# Performance-Based Vessel Collision Modelling

**Peter Matusewitch, P.E.**
Associate
Ove Arup and Partners PC
New York, NY, USA
*Peter.Matusewitch@arup.com*

Peter Matusewitch received his civil engineering degree from Polytechnic University in New York. He has 20 years experience in design and rehabilitation of conventional, long span and movable bridges at Hardesty & Hanover, Parsons Transportation Group and now with Arup. He was the Project Engineer for this study.

## Summary

A performance-based dynamic vessel collision analysis was performed to access the vulnerability of the in-water anchorages of a suspension bridge, using the LS-DYNA software package. Failure was defined as either penetration of the design vessel through the outer curtain walls or undermining of the main cable saddle supports. The damage to the reinforced concrete was given in terms of plots of maximum principle strain after impact, and before and after plots of stresses in the buttresses supporting the cable saddles.

**Keywords:** bridges; suspension bridges; vessel collision design; dynamic impact modelling; performance-based design.

## 1. Introduction

Preliminary studies by others had concluded that the anchorages of a major U.S. suspension bridge were vulnerable to aberrant vessel collisions. Arup was retained to design internal strengthening retrofits. The anchorages each comprise two massive reinforced concrete anchor blocks with embedded cable anchor grillages, two hollow reinforced concrete buttress cells to support the cable saddles, and reinforced concrete curtain walls that enclose the cable splay chamber. One anchorage is located in deep water and the other straddles the shore, partially in shallow water.

## 2. Methodology

The collision risk analysis was based on Method II of the AASHTO Guide Specifications and Commentary on Vessel Collision Design of Highway Bridges (1991). As a critical bridge, the risk acceptance criterion was an Annual Frequency of Collapse (the probability of bridge collapse from a vessel collision in any given year) of 0.0001, or 1 in 10 000. The collision risk assessment yielded different design vessels and speeds for each anchorage.

Static design impact forces are typically applied to bridge substructure units, which are then designed elastically. This type of simplified pass/fail approach will not capture the true capacity of the existing anchorages of a suspension bridge to withstand an impact without collapse of the bridge. In line with more recent thinking on design for extreme events such as earthquakes, Arup used a performance-based assessment to more rigorously define the risk of bridge collapse and to assess the efficacy of retrofit alternatives. To assess the impact resistance of the bridge anchorages the dynamic and non-linear, large-deformation behavior of the impact events were simulated using the LS-DYNA software package.

The sections curtain wall enclosing the cable splay chamber, and below the cable saddle, were identified as potentially vulnerable impact locations. Finite element models of each anchorage were created. The curtain wall and the areas close to the impacted side of the anchorages were modelled using a non-linear concrete material model which allows a steel reinforcement percentage to be specified. The concrete material and steel reinforcement were given properties typical for the U.S. at the time. The material model used accounts for various types of non-linear concrete behavior

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including increase in compressive strength due to confinement, anisotropic cracking/loss of strength due to tensile stresses, and strain-softening due to damage in tension. The concrete away from the impacted side was assumed to behave elastically.

A simplified model of the ship was developed to apply the appropriate loading to the anchorage model, comprising a rigid impacting plate that represented the size and shape of the crushed bow; a rigid mass representing the displacement tonnage of the ship; and a non-linear spring to represent the crushing characteristics of the ship bow.

## 3. Results

The dynamic analyses found that the smaller design ship for the shallow water anchorage would not penetrate the curtain wall at either impact location. The energy of the impact would mostly be dissipated in the crushing of the ship bow. Principle concrete strains after impact generally would be less than 0.2%, indicating that concrete cracking would be limited and easily repairable. This meets the performance criteria, and no strengthening will be required for this anchorage.

The analyses found that the larger design ship for the deep water anchorage did penetrate through the curtain wall at both impact locations. This does not meet the performance criteria. Before and after plots of principle compressive stresses in the cable saddle buttress revealed that while the stresses in the buttress would increase, they would still be well within the concrete compressive strength, so the impact would not undermine the cable saddle.

Arup developed several strengthening alternatives for each impact location, which included reinforcing the vulnerable wall at the cable splay chamber with either concrete or a steel frame; and filling the hollow cable saddle buttress cell with concrete, sand or a steel frame. Each alternative was added to the model of the deep water anchorage, and the dynamic analyses were repeated to test their efficacy. The alternatives all prevented penetration of the ship into the anchorage, meeting the performance criteria, but they differed in cost and the extent of damage that would result.

## 4. Conclusions and Acknowledgments

Analysis and design of bridges for extreme events such as earthquakes and hurricanes has evolved from elastic, force-based, design procedures to non-linear, inelastic performance-based assessments. Design for large vessel collisions has begun to make the same evolution. This project extended this approach to a collision vulnerability assessment of an existing structure.

The AASHTO design method, while force-based, provides a rational basis for establishing the non-linear behavior of a design vessel during impact. Rather than simply reducing this to static design forces, the availability of non-linear, dynamic software packages such as LS-DYNA permits explicit investigation of the behavior of a structure during a collision, providing a more realistic performance-based assessment. This allows the owner to make informed decisions regarding the risk of collapse. Armed with this knowledge, owners are in a much better position to evaluate the best use of limited funds for addressing the various vulnerabilities that major structures face.

Earlier risk assessments and simplified elastic, force-based analyses by others had suggested that as much as 9 to 10 m of reinforced concrete would be required to harden the anchorage curtain walls. More rigorous collision risk assessment, combined with non-linear, dynamic analyses and a performance-based approach, concluded that no strengthening was needed at one anchorage and as little as 1.2 m of reinforced concrete would be sufficient in the other. This is a vivid illustration of the potential of this approach to rationalize design for vessel collisions, and the potential cost savings that may be realized.

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