

Knott, M., Pruca, Z. "Vessel Collision Design of Bridges."  
*Bridge Engineering Handbook*.  
Ed. Wai-Fah Chen and Lian Duan  
Boca Raton: CRC Press, 2000

# 60

## Vessel Collision Design of Bridges

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## Notations

The following symbols are used in this chapter. The section number in parentheses after definition of a symbol refers to the section or figure number where the symbol first appears or is identified.

$AF$  annual frequency of bridge element collapse (Section 60.5.2)

$B_M$  beam (width) of vessel (Figure 60.2)

$B_p$  width of bridge pier (Figure 60.2)

$DWT$  size of vessel based on deadweight tonnage (one tonne = 2205 lbs = 9.80 kN) (Section 60.4.1)

$H$  ultimate bridge element strength (Section 60.5.2)

$N$  number of one-way vessel passages through the bridge (Section 60.5.2)

$P$  vessel collision impact force (Section 60.5.2)

$P_{BH}$  ship collision impact force for head-on collision between ship bow and a rigid object (Section 60.6.1)

$P_{DH}$  ship collision impact force between ship deckhouse and a rigid superstructure (Section 60.6.1)

$P_{MT}$	ship collision impact force between ship mast and a rigid superstructure (Section 60.6.1)
$P_S$	ship collision impact force for head-on collision between ship bow and a rigid object (Section 60.6.1)
$PA$	probability of vessel aberrancy (Section 60.5.2)
$PC$	probability of bridge collapse (Section 60.5.2)
$PG$	geometric probability of vessel collision with bridge element (Section 60.5.2)
$R_{BH}$	ratio of exposed superstructure depth to the total ship bow depth (Section 60.6.1)
$R_{DH}$	reduction factor for ship deckhouse collision force (Section 60.6.1)
$V$	design impact speed of vessel (Section 60.6.1)
$x$	distance to bridge element from the centerline of vessel transit path (Figure 60.2)
$\phi$	angle between channel and bridge centerlines (Figure 60.2)

## 60.1 Introduction

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### 60.1.1 Background

It was only after a marked increase in the frequency and severity of vessel collisions with bridges that studies of the vessel collision problem have been initiated in recent years. In the period from 1960 to 1998, there have been 30 major bridge collapses worldwide due to ship or barge collision, with a total loss of life of 321 people. The greatest loss of life occurred in 1983 when a passenger ship collided with a railroad bridge on the Volga River, Russia; 176 were killed when the aberrant vessel attempted to transit through a side span of the massive bridge. Most of the deaths occurred when a packed movie theater on the top deck of the passenger ship was sheared off by the low vertical clearance of the bridge superstructure.

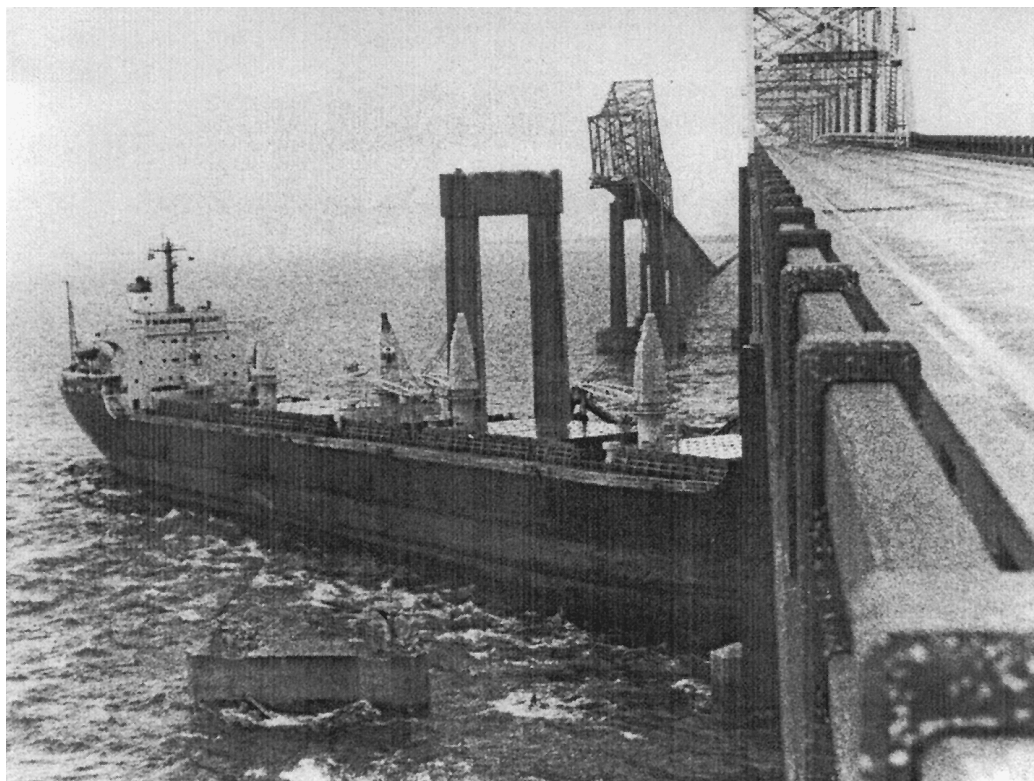
Of the bridge catastrophes mentioned above, 15 have occurred in the United States, including the 1980 collapse of the Sunshine Skyway Bridge crossing Tampa Bay, Florida, in which 396 m of the main span collapsed and 35 lives were lost as a result of the collision by an empty 35,000 DWT (deadweight tonnage) bulk carrier (Figure 60.1).

One of the more publicized tragedies in the United States involved the 1993 collapse of a CSX Railroad Bridge across Bayou Canot near Mobile, Alabama. During dense fog, a barge tow became lost and entered a side channel of the Mobile River where it struck a railroad bridge causing a large displacement of the structure. The bridge collapsed a few minutes later when a fully loaded Amtrak passenger train attempted to cross the damaged structure; 47 fatalities occurred as a result of the collapse and the train derailment.

It should be noted that there are numerous vessel collision accidents with bridges which cause significant damage, but do not necessarily result in collapse of the structure. A study of river towboat collisions with bridges located on the U.S. inland waterway system during the short period from 1970 to 1974 revealed that there were 811 accidents with bridges costing \$23 million in damages and 14 fatalities. On the average, some 35 vessel collision incidents are reported every day to U.S. Coast Guard Headquarters in Washington, D.C.

A recent accident on a major waterway bridge occurred in Portland, Maine in September 1996 when a loaded tanker ship (171 m in length and 25.9 m wide) rammed the guide pile fender system of the existing Million Dollar Bridge over the Fore River. A large portion of the fender was destroyed; the flair of the ship's bow caused significant damage to one of the bascule leafs of the movable structure (causing closure of the bridge until repairs were made); and 170,000 gallons of fuel oil were spilled in the river due to a 9-m hole ripped in the vessel hull by an underwater protrusion of the concrete support pier (a small step in the footing). Although the main cause of the accident was attributed to pilot error, a contributing factor was certainly the limited horizontal clearance of the navigation opening through the bridge (only 29 m).

The 1980 collapse of the Sunshine Skyway Bridge was a major turning point in awareness and increased concern for the safety of bridges crossing navigable waterways. Important steps in the development of modern ship collision design principles and specifications include:



**FIGURE 60.1** Sunshine Skyway Bridge, May 9, 1980 after being struck by the M/V *Summit Venture*.

- In 1983, a “Committee on Ship/Barge Collision,” appointed by the Marine Board of the National Research Council in Washington, D.C., completed a study on the risk and consequences of ship collisions with bridges crossing navigable coastal waters in the United States [1].
- In June 1983, a colloquium on “Ship Collision with Bridges and Offshore Structures” was held in Copenhagen, Denmark under the auspices of the International Association for Bridge and Structural Engineering (IABSE), to bring together and disseminate the latest developments on the subject [2].
- In 1984, the Louisiana Department of Transportation and Development incorporated criteria for the design of bridge piers with respect to vessel collision for structures crossing waterways in the state of Louisiana [3,4].
- In 1988, a pooled-fund research project was sponsored by 11 states and the Federal Highway Administration to develop vessel collision design provisions applicable to all of the United States. The final report of this project [5] was adopted by AASHTO as a Vessel Collision Design Guide Specification in February, 1991 [6].
- In 1993, the International Association for Bridge and Structural Engineering (IABSE) published a comprehensive document that included a review of past and recent developments in the study of ship collisions and the interaction between vessel traffic and bridges [7].
- In 1994, AASHTO adopted the recently developed LRFD bridge design specifications [8], which incorporate the vessel collision provisions developed in Reference [6] as an integral part of the bridge design criteria.
- In December 1996, the Federal Highway Administration sponsored a conference on “The Design of Bridges for Extreme Events” in Atlanta, Georgia to discuss developments in design

loads (vessel collision, earthquake, and scour) and issues related to the load combinations of extreme events [9].

- In May 1998, an international symposium on “Advances in Bridge Aerodynamics, Ship Collision Analysis, and Operation & Maintenance” was held in Copenhagen, Denmark in conjunction with the opening of the record-setting Great Belt Bridge to disseminate the latest developments on the vessel collision subject [10].

Current highway bridge design practices in the United States follow the AASHTO specifications [6,8]. The design of railroad bridge protection systems against vessel collision is addressed in the American Railway Engineering and Maintenance-of-Way Association (AREMA) Manual for Railway Engineering [11]. Research and development work in the area of vessel collision with bridges continues. Several aspects, such as the magnitude of the collision loads to be used in design, and the appropriate combination of extreme events (such as collision plus scour) are not yet well established and understood. As further research results become available, appropriate code changes and updates can be expected.

### 60.1.2 Basic Concepts

The vulnerability of a bridge to vessel collision is affected by a variety of factors, including:

- Waterway geometry, water stage fluctuations, current speeds, and weather conditions;
- Vessel characteristics and navigation conditions, including vessel types and size distributions, speed and loading conditions, navigation procedures, and hazards to navigation;
- Bridge size, location, horizontal and vertical geometry, resistance to vessel impact, structural redundancy, and effectiveness of existing bridge protection systems;
- Serious vessel collisions with bridges are extreme events associated with a great amount of uncertainty, especially with respect to the impact loads involved. Since designing for the worst-case scenario could be overly conservative and economically undesirable, a certain amount of risk must be considered as acceptable. The commonly accepted design objective is to minimize (in a cost-effective manner) the risk of catastrophic failure of a bridge component, and at the same time reduce the risk of vessel damage and environmental pollution.

The intent of vessel collision provisions is to provide bridge components with a “reasonable” resistance capacity against ship and barge collisions. In navigable waterway areas where collision by merchant vessels may be anticipated, bridge structures should be designed to prevent collapse of the superstructure by considering the size and type of vessel, available water depth, vessel speed, structure response, the risk of collision, and the importance classification of the bridge. It should be noted that damage to the bridge (even failure of secondary structural members) is usually permitted as long as the bridge deck carrying motorist traffic does not collapse (i.e., sufficient redundancy and alternate load paths exist in the remaining structure to prevent collapse of the superstructure).

### 60.1.3 Application

The vessel collision design recommendations provided in this chapter are consistent with the AASHTO specifications [6,8] and they apply to all bridge components in navigable waterways with water depths over 2.0 ft (0.6 m). The vessels considered include merchant ships larger than 1000 DWT and typical inland barges.

## 60.2 Initial Planning

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It is very important to consider vessel collision aspects as early as possible in the planning process for a new bridge, since they can have a significant effect on the total cost of the bridge. Decisions related to the bridge type, location, and layout should take into account the waterway geometry, the navigation channel layout, and the vessel traffic characteristics.

### **60.2.1 Selection of Bridge Site**

The location of a bridge structure over a waterway is usually predetermined based on a variety of other considerations, such as environmental impacts, right-of-way, costs, roadway geometry, and political considerations. However, to the extent possible, the following vessel collision guidelines should be followed:

- Bridges should be located away from turns in the channel. The distance to the bridge should be such that vessels can line up before passing the bridge, usually at least eight times the length of the vessel. An even larger distance is preferable when high currents and winds are likely to occur at the site.
- Bridges should be designed to cross the navigation channel at right angles and should be symmetrical with respect to the channel.
- An adequate distance should exist between bridge locations and areas with congested navigation, port facilities, vessel berthing maneuvers, or other navigation problems.
- Locations where the waterway is shallow or narrow so that bridge piers could be located out of vessel reach are preferable.

### **60.2.2 Selection of Bridge Type, Configuration, and Layout**

The selection of the type and configuration of a bridge crossing should consider the characteristics of the waterway and the vessel traffic, so that the bridge would not be an unnecessary hazard to navigation. The layout of the bridge should maximize the horizontal and vertical clearances for navigation, and the bridge piers should be placed away from the reach of vessels. Finding the optimum bridge configuration and layout for different bridge types and degrees of protection is an iterative process which weighs the costs involved in risk reduction, including political and social aspects.

### **60.2.3 Horizontal and Vertical Clearance**

The horizontal clearance of the navigation span can have a significant impact on the risk of vessel collision with the main piers. Analysis of past collision accidents has shown that bridges with a main span less than two to three times the design vessel length or less than two times the channel width are particularly vulnerable to vessel collision.

The vertical clearance provided in the navigation span is usually based on the highest vessel that uses the waterway in a ballasted condition and during periods of high water level. The vertical clearance requirements need to consider site-specific data on actual and projected vessels, and must be coordinated with the Coast Guard in the United States. General data on vessel height characteristics are included in References [6,7].

### **60.2.4 Approach Spans**

The initial planning of the bridge layout should also consider the vulnerability of the approach spans to vessel collision. Historical vessel collisions have shown that bridge approach spans were damaged in over 60% of the total number of accidents. Therefore, the number of approach piers exposed to vessel collision should be minimized, and horizontal and vertical clearance considerations should also be applied to the approach spans.

### **60.2.5 Protection Systems**

Bridge protection alternatives should be considered during the initial planning phase, since the cost of bridge protection systems can be a significant portion of the total bridge cost. Bridge protection systems include fender systems, dolphins, protective islands, or other structures designed to redirect, withstand, or absorb the impact force and energy, as described in Section 60.8.

## **60.3 Waterway Characteristics**

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The characteristics of the waterway in the vicinity of the bridge site such as the width and depth of the navigation channel, the current speed and direction, the channel alignment and cross section, the water elevation, and the hydraulic conditions, have a great influence on the risk of vessel collision and must be taken into account.

### **60.3.1 Channel Layout and Geometry**

The channel layout and geometry can affect the navigation conditions, the largest vessel size that can use the waterway, and the loading condition and speed of vessels.

The presence of bends and intersections with other waterways near the bridge increases the probability of vessels losing control and become aberrant. The navigation of downstream barge tows through bends is especially difficult.

The vessel transit paths in the waterway in relation to the navigation channel and the bridge piers can affect the risk of aberrant vessels hitting the substructure.

### **60.3.2 Water Depth and Fluctuations**

The design water depth for the channel limits the size and draft of vessels using the waterway. In addition, the water depth plays a critical role in the accessibility of vessels to piers outside the navigation channel. The vessel collision analysis must include the possibility of ships and barges transiting ballasted or empty in the waterway. For example, a loaded barge with a 6 m draft would run aground before it could strike a pier in 4 m of water, but the same barge empty with a 1 m draft could potentially strike the pier.

The water level along with the loading condition of vessels influences the location on the pier where vessel impact loads are applied, and the susceptibility of the superstructure to vessel hits. The annual mean high water elevation is usually the minimum water level used in design. In waterways with large water stage fluctuations, the water level used can have a significant effect on the structural requirements for the pier and/or pier protection design. In these cases, a closer review of the water stage statistics at the bridge site is necessary in order to select an appropriate design water level.

### **60.3.3 Current Speed and Direction**

Water currents at the location of the bridge can have a significant effect on navigation and on the probability of vessel aberrancy. The design water currents commonly used represent annual average values rather than the occasional extreme values that occur only a few times per year, and during which vessel traffic restrictions may also apply.

## **60.4 Vessel Traffic Characteristics**

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### **60.4.1 Physical and Operating Characteristics**

General knowledge on the operation of vessels and their characteristics is essential for safe bridge design. The types of commercial vessels encountered in navigable waterways may be divided into ships and barge tows.

#### **60.4.1.1 Ships**

Ships are self-propelled vessels using deep-draft waterways. Their size may be determined based on the DWT. The DWT is the weight in metric tonnes (1 tonne = 2205 lbs = 9.80 kN) of cargo, stores, fuel, passenger, and crew carried by the ship when fully loaded. There are three main classes of merchant ships: bulk carriers, product carriers/tankers, and freighter/containers. General information on ship



profiles, dimensions, and sizes as a function of the class of ship and its DWT is provided in References [6,7]. The dimensions given in References [6,7] are typical values, and due to the large variety of existing vessels, they should be regarded as general approximations.

The steering of ships in coastal waterways is a difficult process. It involves constant communications between the shipmaster, the helmsman, and the engine room. There is a time delay before a ship starts responding to an order to change speed or course, and the response of the ship itself is relatively slow. Therefore, the shipmaster has to be familiar with the waterway and be aware of obstructions and navigation and weather conditions in advance. Very often local pilots are used to navigate the ships through a given portion of a coastal waterway. When the navigation conditions are difficult, tugboats are used to assist ships in making turns. Ships need speed to be able to steer and maintain rudder control. A minimum vessel speed of about 5 knots (8 km/h) is usually needed to maintain steering. Fully loaded ships are more maneuverable, and in deep water they are directionally stable and can make turns with a radius equal to one to two times the length of the ship. However, as the underkeel clearance decreases to less than half the draft of the ship, many ships tend to become directionally unstable, which means that they require constant steering to keep them traveling in a straight line. In the coastal waterways of the United States, the underkeel clearance of many laden ships may be far less than this limit, in some cases as small as 5% of the draft of the ship. Ships riding in ballast with shallow draft are less maneuverable than loaded ships, and, in addition, they can be greatly affected by winds and currents. Historical accident data indicate that most bridge accidents involve empty or ballasted vessels.

#### **60.4.1.2 Barge Tows**

Barge tows use both deep-draft and shallow-draft waterways. The majority of the existing bridges cross shallow draft waterways where the vessel fleet comprises barge tows only. The size of barges in the United States is usually defined in terms of the cargo-carrying capacity in short tons (1 ton = 2000 lbs = 8.90 kN). The types of inland barges include open and covered hoppers, tank barges, and deck barges. They are rectangular in shape and their dimensions are quite standard so they can travel in tows. The number of barges per tow can vary from one to over 20, and their configuration, is affected by the conditions of the waterway. In most cases barges are pushed by a towboat. Information on barge dimensions and capacity, as well as on barge tow configurations is included in References [6,7]. A statistical analysis of barge tow types, configurations, and dimensions, which utilizes barge traffic data from the Ohio River, is reported in Reference [12].

It is very difficult to control and steer barge tows, especially in waterways with high stream velocities and cross currents. Taking a turn in a fast waterway with high current is a serious undertaking. In maneuvering a bend, tows experience a sliding effect in a direction opposite to the direction of the turn, due to inertial forces, which are often coupled with the current flow. Sometimes, bridge piers and fenders are used to line up the tow before the turn. Bridges located in a high-velocity waterway near a bend in the channel will probably be hit by barges numerous times during their lifetime. In general, there is a high likelihood that any bridge element that can be reached by a barge will be hit during the life of the bridge.

### **60.4.2 Vessel Fleet Characteristics**

The vessel data required for bridge design include types of vessels and size distributions, transit frequencies, typical vessel speeds, and loading conditions. In order to determine the vessel size distribution at the bridge site, detailed information on both present and projected future vessel traffic is needed. Collecting data on the vessel fleet characteristics for the waterway is an important and often time-consuming process.

Some of the sources in the United States for collecting vessel traffic data are listed below:

- U.S. Army Corps of Engineers, District Offices
- Port authorities and industries along the waterway



- Local pilot associations and merchant marine organizations
- U.S. Coast Guard, Marine Safety & Bridge Administration Offices
- U.S. Army Corps of Engineers, “Products and Services Available to the Public,” Water Resources Support Center, Navigation Data Center, Fort Belvoir, Virginia, NDC Report 89-N-1, August 1989
- U.S. Army Corps of Engineers, “Waterborne Commerce of the United States (WCUS), Parts 1 thru 5,” Water Resources Support Center (WRSC), Fort Belvoir, Virginia
- U.S. Army Corps of Engineers, “Lock Performance Monitoring (LPM) Reports,” Water Resources Support Center (WRSC), Fort Belvoir, Virginia
- Shipping registers (American Bureau of Shipping Register, New York; and Lloyd’s Register of Shipping, London)
- Bridge tender reports for movable bridges

Projections for anticipated vessel traffic during the service life of the bridge should address both changes in the volume of traffic and in the size of vessels. Factors that need to be considered include:

- Changes in regional economics;
- Plans for deepening or widening the navigation channel;
- Planned changes in alternate waterway routes and in navigation patterns;
- Plans for increasing the size and capacity of locks leading to the bridge;
- Port development plans.

Vessel traffic projections that are made by the Maritime Administration of the U.S. Department of Transportation, Port Authorities, and U.S. Army Corps of Engineers in conjunction with planned channel-deepening projects or lock replacements are also good sources of information for bridge design. Since a very large number of factors can affect the vessel traffic in the future, it is important to review and update the projected traffic during the life of the bridge.

## 60.5 Collision Risk Analysis

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### 60.5.1 Risk Acceptance Criteria

Bridge components exposed to vessel collision could be subjected to a very wide range of impact loads. Due to economic and structural constraints bridge design for vessel collision is not based on the worst-case scenario, and a certain amount of risk is considered acceptable.

The risk acceptance criteria consider both the probability of occurrence of a vessel collision and the consequences of the collision. The probability of occurrence of a vessel collision is affected by factors related to the waterway, vessel traffic, and bridge characteristics. The consequences of a collision depend on the magnitude of the collision loads and the bridge strength, ductility, and redundancy characteristics. In addition to the potential for loss of life, the consequences of a collision can include damage to the bridge, disruption of motorist and marine traffic, damage to the vessel and cargo, regional economic losses, and environmental pollution.

Acceptable risk levels have been established by various codes and for individual bridge projects [2–10]. The acceptable annual frequencies of bridge collapse values used generally range from 0.001 to 0.0001. These values were usually determined in conjunction with the risk analysis procedure recommended, and should be used accordingly.

The AASHTO provisions [6,8] specify an annual frequency of bridge collapse of 0.0001 for critical bridges and an annual frequency of bridge collapse of 0.001 for regular bridges. These annual frequencies correspond to return periods of bridge collapse equal to 1 in 10,000 years, and 1 in 1000 years, respectively. Critical bridges are defined as those bridges that are expected to continue to function after a major impact, because of social/survival or security/defense requirements.

## 60.5.2 Collision Risk Models

### 60.5.2.1 General Approach

Various collision risk models have been developed to achieve design acceptance criteria [2–10]. In general, the occurrence of a collision is separated into three events: (1) a vessel approaching the bridge becomes aberrant, (2) the aberrant vessel hits a bridge element, and (3) the bridge element that is hit fails. Collision risk models consider the effects of the vessel traffic, the navigation conditions, the bridge geometry with respect to the waterway, and the bridge element strength with respect to the impact loads. They are commonly expressed in the following form [6,8]:

$$AF = (N) (PA) (PG) (PC) \quad (60.1)$$

where  $AF$  is the annual frequency of collapse of a bridge element;  $N$  is the annual number of vessel transits (classified by type, size, and loading condition) which can strike a bridge element;  $PA$  is the probability of vessel aberrancy;  $PG$  is the geometric probability of a collision between an aberrant vessel and a bridge pier or span;  $PC$  is the probability of bridge collapse due to a collision with an aberrant vessel.

### 60.5.2.2 Vessel Traffic Distribution, $N$

The number of vessels,  $N$ , passing the bridge based on size, type, and loading condition and available water depth has to be developed for each pier and span component to be evaluated. All vessels of a given type and loading condition have to be divided into discrete groupings of vessel size by DWT to determine the contribution of each group to the annual frequency of bridge element collapse. Once the vessels are grouped and their frequency distribution is established, information on typical vessel characteristics may be obtained from site-specific data, or from published general data such as References [6,7].

### 60.5.2.3 Probability of Aberrancy, $PA$

The probability of vessel aberrancy reflects the likelihood that a vessel is out of control in the vicinity of a bridge. Loss of control may occur as a result of pilot error, mechanical failure, or adverse environmental conditions. The probability of aberrancy is mainly related to the navigation conditions at the bridge site. Vessel traffic regulations, vessel traffic management systems, and aids to navigation can improve the navigation conditions and reduce the probability of aberrancy.

The probability of vessel aberrancy may be evaluated based on site-specific information that includes historical data on vessel collisions, rammings, and groundings in the waterway, vessel traffic, navigation conditions, and bridge/waterway geometry. This has been done for various bridge design provisions and specific bridge projects worldwide [2,3,7,9,12]. The probability of aberrancy values determined range from  $0.5 \times 10^{-4}$  to over  $7.0 \times 10^{-4}$ .

As an alternative, the AASHTO provisions [6,8] recommend base rates for the probability of vessel aberrancy that are multiplied by correction factors for bridge location relative to bends in the waterway, currents acting parallel to vessel transit path, crosscurrents acting perpendicular to vessel transit path, and the traffic density of vessels using the waterway. The recommended base rates are  $0.6 \times 10^{-4}$  for ships, and  $1.2 \times 10^{-4}$  for barges.

### 60.5.2.4 Geometric Probability, $PG$

The geometric probability is the probability that a vessel will hit a particular bridge pier given that it has lost control (i.e., is aberrant) in the vicinity of the bridge. It is mainly a function of the geometry of the bridge in relation to the waterway. Other factors that can affect the likelihood that an aberrant vessel will strike a bridge element include the original vessel transit path, course, rudder position, velocity at the time of failure, vessel type, size, draft and maneuvering characteristics, and the hydraulic and environmental conditions at the bridge site. Various geometric probability models, some based on simulation studies, have been recommended and used on different bridge projects

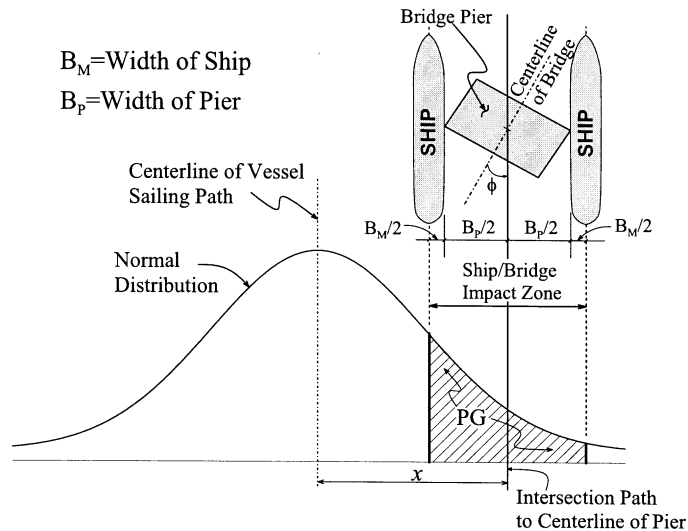


FIGURE 60.2 Geometric probability of pier collision.

[2,3,7]. The AASHTO provisions [6,8] use a normal probability density function about the centerline of the vessel transit path for estimating the likelihood of an aberrant vessel being within a certain impact zone along the bridge axis. Using a normal distribution accounts for the fact that aberrant vessels are more likely to pass under the bridge closer to the navigation channel than farther away from it. The standard deviation of the distribution equals the length of the design vessel considered. The probability that an aberrant vessel is located within a certain zone is the area under the normal probability density function within that zone (Figure 60.2).

Bridge elements beyond three times the standard deviation from the centerline of vessel transit path are designed for specified minimum impact load requirements, which are usually associated with an empty vessel drifting with the current.

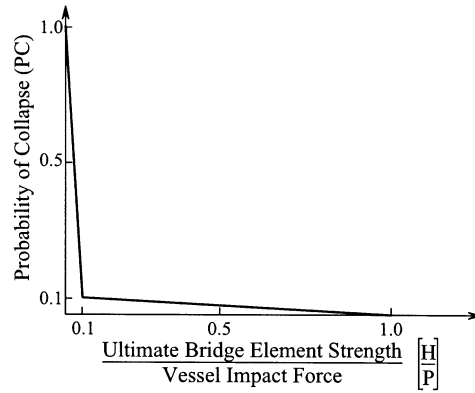
#### 60.5.2.5 Probability of Collapse, $PC$

The probability of collapse,  $PC$ , is a function of many variables, including vessel size, type, forepeak ballast and shape, speed, direction of impact, and mass. It is also dependent on the ultimate lateral load strength of the bridge pier (particularly the local portion of the pier impacted by the bow of the vessel). Based on collision damages observed from numerous ship–ship collision accidents which have been correlated to the bridge–ship collision situation [2], an empirical relationship has been developed based on the ratio of the ultimate pier strength,  $H$ , to the vessel impact force,  $P$ . As shown in Figure 60.3, for  $H/P$  ratios less than 0.1,  $PC$  varies linearly from 0.1 at  $H/P = 0.1$  to 1.0 at  $H/P = 0.0$ . For  $H/P$  ratios greater than 0.1,  $PC$  varies linearly from 0.1 at  $H/P = 0.1$  to 0.0 at  $H/P = 1.0$ .

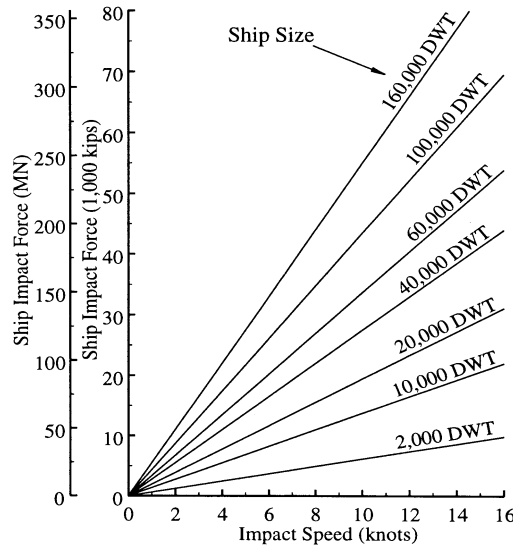
## 60.6 Vessel Impact Loads

### 60.6.1 Ship Impact

The estimation of the load on a bridge pier during a ship collision is a very complex problem. The actual force is time dependent, and varies depending on the type, size, and construction of the vessel; its velocity; the degree of water ballast in the forepeak of the bow; the geometry of the collision; and the geometry and strength characteristics of the bridge. There is a very large scatter among the collision force values recommended in various vessel collision guidelines or used in various bridge projects [2–10].



**FIGURE 60.3** Probability of collapse distribution.



**FIGURE 60.4** Ship impact force.

Ship collision forces are commonly applied as equivalent static loads. Procedures for evaluating dynamic effects when the vessel force indentation behavior is known are included in References [3,4,10,13,14]. The AASHTO provisions [6,8] use the following formula for estimating the static head-on ship collision force,  $P_s$ , on a rigid pier:

$$P_s = 0.98(DWT)^{1/2}(V/16) \quad (60.2)$$

where  $P_s$  is the equivalent static vessel impact force (MN); DWT is the ship deadweight tonnage in tonnes; and  $V$  is the vessel impact velocity in knots (Figure 60.4). This formulation was primarily developed from research conducted by Woisin in West Germany during 1967 to 1976 on physical ship models to generate data for protecting the reactors of nuclear power ships from collisions with other ships. A schematic representation of a typical impact force time history is shown in Figure 60.6 based on Woisin's test data. The scatter in the results of these tests is of the order of  $\pm 50\%$ . The formula recommended (Eq. 60.2) uses a 70% fractile of an assumed triangular distribution with zero values at 0% and 100% and a maximum value at the 50% level (Figure 60.7).

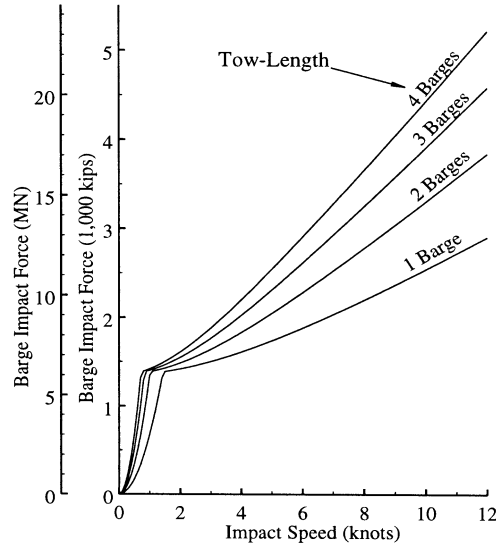


FIGURE 60.5 Barge impact force.

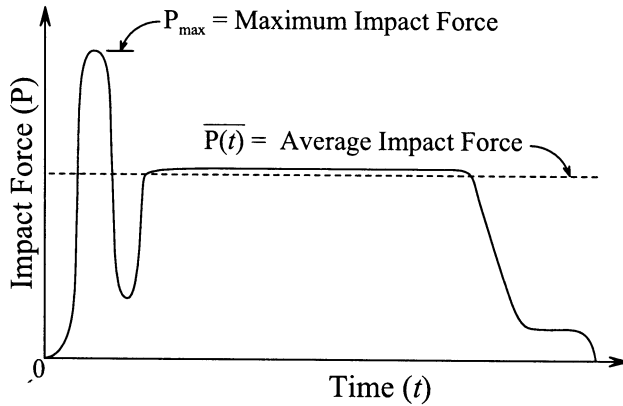


FIGURE 60.6 Typical ship impact force time history by Woisin.

Formulas for computing design ship collision loads on a bridge superstructure are given in the AASHTO provisions [6,8] as a function of the design ship impact force,  $P_s$ , as follows:

- Ship Bow Impact Force,  $P_{BH}$ :

$$P_{BH} = (R_{BH}) (P_s) \quad (60.3)$$

where  $R_{BH}$  is a reduction coefficient equal to the ratio of exposed superstructure depth to the total bow depth.

- Ship Deckhouse Impact Force,  $P_{DH}$ :

$$P_{DH} = (R_{DH}) (P_s) \quad (60.4)$$

where  $R_{DH}$  is a reduction coefficient equal to 0.10 for ships larger than 100,000 DWT, and

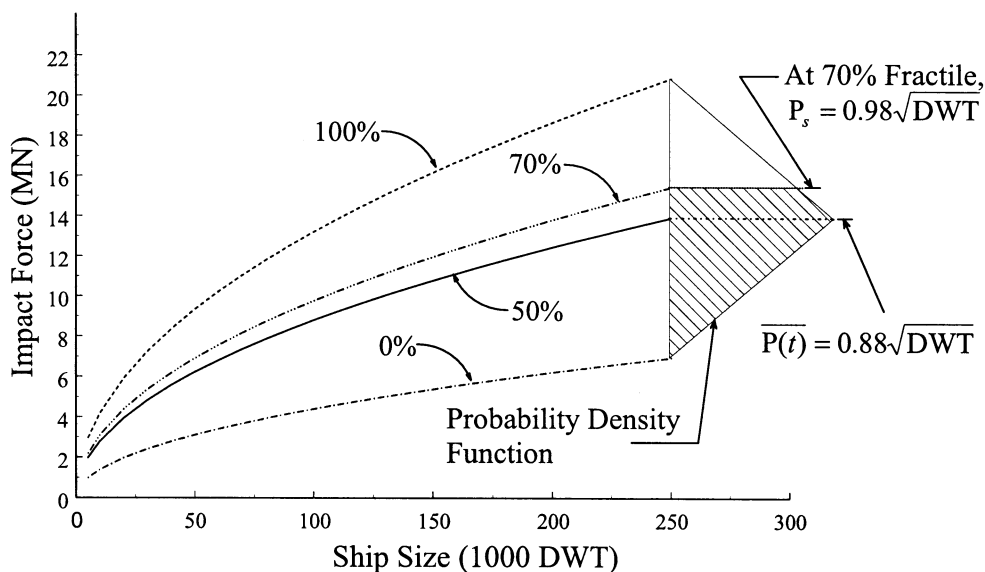


FIGURE 60.7 Probability density function of ship impact force.

$$0.2 - \frac{DWT}{100,000} (0.10)$$

for ships under 100,000 DWT.

- Ship Mast Impact Force,  $P_{MT}$ :

$$P_{MT} = 0.10 P_{DH} \quad (60.5)$$

where  $P_{DH}$  is the ship deckhouse impact force.

The magnitude of the impact loads computed for ship bow and deckhouse collisions are quite high relative to the strength of most bridge superstructure designs. Also, there is great uncertainty associated with predicting ship collision loads on superstructures because of the limited data available and the ship–superstructure load interaction effects. It is therefore suggested that superstructures, and also weak or slender parts of the substructure, be located out of the reach of a ship's hull or bow.

### 60.6.2 Barge Impact

The barge collision loads recommended by AASHTO for the design of piers are shown in Figure 60.5 as a function of the tow length and the impact speed. Numerical formulations for deriving these relationships may be found in References [6,8].

The loads in Figure 60.5 were computed using a standard  $59.5 \times 10.7$  m hopper barge. The impact force recommended for barges larger than the standard hopper barge is determined by increasing the standard barge impact force by the ratio of the width of the wider barge to the width of the standard hopper barge.

### 60.6.3 Application of Impact Forces

Collision forces on bridge substructures are commonly applied as follows:

- 100% of the design impact force in a direction parallel to the navigation channel (i.e., head-on);
- 50% of the design impact force in the direction normal to the channel (but not simultaneous with the head-on force);
- For overall stability, the design impact force is applied as a concentrated force at the mean high water level;
- For local collision forces, the design impact force is applied as a vertical line load equally distributed along the ship's bow depth for ships, and along head log depth for barges;
- For superstructure design the impact forces are applied transversely to the superstructure component in a direction parallel to the navigation channel.

When determining the bridge components exposed to physical contact by any portion of the hull or bow of the vessel considered, the bow overhang, rake, or flair distance of vessels have to be taken into account. The bow overhang of ships and barges is particularly dangerous for bridge columns and for movable bridges with relatively small navigation clearances.

## 60.7 Bridge Analysis and Design

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Vessel collisions are extreme events with a very low probability of occurrence; therefore the limit state considered is usually structural survival. Depending on the importance of the bridge, various degrees of damage are allowed — provided that the structure maintains its integrity, hazards to traffic are minimized, and repairs can be made in a relatively short period of time. When the design is based on more frequent but less severe collisions, structural damage and traffic interruptions are not allowed.

Designing for vessel collision is commonly based on equivalent static loads that include global forces for checking overall capacity and local forces for checking local strength of bridge components. A clear load path from the location of the vessel impact to the bridge foundation needs to be established and the components and connections within the load path must be adequately designed and detailed. The design of individual bridge components is based on strength and stability criteria. Overall stability, redundancy, and ductility are important criteria for structural survival.

The contribution of the superstructure to the transfer of loads to adjacent substructure units depends on the capacity of the connection of the superstructure to substructure and the relative stiffness of the substructure at the location of the impact. Analysis guidelines for determining the distribution of collision loads to adjacent piers are included in Reference [15]. To find out how much of the transverse impact force is taken by the pier and how much is transferred to the superstructure, two analytical models are typically used. One is a two-dimensional or a three-dimensional model of the complete pier, and the other is a two-dimensional model of the superstructure projected on a horizontal plane. The projected superstructure may be modeled as a beam with the moment of inertia referred to a vertical axis through the center of the roadway, and with hinges at expansion joint locations. The beam is supported at pier locations by elastic horizontal springs representing the flexibility of each pier. The flexibility of the piers is obtained from pier models using virtual forces. The superstructure model is loaded with a transverse virtual force acting at the place where the pier under consideration is located. The spring in the model at that place is omitted to obtain a flexibility coefficient of the superstructure at the location of the top of the pier under consideration. Thus, the horizontal displacement of the top of the pier due to the impact force on the pier (usually applied at mean high water level) is equal to the true displacement of the superstructure due to the transmitted part of the impact force. The magnitude of the force transmitted to the superstructure is obtained by equating the total true displacement of the top of the pier from the pier model to the displacement of the superstructure. However, in order to consider partial transfer of lateral forces to the superstructure, positive steel or concrete connections of superstructure to substructure, such as shear keys must be provided. Similarly, for partial transfer to the superstructure of the longitudinal component of the impact force the shear capacity of the



bearings must be adequate. When elastomeric bearings are used their longitudinal flexibility may be added to the longitudinal flexibility of the piers. If the ultimate capacity of the bearings is exceeded, then the pier must take the total longitudinal force and be treated as a cantilever.

The modeling of pile foundations could vary from the simple assumption of a point of fixity to nonlinear soil–structure interaction models, depending on the limit state considered and the sensitivity of the response to the soil conditions. Lateral load capacity analysis methods for pile groups that include nonlinear behavior are recommended in References [15,16] and the features of a finite-element analysis computer program developed for bridge piers composed of pier columns and cap supported on a pile cap and nonlinear piles and soil are presented in Reference [17]. Transient foundation uplift or rocking involving separation from the subsoil of an end bearing foundation pile group or the contact area of a foundation footing could be allowed under impact loading provided sufficient consideration is given to the structural stability of the substructure.

## 60.8 Bridge Protection Measures

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The cost associated with protecting a bridge from catastrophic vessel collision can be a significant portion of the total bridge cost, and must be included as one of the key planning elements in establishing a bridge's type, location, and geometry. The alternatives listed below are usually evaluated in order to develop a cost-effective solution for a new bridge project:

- Design the bridge piers, foundations, and superstructure to withstand directly the vessel collision forces and impact energies;
- Design a pier fender system to reduce the impact loads to a level below the capacity of the pier and foundation;
- Increase span lengths and locate piers in shallow water out of reach of large vessels in order to reduce the impact design loads; and
- Protect piers from vessel collision by means of physical protection systems.

### 60.8.1 Physical Protection Systems

Piers exposed to vessel collision can be protected by special structures designed to absorb the impact loads (forces or energies), or redirect the aberrant vessel away from the pier. Because of the large forces and energies involved in a vessel collision, protection structures are usually designed for plastic deformation under impact (i.e., they are essentially destroyed during the head-on design collision and must be replaced). General types of physical protection systems include:

*Fender Systems.* These usually consist of timber, rubber, steel, or concrete elements attached to a pier to fully, or partially, absorb vessel impact loads. The load and energy absorbing characteristics of such fenders is relatively low compared with typical vessel impact design loads.

*Pile-Supported Systems.* These usually consist of pile groups connected by either flexible or rigid caps to absorb vessel impact forces. The piles may be vertical (plumb) or battered depending on the design approach followed, and may incorporate relatively large-diameter steel pipe or concrete pile sizes. The pile-supported protection structure may be either freestanding away from the pier, or attached to the pier itself. Fender systems may be attached to the pile structure to help resist a portion of the impact loads.

*Dolphin Protection Systems.* These usually consist of large-diameter circular cells constructed of driven steel sheet piles, filled with rock or sand, and topped by a thick concrete cap. Vessel collision loads are absorbed by rotation and lateral deformation of the cell during impact.

*Island Protection Systems.* These usually consist of protective islands built of a sand or quarry-run rock core and protected by outer layers of heavy rock riprap for wave, current, and ice protection. The island geometry is developed to stop an aberrant vessel from hitting a pier

by forcing it to run aground. Although extremely effective as protection systems, islands are often difficult to use due to adverse environmental impacts on river bottoms (dredge and fill permits) and river currents (increase due to blockage), as well as impacts due to settlement and downdrag forces on the bridge piers.

*Floating Protection Systems.* These usually consist of cable net systems suspended across the waterway to engage and capture the bow of an aberrant vessel, or floating pontoons anchored in front of the piers. Floating protection systems have a number of serious drawbacks (environmental, effectiveness, maintenance, cost, etc.) and are usually only considered for extremely deep water situations where other protection options are not practicable.

The AASHTO Guide Specification [6] provides examples and contains a relatively extensive discussion of various types of physical protection systems, such as fenders, pile-supported structures, dolphins, protective islands, and floating structures. However, the code does not include specific procedures and recommendations on the actual design of such protection structures. Further research is needed to establish consistent analysis and design methodologies for protection structures, particularly since these structures undergo large plastic deformations during the collision.

## 60.8.2 Aids to Navigation Alternatives

Since 60 to 85% of all vessel collisions are caused by pilot error, it is important that all aspects of the bridge design, siting, and aids to navigation with respect to the navigation channel be carefully evaluated with the purpose of improving or maintaining safe navigation in the waterway near the bridge. Traditional aids include buoys, range markers, navigation lighting, and radar reflectors, as well as standard operating procedures and regulations specifically developed for the waterway by government agencies and pilot associations. Modern aids include advanced vessel traffic control systems (VTS) using shore-based radar surveillance and radio-telephone communication systems; special electronic transmitters known as Raycon devices mounted to bridge spans for improved radar images indicating the centerline of the channel; and advanced navigation positioning systems based on shipboard global positioning satellite (GPS) receivers using differential signal techniques to improve location accuracy.

Studies have indicated that improvements in the aids to navigation near a bridge can provide extremely cost-effective solutions to reducing the risk of collisions to acceptable levels. The cost of such aid to navigation improvements and shipboard electronic navigation systems is usually a fraction of the cost associated with expensive physical protection alternatives. However, few electronic navigation systems have ever been implemented (worldwide) due to legal complications arising from liability concerns; impacts on international laws governing trade on the high seas; and resistance by maritime users.

It should be noted that the traditional isolation of the maritime community must come to an end. In addition to the bridge costs, motorist inconvenience, and loss of life associated with a catastrophic vessel collision, significant environmental damage can also occur due to spilled hazardous or noxious cargoes in the waterway. The days when the primary losses associated with an accident rested with the vessel and her crew are over. The \$13 million value of the *M/V Summit Venture* was far below the \$250 million replacement cost of the Sunshine Skyway Bridge which the vessel destroyed. The losses associated with the 11 million gallons of crude oil spilled from the *M/V Exxon Valdez* accident off the coast of Alaska in 1989 are over \$3.5 billion. Both of these accidents could have been prevented using shipboard advanced electronic navigation systems.

## 60.9 Conclusions

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Experience to date has shown that the use of the vessel impact and bridge protection requirements (such as the AASHTO specifications [6,8]) for planning and design of new bridges has resulted in a significant change in proposed structure types over navigable waterways. Incorporation of the risk

of vessel collision and cost of protection in the total bridge cost has almost always resulted in longer-span bridges being more economical than traditional shorter span structures, since the design goal for developing the bridge pier and span layout is the least cost of the total structure (including the protection costs). Typical costs for incorporating vessel collision and protection issues in the planning stages of a new bridge have ranged from 5% to 50% of the basic structure cost without protection.

Experience has also shown that it is less expensive to include the cost of protection in the planning stages of a proposed bridge, than to add it after the basic span configuration has been established without considering vessel collision concerns. Typical costs for adding protection, or for retrofitting an existing bridge for vessel collision, have ranged from 25% to over 100% of the existing bridge costs.

It is recognized that vessel collision is but one of a multitude of factors involved in the planning process for a new bridge. The designer must balance a variety of needs including political, social, and economic in arriving at an optimal bridge solution for a proposed highway crossing. Because of the relatively high bridge costs associated with vessel collision design for most waterway crossings, it is important that additional research be conducted to improve our understanding of vessel impact mechanics, the response of the structure, and the development of cost-effective protection systems.

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