SHIP IMPACT FORCES AND RESISTING STRATEGIES ON INLAND WATERWAYS

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ABSTRACT

The collision of ships with bridge piers poses a significant hazard for bridges over major waterways with heavy ship traffic. The impact forces from such collisions can be extremely high, potentially becoming a critical design factor. This paper outlines some of the strategies implemented by LAP in already built examples like the Second Orinoco Bridge and the Rosario-Victoria Bridge, explaining the solutions adopted and the different analyses performed. Additionally, the latest research carried out by LAP on inland waterways ship impacts are presented, exploring how different parameters influence energy absorption and the resulting impact forces.

KEYWORDS: Ship impact, Vessel collision, Inland waterways, Nonlinear analysis, Dynamic analysis, Plastic hinge, Orinico, Rosario-Victoria.

1. Introduction

The collision of ships with bridge piers poses a significant hazard for bridges over major waterways with heavy ship traffic. The impact forces from such collisions can be extremely high, potentially becoming a critical design factor. Different strategies may be adopted to protect against the ship collision:

1. Out of reach pier:
   This is the safest method for protecting the pier and it could be achieved by either building artificial islands or increasing the span so that the piers are located onshore.
2. Strong pier:
   If placing out of reach piers are not possible, either because of deep or wide waterways, an alternative approach is to design the piers strong enough to withstand the collision forces themselves (hard impact).
3. Independent protective structures:
   If the above strategies are not feasible due to high impact energies and wide/deep waterways, independent sacrificial structures can be designed in front of the pier in order to absorb the kinetic energy through large plastic deformations (soft impact).

2. Independent protective structures

This chapter explores several LAP-built projects featuring independent protective structures, with a focus on examples such as the Second Orinoco Bridge and the Rosario-Victoria Bridge. These case studies highlight the design and implementation of protective measures to mitigate the risks associated with ship collision.

2.1 Rosario Victoria bridge

The fixed link between the cities of Rosario and Victoria provides a second connection between two provinces in Argentina, Santa Fe and Entre Rios. This link comprises a 350m span cable-stayed bridge across the Paraná River, its approaches on both sides of the river and the protection structures against the impact of aberrant vessels with sizes up to 100000 tons.

With the navigation channel located in the centre of the main span of the cable stayed bridge, the pylons and piers of the main bridge are under the risk of impact by aberrant ships. Due to the deep foundations with provisions for deep scouring, separate protection structures were found to be the adequate ship impact resisting strategy.

Figure 1. Rosario Victoria Bridge

The structural analysis and design of the protection structures is the final step in a series of studies and investigations dealing with the impact scenario. These are the ship traffic study, the investigation of relevant ship geometry, the geotechnical report, the analysis of natural protection and the scour analysis. The relevant data from the traffic study and all possible sailing courses are considered and applied in the probabilistic analysis. Based on the virtual resistance of piers and / or protection structures, the probabilistic analysis led to the total annual frequency of collapse and defined the design ships and corresponding kinetic energy to be considered for each pier. As a result, the defence structures for the main towers were designed for a ship of 43000 displacement tons sailing downstream at 4.64 m/s and a kinetic energy of KE = 453 MNm. This ship's size is about 204 m x 32 m.

The selection of the protection system was conditioned by the need to absorb high impact energies and also to cope with erosion and scour in the range of 20 to 30 meters. The most important advantage of the independent protection systems is the sacrificial use of all these structures, allowing large deformations that lead to a reduction of the impact forces.

The protection structures consist of a concrete platform supported by 2 m diameter composite steel piles filled with concrete. The platforms have clear distances of 17.5 m to the bridge foundation to allow large horizontal displacements when subject to impact under the maximum scour scenario (refer to Figure 2 and 3).

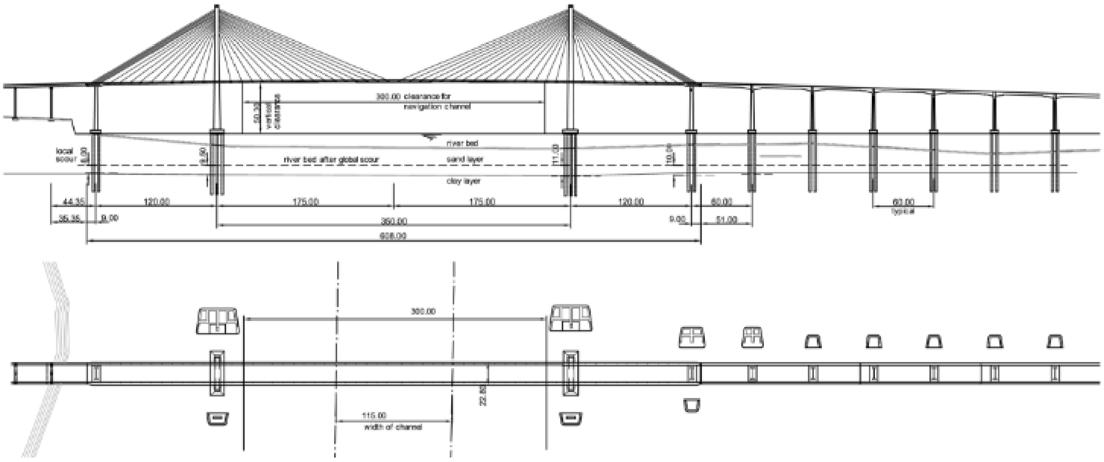

Figure 2. Rosario Victoria bridge view and plan of the main bridge and protective structures

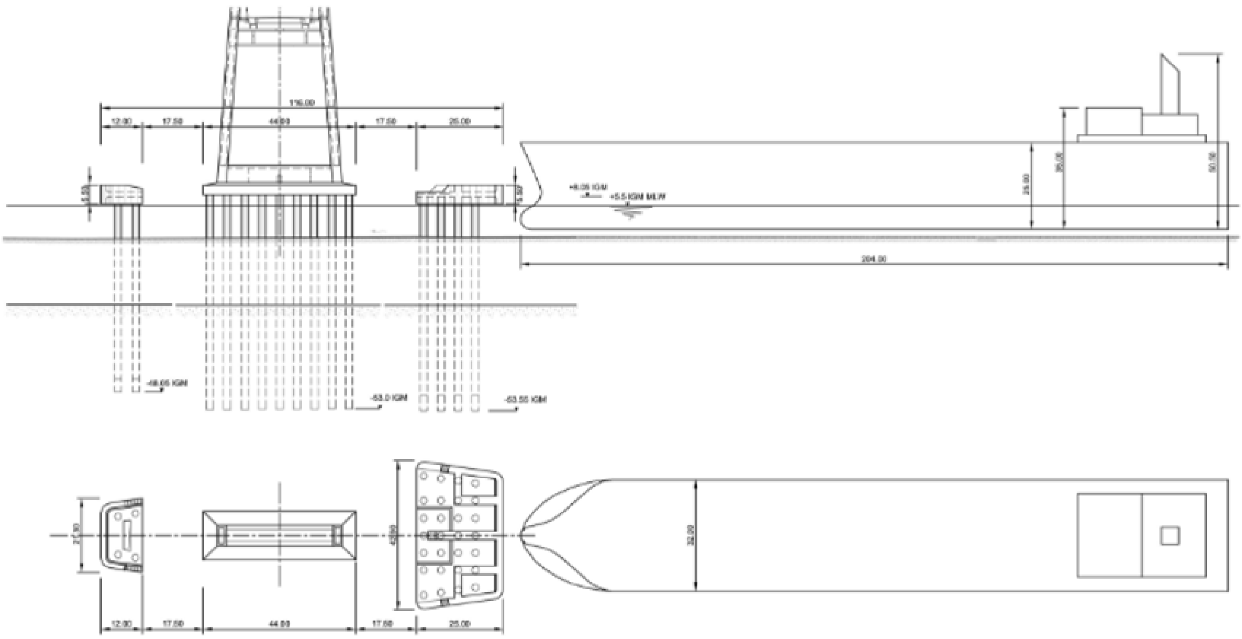

Figure 3. Rosario Victoria independent protective structures.

The absorbed impact energy originates from the load-deflection characteristics of the piles (Figure 4). The platform is very rigid and is designed to ensure uniform displacement across all piles, thereby activating the full energy absorption mechanism of the protective structure. The mechanical behavior of the piles under ship impact loads is a complex phenomenon due to the geometrically nonlinear behavior of the pile-soil system, as well as the nonlinear mechanical properties of both the soil and the piles within the expected deflection range.

The analysis of the pile-soil system was carried out by means of a numerical model with the SOFISTIK software based on a non-linear formulation of beam elements and lateral springs. The development of a plastic hinge in the composite pile results in a maximum rotation of approximately 20°. The plastic deformation zone in the pile extends over a range of 16 to 20 meters, depending on soil stiffness and free pile length (scour). Furthermore, the location of the plastic hinge varies along the pile length due to the changes in the riverbed level, which significantly influences the sizing and material distribution of the composite pile.

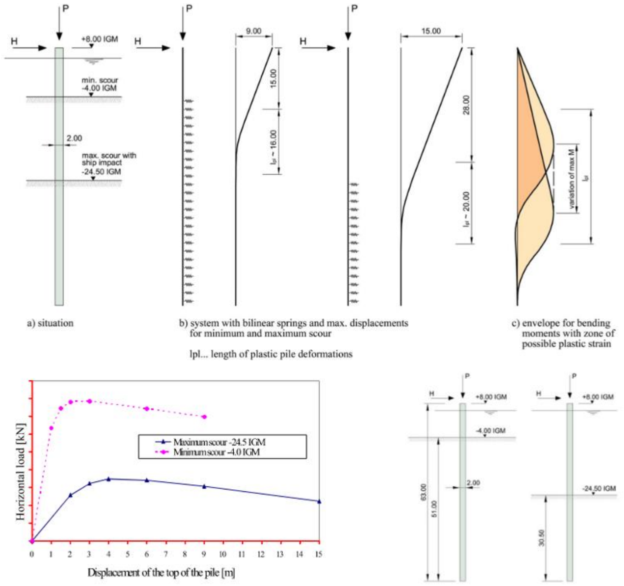

Figure 4. Pile non-linear load-deflection.

Design calculations indicated that the maximum scour condition requires the greatest platform displacement to absorb the design impact energy, corresponding to a 15 meter lateral displacement. This represents a limiting factor for the design.

Regarding the ductility capacity of the composite pile, particular attention was given to assessing the buckling behavior of the steel casing. While most codes impose diameter-to-thickness limitations to ensure local buckling stability of the steel casing, these requirements would result in uneconomical casing thicknesses. Therefore, it was decided to incorporate perfobond-type connectors to prevent local outward buckling. To validate this approach, load tests were conducted at the laboratories of Córdoba University, Argentina (Figure 5). The tests showed a monotonically increasing load until failure, with the failure mode characterized by tension in the steel and local buckling on the compression side as a consequence. A test calculation was performed to simulate this laboratory tests (Figure 6).

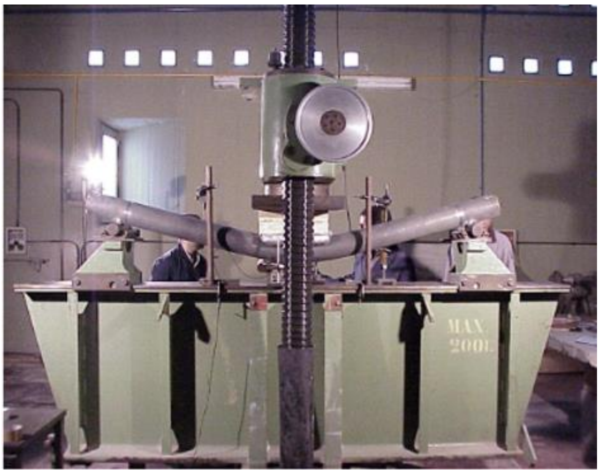

Figura 5. Plastic hinge laboratory test.

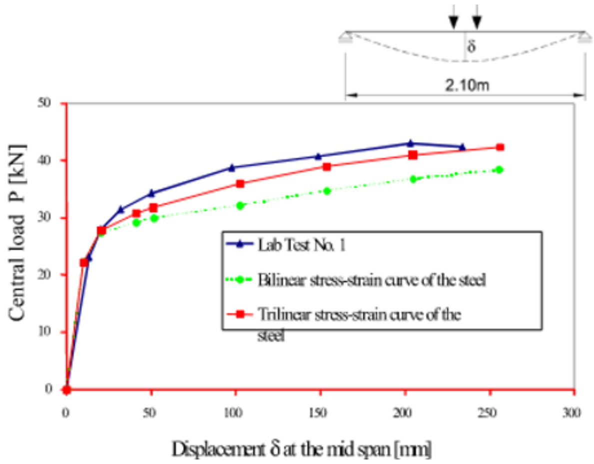

Figure 6. Test calculation to simulate laboratory test.

2.2 Second Orinoco bridge

This Road and Rail Bridge has a total length of 3,156 meters, featuring two cable-stayed sections with main spans of 300 meters each. The deck is designed as a steel-concrete composite girder. The cable-stayed portions are built using the free-cantilever method, while the approach viaducts are built through incremental launching.

The deep pile foundations, reaching depths of 80 meters, were specifically designed to address the challenging river conditions, where water depths range from 12 to 40 meters. To mitigate the risk of ship collisions, independent protective structures were adopted as the primary impact resisting strategy. Comprehensive studies on vessel collision scenarios were conducted to ensure the safety of this combined Road and Rail Bridge.

Figure 7. Second Orinico bridge.

The ship traffic on the river primarily consists of large barge tows with configurations of 3 x 5 or 5 x 5. For the vessel navigation at the bridge, two channels have been designated: the north and south channels (Figure 8). The 5x5 configuration, including the tugboat, has an overall length of approximately 350 meters, a total width of 53.3 meters, and a displacement of 71165 tons.

A detailed probabilistic analysis of both barge tow configurations was conducted in compliance with AASHTO regulations. This analysis determined the number of required independent protection systems and their necessary design resistance. As a result, independent ring defense structures, supported by deep piles, were designed (Figure 9). These structures incorporate provisions for plastic hinge development, serving as the primary energy dissipation mechanism.

Figure 8. La figura puede disponerse con una anchura similar a la de una columna.

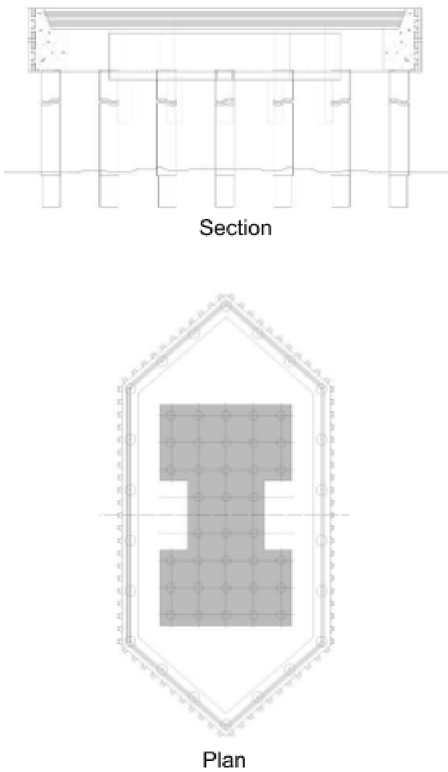

Figure 9. Independent ring defense structure for second Orinoco bridge.

3. Strong piers

This chapter presents the Third Orinoco Bridge as a key example where the "strong piers" strategy was implemented. Additionally, it highlights the latest in-house research conducted on the derivation of impact forces in inland waterways, providing valuable insights into the factors influencing pier design.

3.1 Third Orinoco bridge

The Third Orinico bridge is a combined Road and Rail Bridge with a total length of 11125 meters, crossing the Orinoco river and its floodplain. This significant infrastructure project comprises the river crossing and approach viaducts on both sides.

Figure 10. Third Orinoco bridge.

The 4440 m long double deck river crossing includes a 1080 m main bridge and two 1680 m approach bridges. The deck of the combined road and rail bridge features a steel composite truss girder. The 19.9-meter wide upper deck accommodates four lanes of road traffic, while the lower deck includes the railway located inside the truss. The truss depth is a constant 12.0 meters throughout the entire length of the bridge. A stay-cable main bridge with 360 m main span and central cable plane is designed for the crossing of the 320 m wide navigation channel.

The substructure features diamond-shaped concrete pylons with a height of 135 meters, supported by piles with a diameter of 2.5 meters and lengths of up to 80 meters. The side spans of the cable-stayed bridge, along with the spans of the approach bridges, have a uniform length of 120 meters. All substructures are meticulously designed to withstand ship impact loads. To evaluate their resistance capacity against potential ship collisions, nonlinear time history analyses were conducted, ensuring the robustness and safety of the bridge under such scenarios.

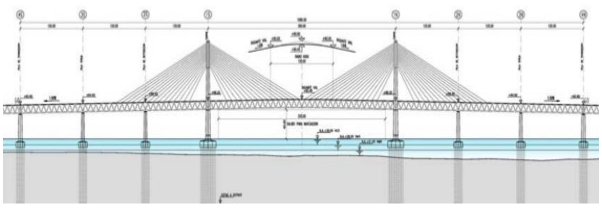

Figure 11. Third Orinoco bridge elevation.

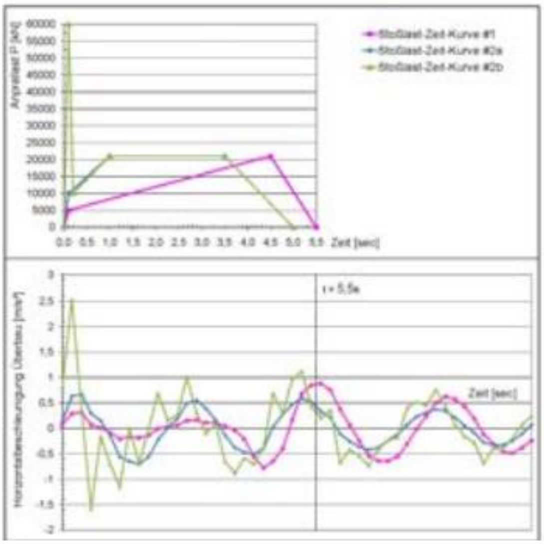

Figure 12. Load time and acceleration history for subestructure

3.2 Research on inland waterways impact forces

During a barge collision against a strong pier, the deformation and damage of the colliding barge's bow absorb most of the kinetic energy. Consequently, the crushing behaviour of the bow significantly influences the impact force exerted on the pier.

To better evaluate the design forces acting on these piers, a research study was conducted at LAP using finite element (FE) parametric analysis of various barge impact scenarios. This approach provides a more accurate assessment of the forces involved, ensuring the piers are designed to withstand such impacts effectively.

A standard inland waterway Jumbo hoper barge (JH) is adopted for these analyses, with the dimensions highlighted in table 1, and a fully loaded weight of 1723.7 tons.

Table 1. Barge dimensions.

Description	Symbol	Dimension (mm)
Barge length	Lb	59.48
Barge width	Wb	10.68
Depth of bow	hb	3.97
Head log height	Hl	0.76
Depth of barge	Hv	3.66
Bow rake length	rl	6.10

Shell elements are utilised to model the barge's outer skin, while the bow consists of an array of evenly spaced internal trusses. For analytical purposes, the barge model is divided into two distinct zones: Zone 1, which includes the front section and extends 6.10 meters, and Zone 2, which comprises the rear section and spans 53.38 meters, as illustrated in Figure 13. This division is based on the differing deformation behaviors observed during impact.

The contact between the barge and the pier column is simulated using automatic surface-to-surface contact, which is a method that accurately captures the interaction between the two surfaces. Additionally, different pier geometries are analysed in order to assess how their shape influences the impact force exerted on the pier. These pier elements are modelled using rigid material and solid elements.

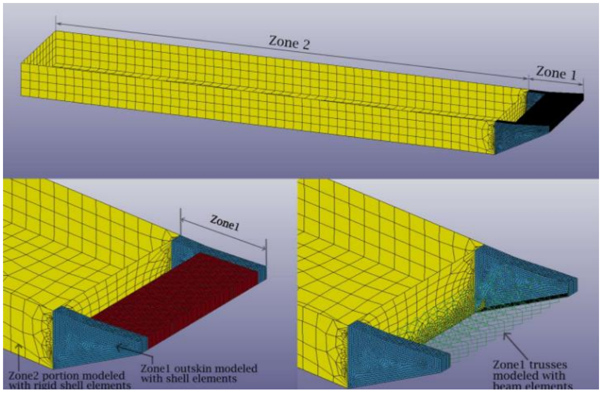

Figure 13. Barge FE model

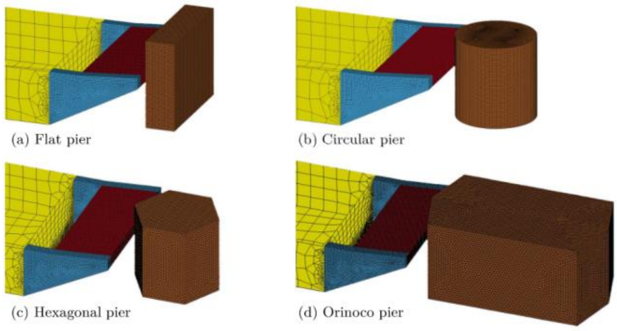

Figure 14. Barge FE model with different pier shapes

A series of four different pier cross-sections were analysed, varying the pier width-to-barge width ratio (α). The first set featured flat cross-sections, the second set circular cross-sections, the third set regular hexagonal cross-sections, and the fourth set irregular hexagonal cross-sections, as illustrated in Figure 14. To evaluate the impact forces, simulations were performed using a fully loaded barge at three different impact velocities: 2.00 m/s, 3.00 m/s, and 4.00 m/s. Each velocity scenario was analysed for all pier cross-section types to understand their behavior under collision conditions.

The resulting time histories of impact forces and barge bow crushing depths are shown in Figures 15 and 16 for the flat and circular piers. These profiles generally follow a pattern: a rapid rise to a peak force shortly after impact, followed by a sharp drop until a force plateau after the barge's inner bow trusses buckle locally. It is worth noting that the peak force for the rigid circular and hexagonal piers are significantly lower than that of the rigid flat pier with the same α value. This reduction is likely attributed to the gradual increase in contact area between the barge's bow and the pier, which causes greater bow deformation and requires lower forces to absorb the same kinetic energy.

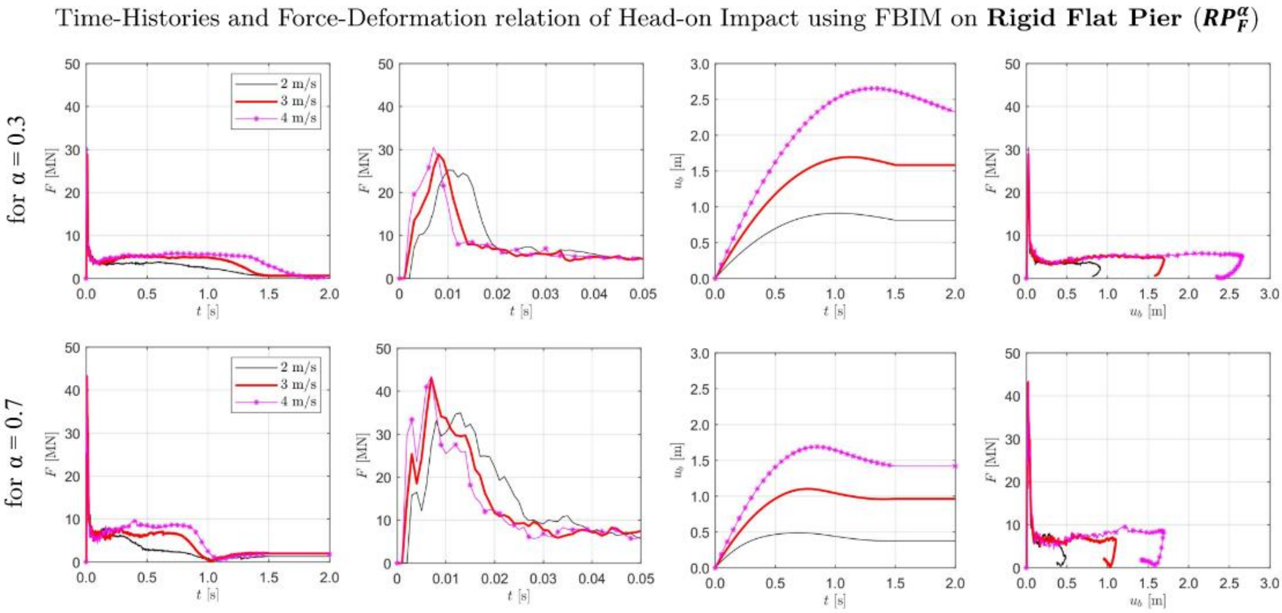

Figure 15. Time histories and force-deformation on rigid flat pier

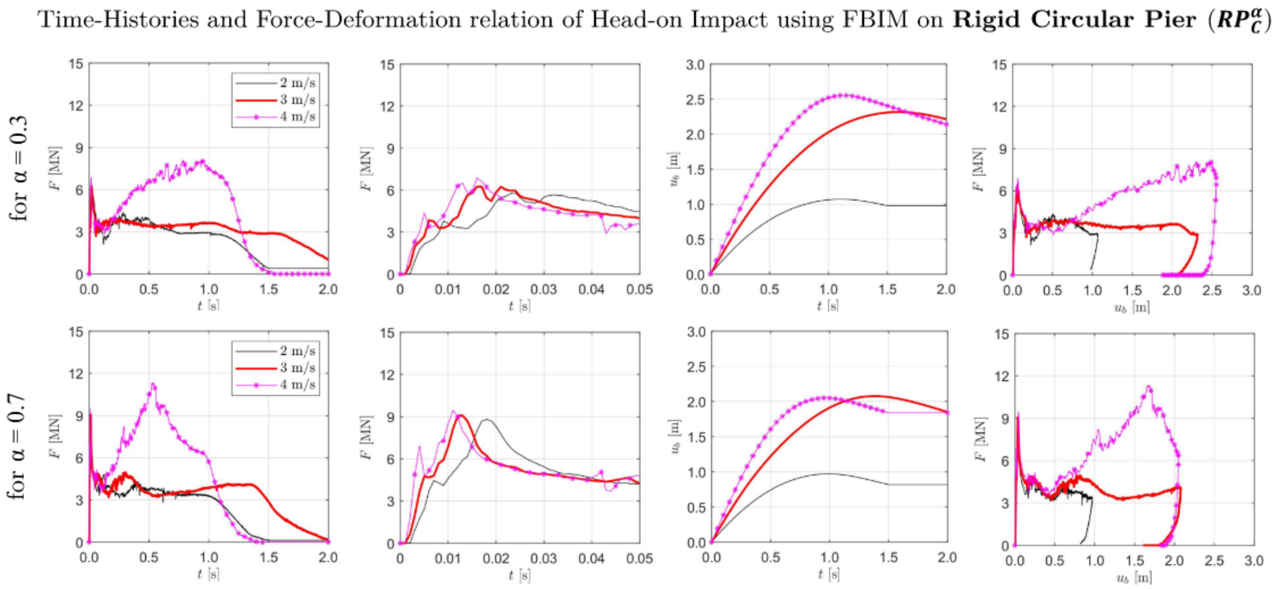

Figure 16. Time histories and force-deformation on rigid circular pier

Additionally, smaller pier widths (lower α ratios) correspond to reduced impact forces, while higher impact velocities result in greater forces and more severe crushing of the barge bow, as summarised in Table 2.

Table 2. Maximum impact forces Fmax (MN)

Pier (α=0.7)	2 m/s	3 m/s	4 m/s
Flat	34.95	43.14	43.46
Circular	8.80	9.10	11.30
Hexagonal	4.42	6.20	10.72

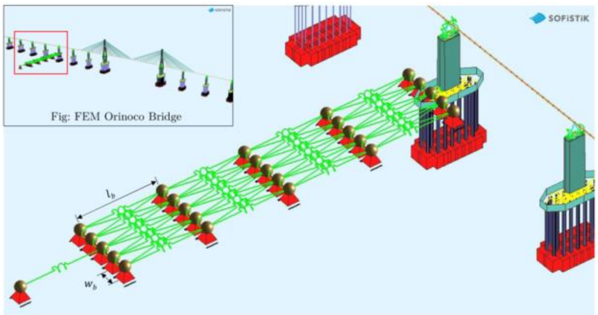

Figure 17. FL5x5 barge flotilla NSM

Based on the results presented above, a nonlinear spring model was developed to study the impact of multi-barge flotillas, using the Third Orinoco Bridge as a benchmark for this analysis. In this model, the bow is represented as a nonlinear spring element connected to the pier of the cable-stayed bridge, while the barges are modeled as nodal masses connected to the spring. In multi-barge flotillas, the barges are typically connected using various methods to ensure stability, maneuverability, and safety during transport. Stranded wire ropes (lashings) are commonly used to tie the barges together within the flotilla. This connection is represented in the model by tension-only springs between adjacent barges.

A transient dynamic analysis was performed for two flotilla configurations: a 5x5 multi-barge arrangement with a pusher and a single column of five barges. The comparison of results from the dynamic analysis of the single-barge column and the multi-barge flotilla revealed that the response of the impacted pier is significantly greater for the multi-barge configuration compared to the single-barge column during a collision. Furthermore, the lashing configuration has a more pronounced effect on the impact response of the multi-barge flotilla at lower velocities, with the influence decreasing as the impact velocity increases.

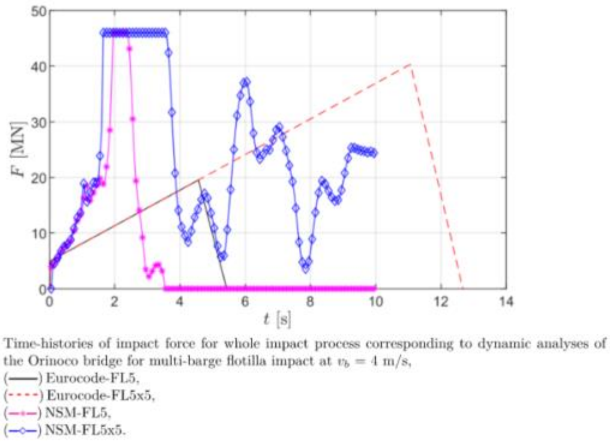

Figure 18. Time history of impact force for different barge configurations for the Orinico bridge

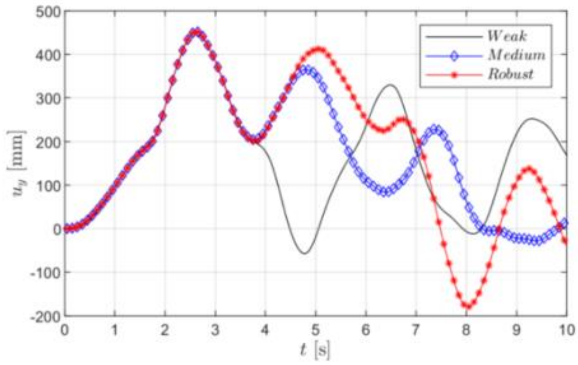

Figure 19. Time history of pier top displacement for different lashing configurations

It can be concluded that, the shape and size of the pier cross-section play a critical role in determining the forces exerted by barges during collisions. Furthermore, the configuration of the multi-barge flotilla significantly influences the overall impact behavior. These important factors are not yet fully accounted for in existing structural design codes.

4. Conclusions

This paper outlines three main strategies for resisting ship impacts on inland waterway bridges: out-of-reach piers, strong piers, and independent protective structures. Case studies like the Rosario-Victoria and Second Orinoco bridges demonstrate the use of sacrificial independent protective structures, where large deformations are anticipated. In contrast, the Third Orinoco bridge exemplifies the strong pier approach, where piers are designed to directly withstand collision forces. Additionally, LAP's internal research highlights the critical role of pier cross-section shape and size in determining the forces exerted by barges during collisions. Moreover, the configuration of the multi-barge flotilla significantly influences the overall impact behavior. These important factors are not yet fully accounted for in existing structural design codes.

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