- Total length = 300 m, Width = 40.57 m
- 38,000 Nodes and 54,500 Elements in LS-DYNA Model
- **Behavior of the model tested with existing data in literature**







Testing of the ship model against a rigid wall

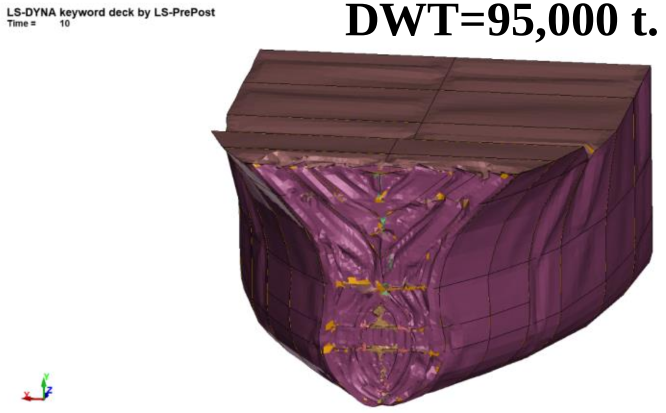


Maximum crushing force for fully loaded ships

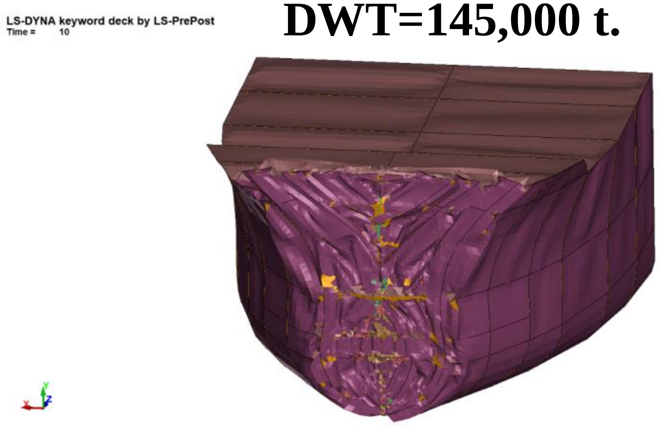
Pedersen, P. T., Chen, J., & Zhu, L. (2020). Design of bridges against ship collisions. *Marine Structures*, *74*, 102810.

Damage to the Ship Bow After Impact

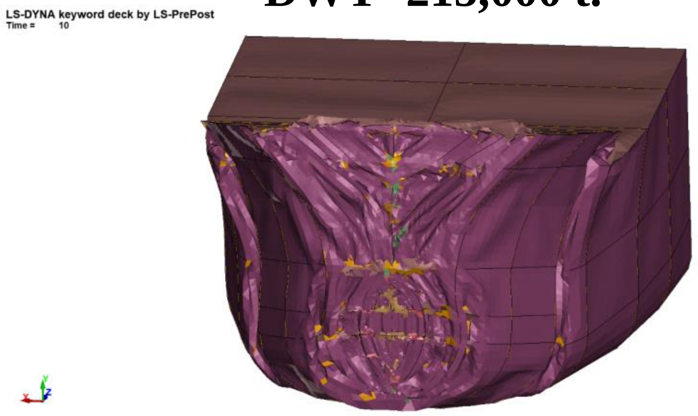
DWT=95,000 t.



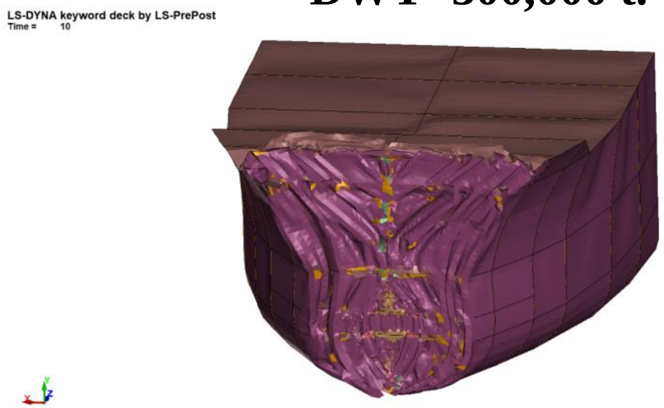
DWT=145,000 t.



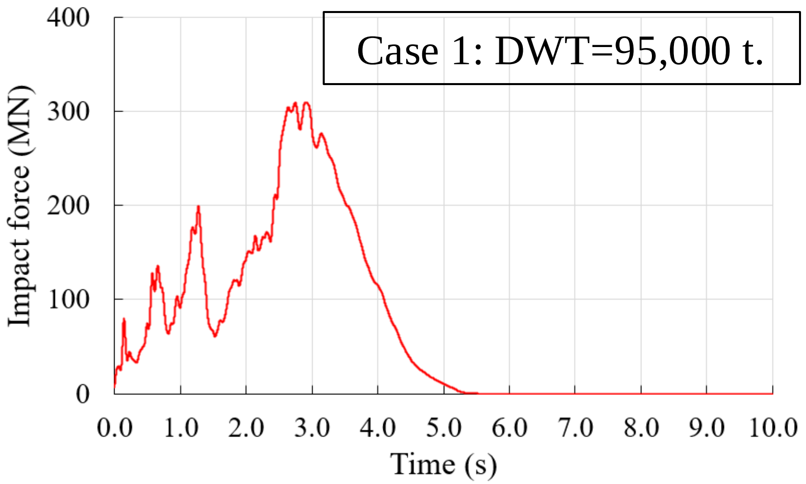
DWT=215,000 t.

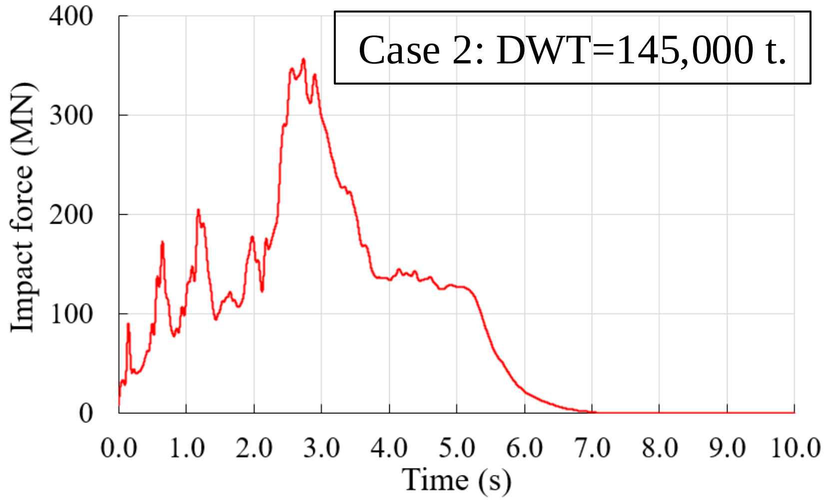


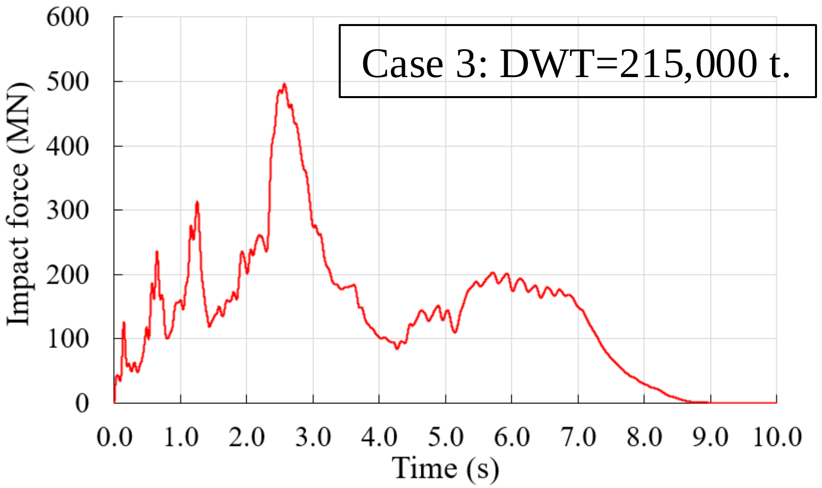
DWT=300,000 t.

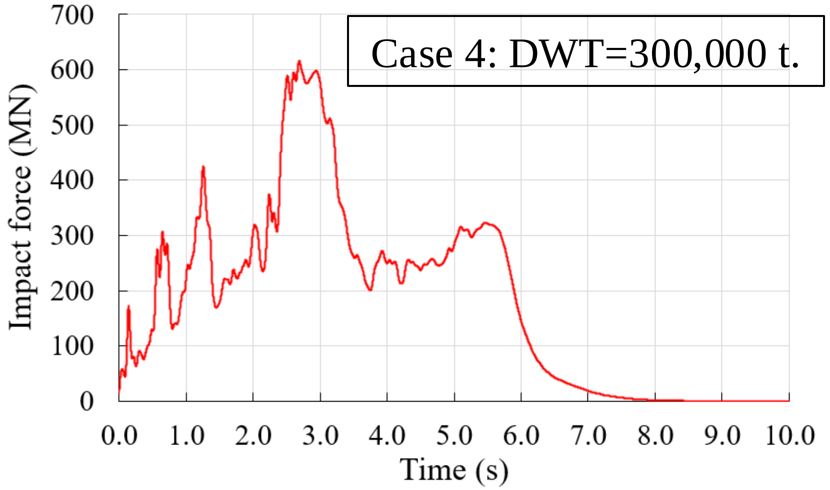


Time history of Crushing Forces



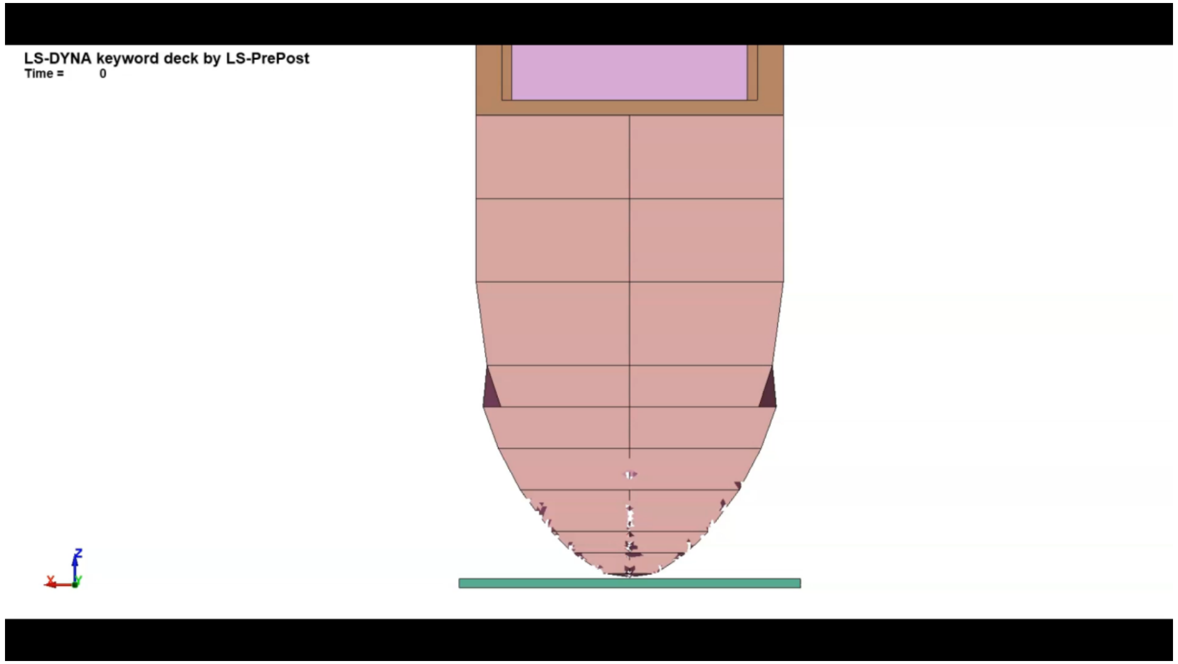


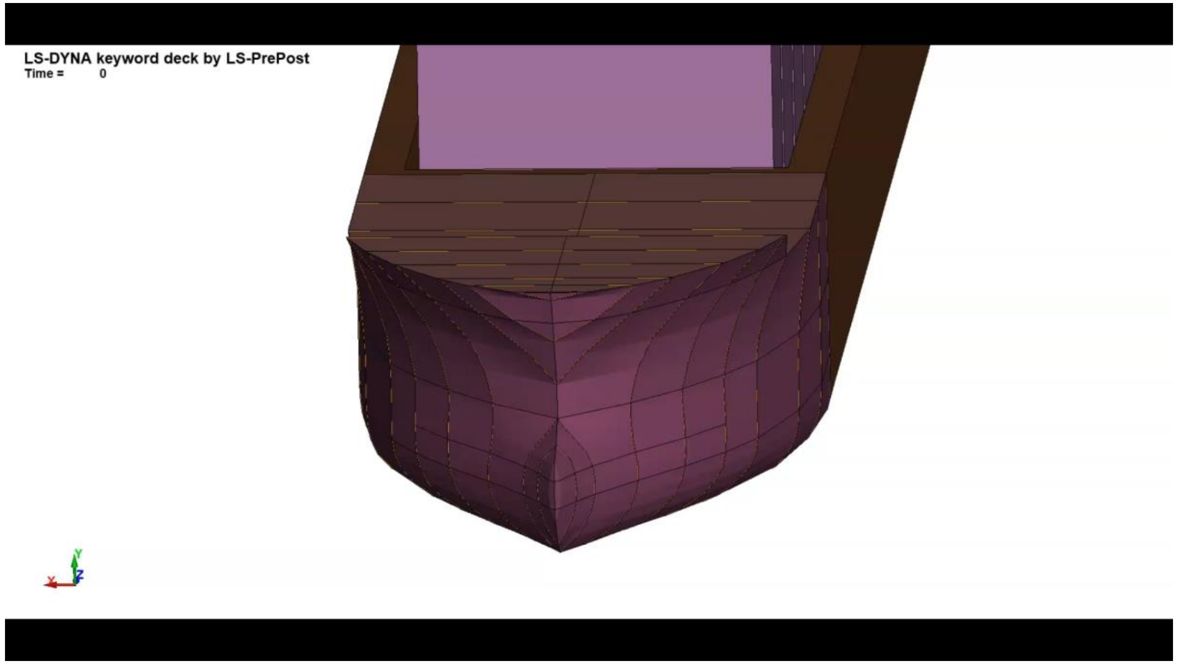




Simulation Video of Ship Impact on Rigid Wall

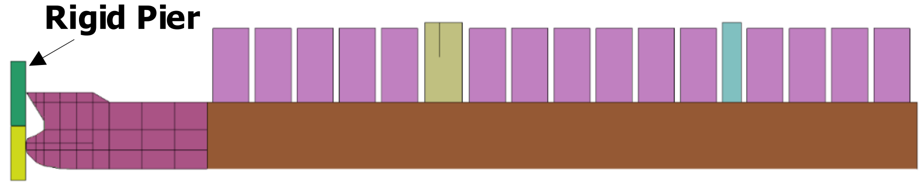
Ship (DWT=145,000 t) impact on a rigid wall with v=5.0 m/s.

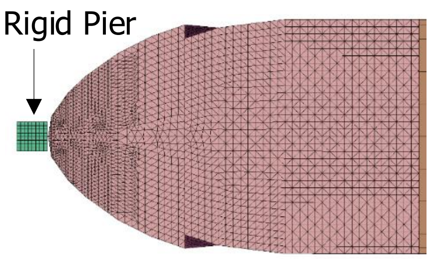




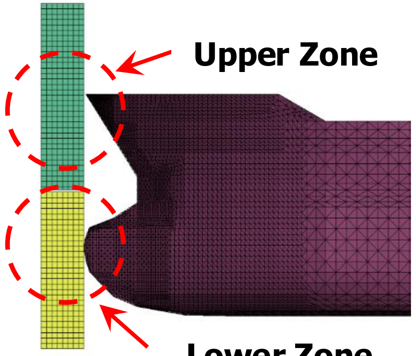
Ship Impact on a Rigid Pier

- Rigid Pier: 5m × 5m, fixed at two ends.
- Ship: Initial velocity = 6.8 knots (3.5 m/s)

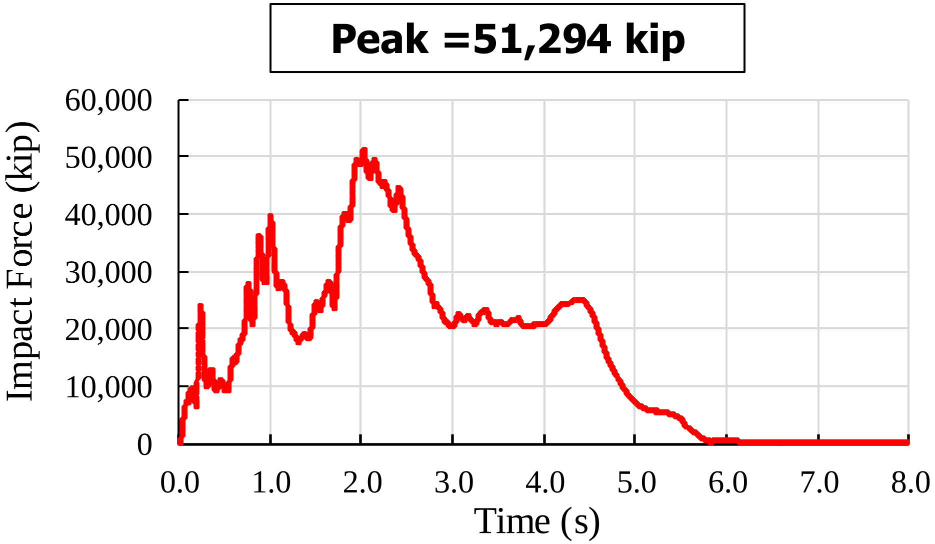




Center Impact (Top view)

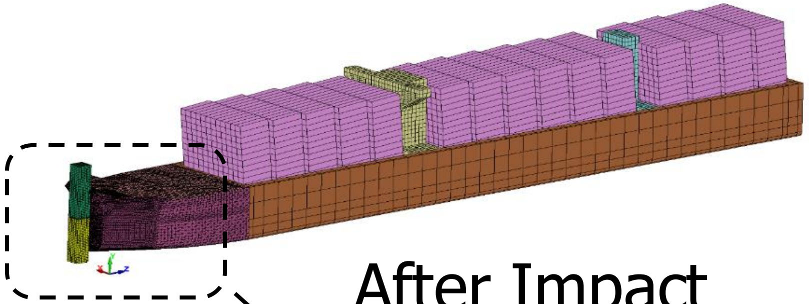


Two impact zones

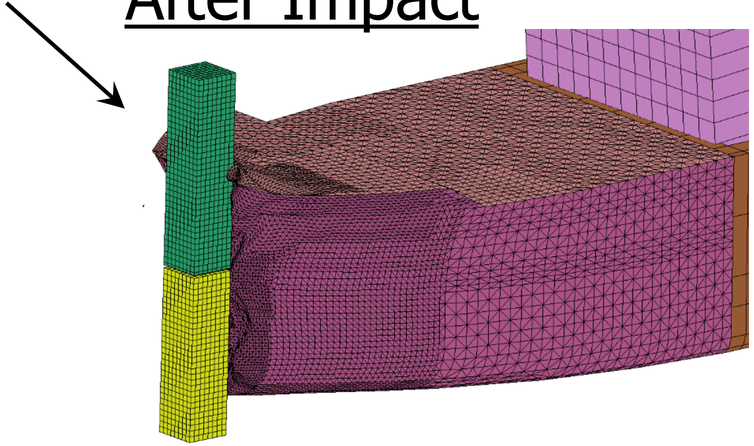


Time history of impact force

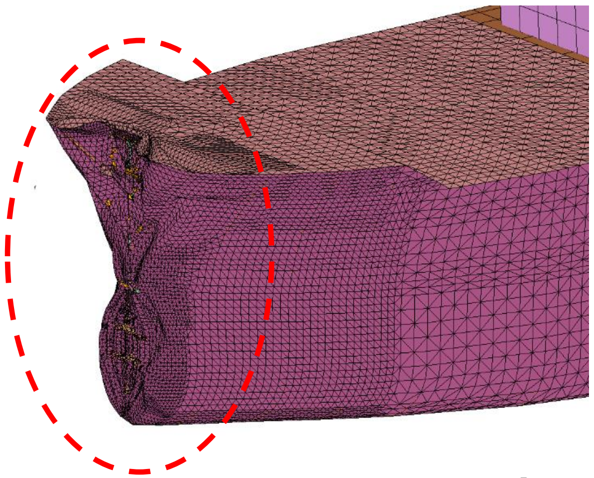
Ship Impact on a Rigid Pier: Center Impact



After Impact

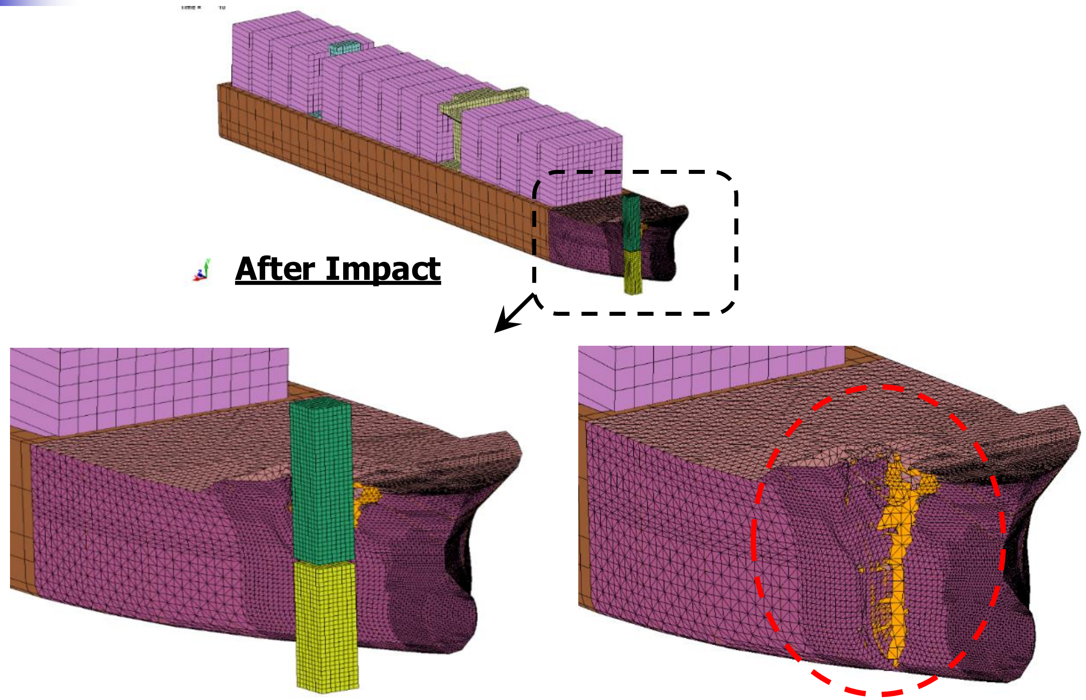


Close-up view of impact zone



Damage to the ship

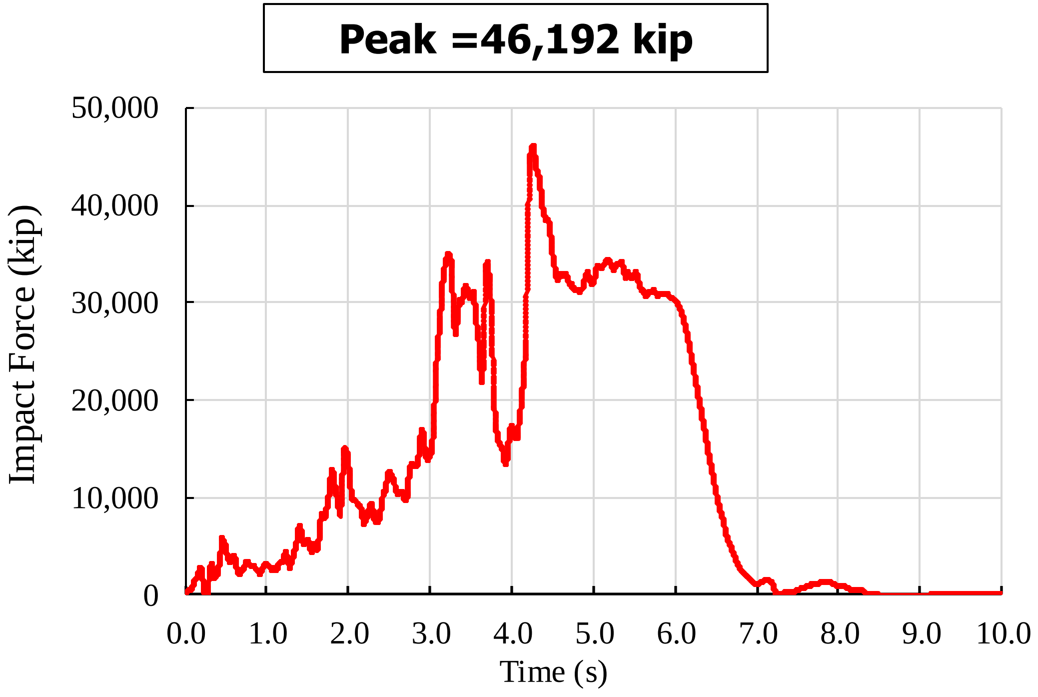
Ship Impact on A Rigid Pier: Off Center Impact



After Impact

Close-up view of impact zone

Damage to the ship

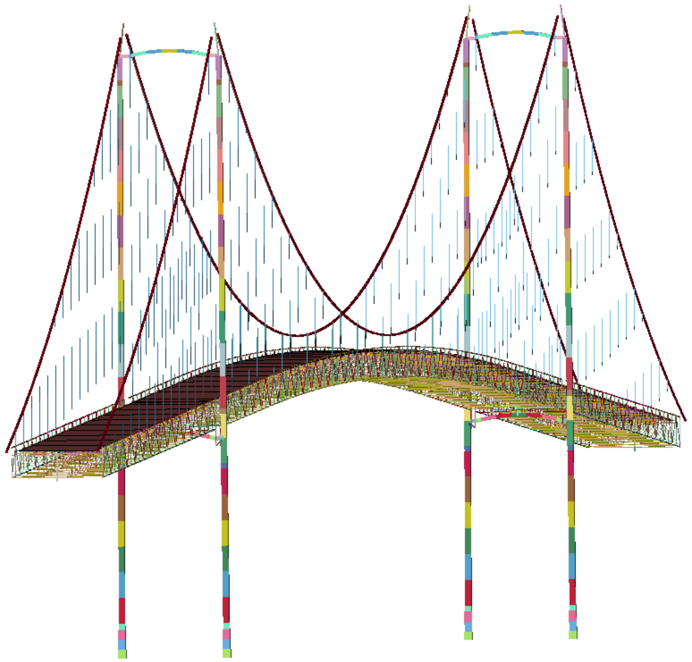


Time history of impact force

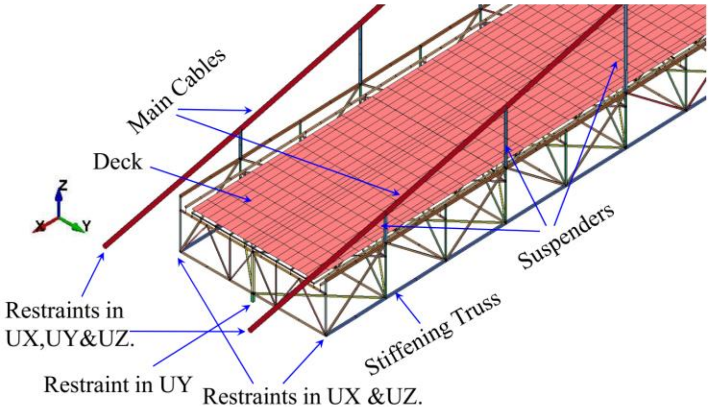
Finite Element Model of Long-Span Bridges

Suspension Bridge

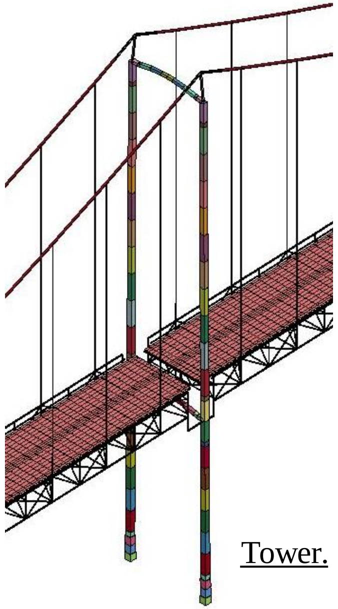
- Based on 1961 AASHTO Specifications, Opened to public in 1968. **Bridge was not designed for impact resistance**.
- Spans: 750ft + 2,150ft + 750ft = 3,650ft & Width: 61.0 ft.
- Main Cables: sag-to-span ratio(center span): 1/10.
- Suspenders: 69 pairs with spacing of 50.43ft to 51.85ft .
- Steel Towers: 418 ft high. A36 Steel.
- Detailed finite element model of the bridge in LS-DYNA
- Reliability and accuracy of the model established in detail during a previous study for FHWA.



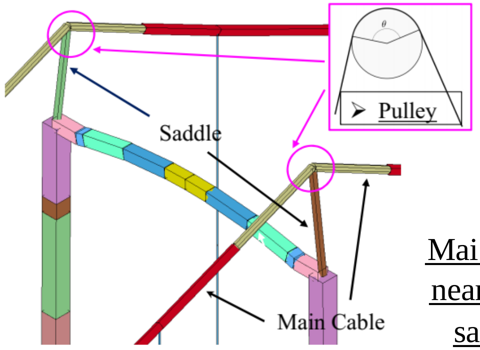
Finite Element Model Details



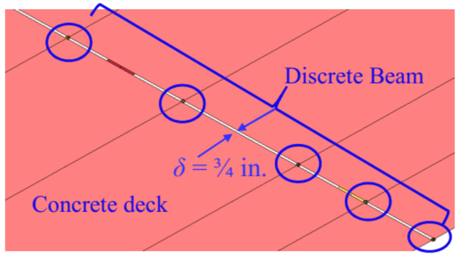
Suspended structure near anchorage.



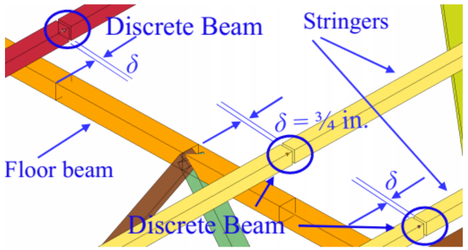
Tower.



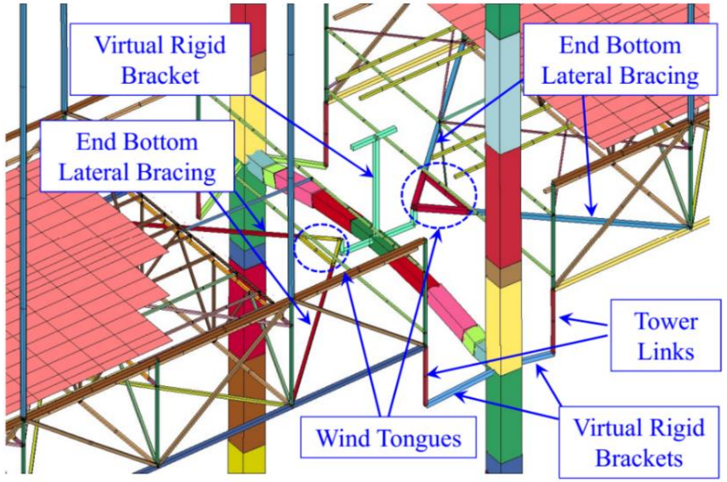
Main cable near tower saddle.



Interior Expansion Joints (IEJ) between deck panels.



IEJ between stringers.



Connections between stiffening trusses and tower at the lower strut

Ship Impact on the Suspension Bridge: **Center Impact**

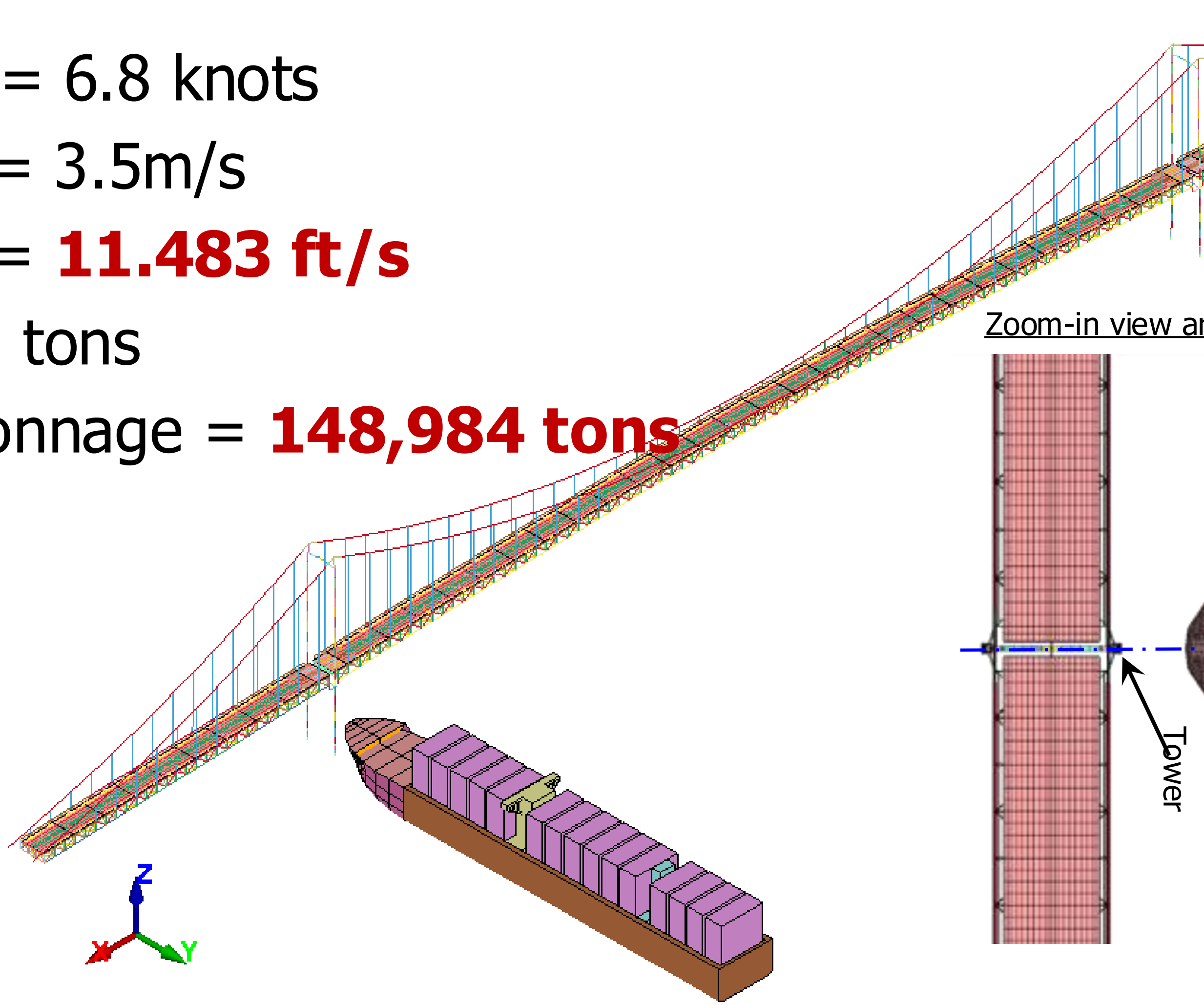
Impact velocity = 6.8 knots

= 3.5m/s

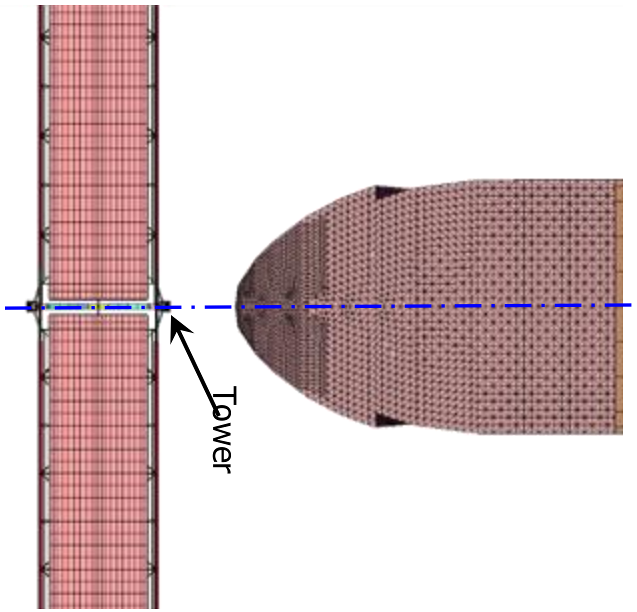
= **11.483 ft/s**

DWT = 116,851 tons

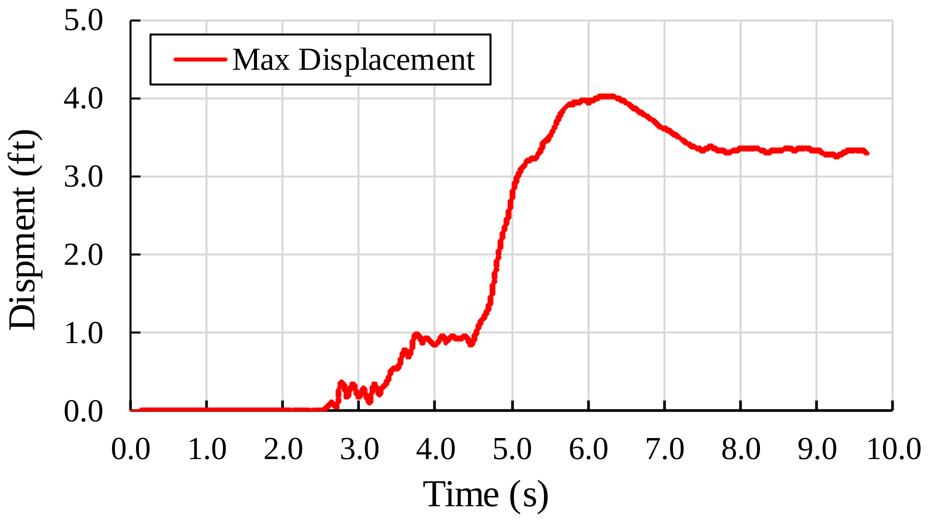
Displacement Tonnage = **148,984 tons**

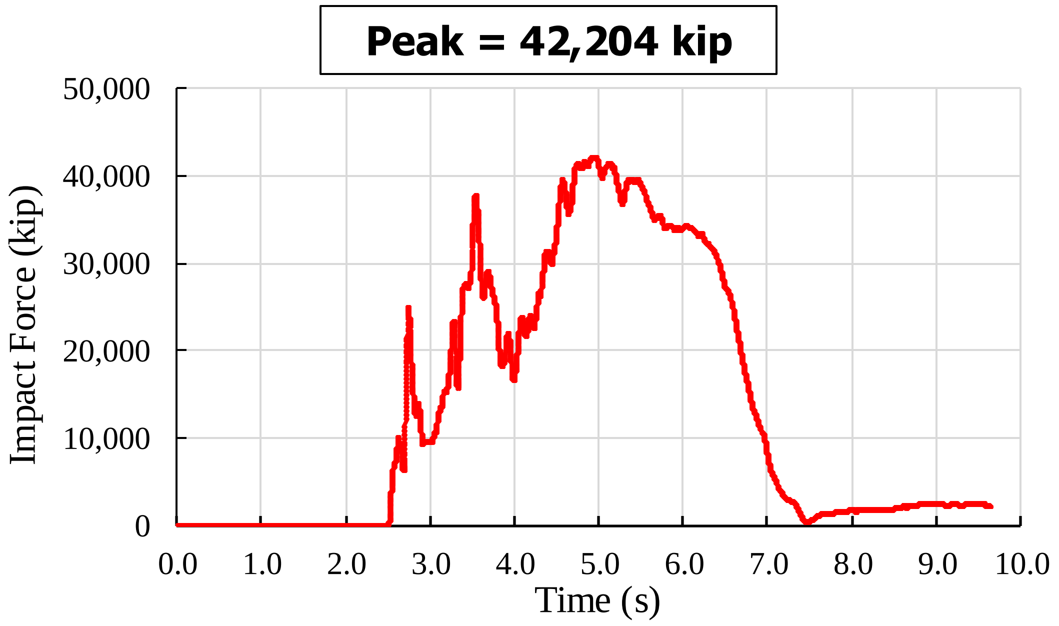


Zoom-in view around tower



Ship Impact on the Suspension Bridge: Center Impact

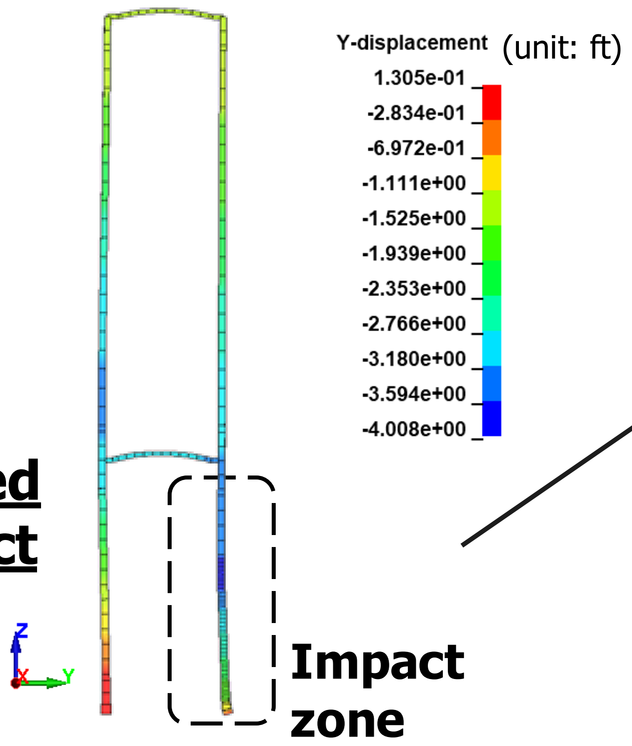


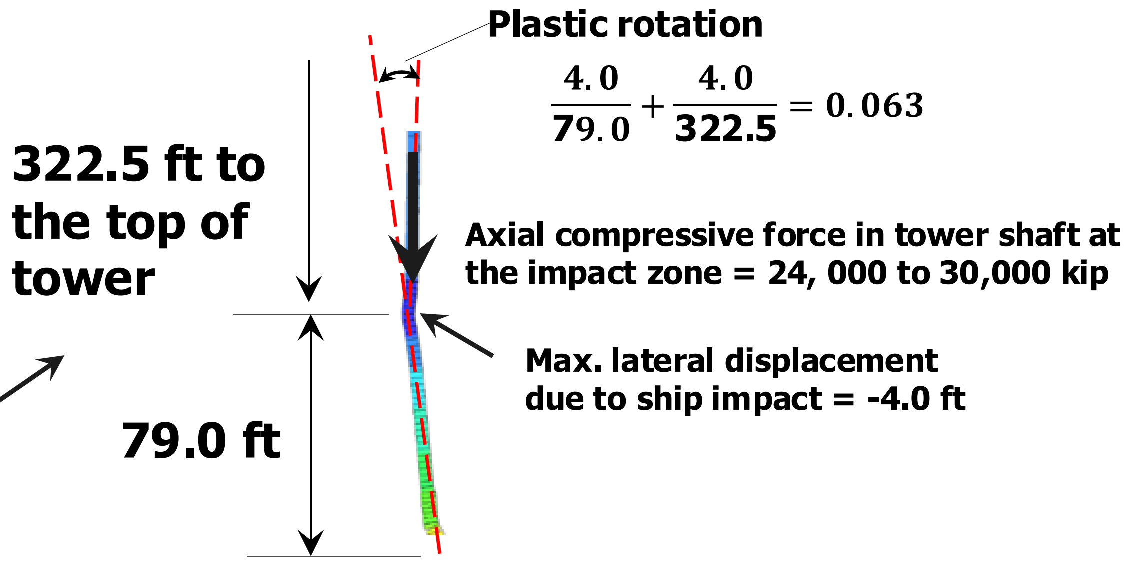


Time Histories of Max. Displacement and Impact Force of Tower Shaft

Ship Impact on the Suspension Bridge: Center Impact

Tower Subjected to Impact

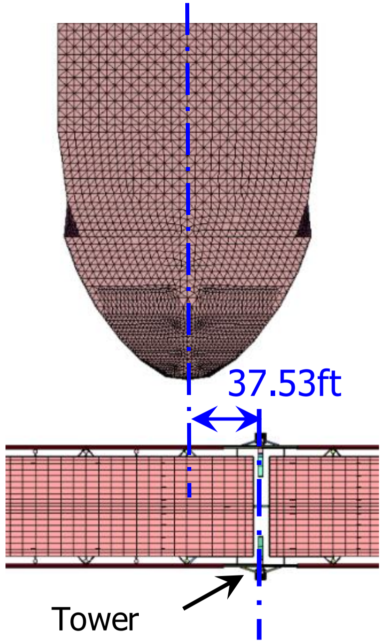


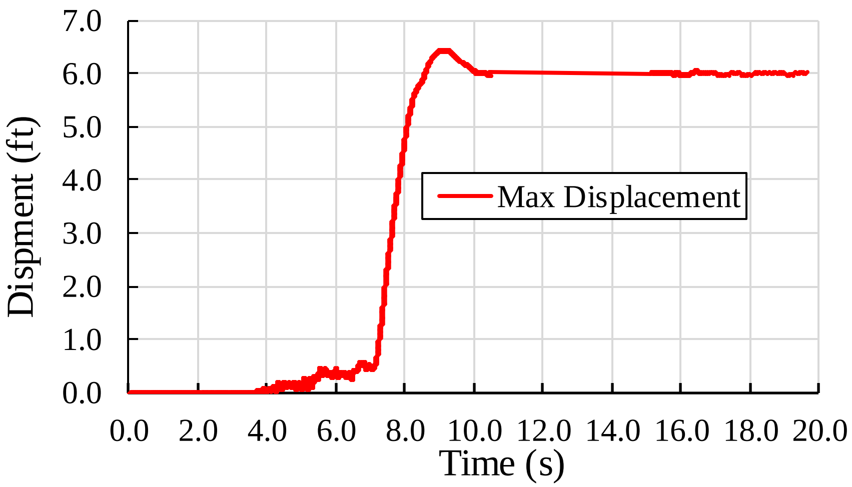


Close-up view of tower shaft at impact zone (scale factor =3)

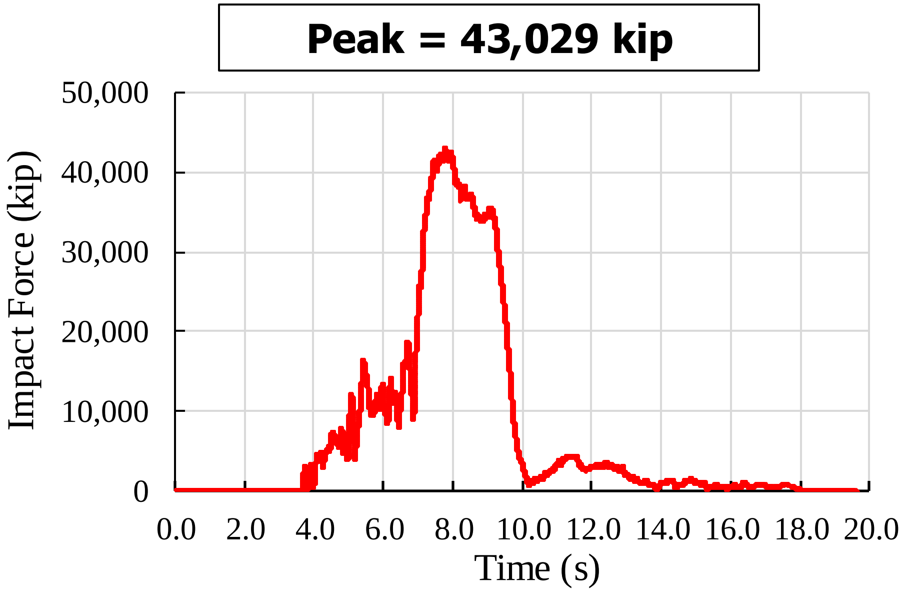
Bridge tower severally damaged, but the bridge collapse was prevented.

Ship Impact on the Suspension Bridge: Off-Center Impact





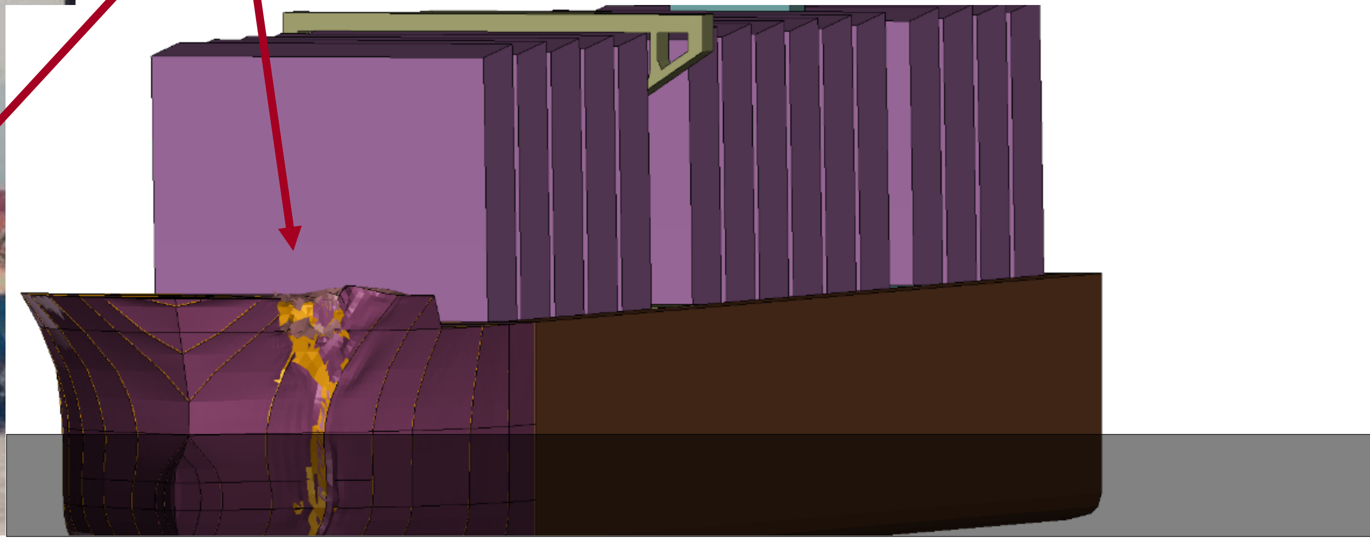
Time History of Max. Displacement



Time History of Impact Force

Ship Impact on the Suspension Bridge: Off-Center Impact

Damage to ship



Robustness Must Be Ensured for Long Span Bridge

- What is the design ship?
  - There will always be a bigger ships (33,000 GWT for Sunshine Skyway to approximately 115,000 GWT for Francis Key Bridge).
  - Can we limit the size and characteristics of ships using American ports?
- Design philosophy: employ a **multilayered approach** to prevent direct impact on bridge piers
  - Ensure a **minimum lateral** resistance for piers
  - Deploy supplementary protective systems such as: **barriers, raised concrete platforms, islands, rock walls, energy absorbing fenders, or a combination of systems**.
  - Develop a performance-based design approach for protective system:
    - No damage for low level impact
    - Acceptable damage for high level impact but bridge will not collapse
    - Use simulation to assess performance and develop meaningful acceptance criteria

Risk Management of bridges against large ship impacts

- **Long-span Bridges**: Very high value and very high consequence infrastructure assets
- **Collapse Vulnerability Assessment**: Direct computational simulation to develop reliable assessment
  - Maximum credible risk ship
  - Future increase in ship
  - Current capacity and need to increase capacity in future
  - Safety guaranteed in **absolute terms**. **No need for probabilistic risk, when the risk of disproportionate damage is so high.**