Determination of Impact Force History during Multicolumn Barge Flotilla Collisions against Bridge Piers

Francisco J. Luperi[1] and Federico Pinto[2]

Abstract: The collision of barge flotillas against bridge piers is a design scenario that often controls the design of bridges that span navigable waterways. Current design approaches vary significantly in their assumptions and mostly rely on design code guidelines. The influence of adjacent barge columns on multicolumn flotilla impacts is not well established in the literature; some design codes ignore the effects of adjacent barge columns, assuming they break away upon impact, whereas others assume full contribution. The actual contribution of adjacent barge columns has a major influence on the amount of energy absorbed by the impacted structure and, therefore, on the load history attributable to the impact. The behavior of barge flotillas during impact depends upon several factors, such as configuration of flotilla, impact speed, barge bow-crushing behavior, and dynamic response of pier. This paper presents a simplified procedure that allows the estimation of the impulse delivered by the adjacent barge columns for head-on impacts. The proposed simplified procedure is based on a parametric study performed by means of a multidegree-of-freedom, two-dimensional model described in this paper. The proposed model is able to account for nonlinear interaction between barges, nonlinear barge bow behavior, and dynamic structural response. The proposed procedure allows for an improved estimation of impact load histories attributable to the collision of barge flotillas. **DOI: 10.1061/(ASCE)BE.1943-5592.0000544.** © *2014 American Society of Civil Engineers.*

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Introduction

The design of bridge structures across navigable waterways is often heavily influenced by the possibility of vessel collision against the piers. An average of one catastrophic accident per year involving bridge collisions by vessels is recorded worldwide (AASHTO 2008; Harik et al. 2008a). Current design codes (AASHTO 2008) prescribe a vessel-collision loading case under the design scenarios, for which a reasonable characterization of the load history during impact is warranted.

Cargo transportation on inland waterways normally involves barge flotillas, which are formed by a number of barges joined by wire ropes—referred to as lashings—and pushed by a towboat. These flotillas are generally formed by several columns of barges. For geometric reasons, during a multicolumn barge flotilla impact with a bridge pier, not all leading barges come in contact with the bridge pier. Because of the fact that the impact load is transferred within one or only a few barge bows, internal loads are generated between individual barges of the flotilla, and computation of the load and energy effectively transferred to the impacted structure is not trivial.

Current design codes either neglect the contribution of adjacent barge columns to the impacting barge column (AASHTO 2008) or assume full contribution (European Committee for Standardization 1991). Recent research by Harik et al. (2008a) considers multicolumn barge flotilla impacts but does not account for the possible breakup of adjacent barge columns and assumes one-dimensional (1D) behavior of the tow (i.e., only longitudinal displacements).

During collision, compression and friction loads develop along contacts between barges, whereas tension loads take place along lashings. Depending upon a number of factors, an impact of a multicolumn barge flotilla may result in the failure of lashings, and the barge flotilla may be divided into two or more groups, or it may remain as a unit. Fig. 1 illustrates typical collision scenarios considered in this paper. The behavior of the barge flotilla during impact has a direct influence on the amount of energy absorbed by the impacted structure and on the resulting load history. In what follows, the existing methods for analysis of barge collision and their limitations for the analysis of multicolumn barge flotilla impacts are discussed, and a new analysis method is proposed.

Existing Analysis Methods

Currently available methods vary greatly in their assumptions. Some are simplified procedures developed for design, whereas others are more complex and are intended mainly for verification purposes.

AASHTO Specifications and Eurocode

The European Committee for Standardization (Eurocode) and AASHTO have developed provisions that serve as guidelines for bridge design under barge-collision scenarios (AASHTO 2008; European Committee for Standardization 1991). Both specifications adopt the results by Meier-Dörnberg (1983) concerning barge bow-crushing behavior based on a series of loading tests on scaled barge models. Both AASHTO and Eurocode define the crushing behavior as a bilinear relation with strain hardening. Based on the envelope-crushing load and energy considerations, the AASHTO guidelines define an equivalent static load to be applied to the impacted structure.

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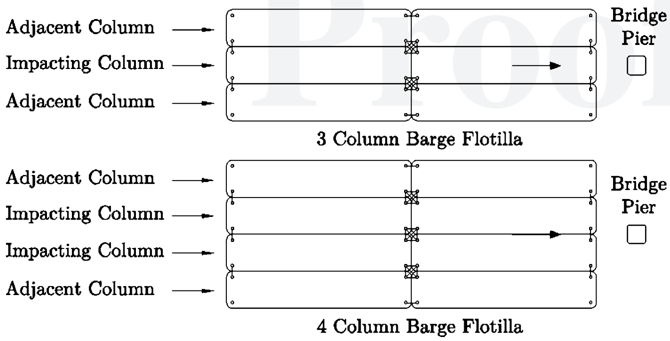

Fig. 1. Head-on impact of multicolumn barge flotilla

The fact that this load does not incorporate the dynamic effects of the impacted structure has been criticized by several authors (Consolazio et al. 2008; Harik et al. 2008a), because the magnification effect of the dynamic loading can be significant with respect to the static effect alone.

Eurocode, however, defines a time history for the impact load and, therefore, allows the designer to perform a dynamic analysis. It should be noted that Eurocode adopts the mean Meier-Dörnberg (1983) crushing load, as opposed to AASHTO, which adopts the envelope crushing load. If a static analysis is desired, Eurocode defines a dynamic magnification factor that ranges between 1.3 and 1.7 depending upon the magnitude of the impact load.

Although both design codes provide simple means for determining demands attributable to barge collision, there are a number of relevant aspects that are not accounted for. One of the main shortcomings is that the Meier-Dörnberg (1983) results do not account for the size or shape of the impacted pier, and there is a significant difference between both provisions with respect to multicolumn barge flotillas. Other aspects not accounted for are the influence of the dynamic behavior of the impacted structure and the stiffness of the barge on the load history. For example, AASHTO only accounts for the contribution of barges in the impacting column, assuming that adjacent barge columns will break away upon impact. Therefore, adjacent barge columns are not included in the kinetic energy and force computation. Eurocode, however, does include the whole mass of the barge flotilla in the force computations. Hence, the impact forces for a multicolumn barge flotilla collision determined by means of both codes differ considerably.

Analysis Methods Proposed by Consolazio et al.

Consolazio et al. (2008, 2010a, b) have made several advances in the field of barge-collision analyses. Their main contributions include updated barge bow-crushing relations for head-on and oblique impacts, a coupled dynamic collision analysis method, and a simplified applied load history technique.

Consolazio et al. (2008) developed a computational procedure, referred to as coupled vessel impact analysis, in which the impacting barge, represented by a single degree of freedom, is coupled to a finite-element model that represents the bridge. This method considers the nonlinear behavior of the barge bow and the nonlinear dynamic response of the impacted structure and was validated by means of results from real-scale impact tests, showing reasonably accurate results. In this procedure, the impact load history is obtained as a result of the barge-bridge interaction modeled by means of numerical analysis.

An alternative simplified procedure, referred to as the applied vessel impact load history method, was also proposed by Consolazio et al. (2008). In this simplified method, the load history is estimated as a first step and then externally applied to the impacted structure. This simplified method has been validated by means of the more elaborate coupled vessel impact analysis. Both methods show reasonable agreement.

However, because of the fact that the barge flotilla in both methods proposed by Consolazio et al. (2008) is represented by a single degree of freedom, the influence of adjacent barge columns cannot be explicitly considered for multicolumn barge flotilla impacts. Although these methods represent significant advances in the field of barge-collision analyses, the effect of adjacent barge columns in both energy and force computations for multicolumn barge flotillas remains uncertain

Analysis Methods Proposed by Harik et al.

Harik et al. (2008a, b) have also made significant contributions in the field of barge-collision analysis, including updated barge bow-crushing behavior, finite-element simulations of single-column flotilla impacts, and a spring-mass model for multicolumn barge flotilla collisions.

Harik et al. (2008a) present detailed finite-element models of box and raked barges. By means of these models, a series of simulations were conducted for impacts of single-column flotillas composed of one to five barges with different velocities and for different sizes and shapes of the bridge piers. Based on these results, the authors derived regression formulas that allow the computation of maximum and average impact forces, as well as impact time duration. By means of finite-element simulations, the authors found that, for the case of single-column flotilla collisions, some portion of the kinetic energy is dissipated through relative displacement of the barges, but that the main source of energy dissipation is the plastic deformation of the barge bow that comes into contact with the bridge pier.

Harik et al. (2008a) proposed a 1D multidegree-of-freedom (MDF) model for the analysis of multicolumn barge flotillas. In this model, each barge is represented by an individual mass. Interactions between the barges and the barge bow that comes in contact with the bridge pier are represented by nonlinear springs. The bridge pier is modeled by a cantilever beam with rotational and translation springs, as well as two concentrated masses that represent superstructure and the mass associated with the point of impact. This model was validated against detailed finite-element results for a single-column flotilla collision.

In the finite-element analyses carried out by Harik et al. (2008a), the influence of adjacent barge columns was not investigated, whereas in the 1D spring-mass model, the elastic-plastic relations that describe the tensile forces of lashings between barges do not account for possible failure attributable to excessive straining. Therefore, the influence of adjacent barge columns considered by these authors is only applicable to collisions where adjacent barge columns do not break away.

Proposed Method

The analysis method proposed in this paper is based on a MDF, two-dimensional (2D) model that represents a generalization of the 1D MDF proposed by Harik et al. (2008a). This 2D model consists of a numerical scheme that allows the analysis of flotilla impacts with bridge piers in a more general manner, as it is able to analyze nonsymmetric or oblique impacts. In this model, barge and pier geometries are defined by meshes, which consist of a group of points that define their contours. The contacts between the different elements of the model are detected based on the contour meshes by means of a contact algorithm. The load-deflection behavior of the barge bows and lashings are represented by nonlinear springs. Barges that do not impact the pier are considered to behave linear elastically. This simplifying assumption was considered valid based on finite-element analysis of barge columns by Harik et al. (2008a), where it was shown that energy dissipation occurs mainly by deformation of the impacting barge bow. The effect of water is currently accounted for by means of an added hydrodynamic mass (AASHTO 2008). However, damping attributable to wave emission is conservatively neglected.

Contact Algorithm

An algorithm that detects contacts between different elements of the model was implemented. The contact algorithm determines which points of a particular barge mesh fall inside the contour defined by an adjacent barge or pier mesh. For this purpose, a straight line is defined from the point that is being considered to a point at a certain distance in a specified direction. If this line intersects the contour of an adjacent element an odd number of times, the point is defined to lie inside the contour (contact point). Otherwise, the point is defined as external to the contour. A contact zone is thus determined by applying this procedure several times along the boundary of a barge. Hence, a contact zone, its normal direction, a contact overlap, and a relative tangent velocity are computed (Figs. 2 and 3). These parameters are used to determine the resulting contact forces within the barge flotilla. The normal force, N, is computed as $N = ku$, where u is the contact overlap and k is the contact stiffness; the frictional magnitude, F, is computed as $F = \mu N$, where its direction depends upon the relative tangential velocity of the barges and μ is the friction coefficient. The point of application of the resultant force is defined by the position of the midpoint of the contact zone.

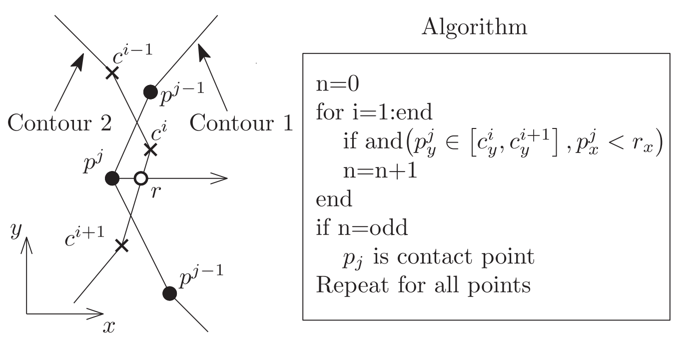

Fig. 2. Contact algorithm

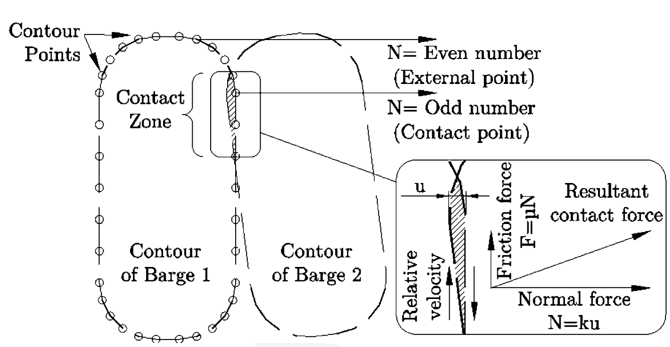

Fig. 3. Contact force computation

Lashing Model

The lashings are represented in the proposed model by means of 1D elements that can only sustain tensile forces and follow an elastic, perfectly plastic behavior. Failure of these elements is considered after the axial deformation exceeds a certain limit defined on the basis of the particular lashing material being considered. The configuration of the lashings was adopted following Arroyo and Ebeling (2005). Each wire rope was thus represented by means of its equivalent bitt location and mechanical properties, summarized in Table 1 and Fig. 4. Longitudinal and transversal displacements are explicitly accounted for in the analyses, whereas vertical displacements are not included in the proposed 2D model. As relative displacements develop, the axial directions of lashings are updated. Once a lashing has failed, the model supposes that it can no longer sustain axial loads.

Barge Bow-Crushing Relations

The load-deflection behavior of the barge bow has a strong influence on the collision forces, as it not only determines the maximum possible impact force but may also provide a significant amount of energy dissipation. The crushing behavior of barge bows was studied by Consolazio et al. (2008) and Harik et al. (2008a) by means of high-resolution finite-element models. These studies found that the size and shape of the impacted pier have a significant influence on the load-deformation behavior. Based on detailed results obtained from several simulations, the authors proposed simplified relations for barge bows suitable for use in bridge design. The elastic, perfectly plastic relations proposed by Consolazio et al. (2008, 2010b) for frontal and oblique impacts are adopted in the analysis presented in this paper.

Dynamic Response of Structure

The load history generated during impact depends on both the characteristics of the barge flotilla and the structural response of the impacted structure. In the proposed model, two different approaches are followed according to the type of impacted structure considered.

When the impacted structure is the bridge itself, the dynamic response of the structure is accounted for by the convolution of the load history developed until a certain time step and the impulse response function of the structure at the impact point. Hence, the full dynamic response of the structure is considered. This procedure, only applicable for elastic systems, is considered appropriate given the fact that an elastic structural response is generally expected. It should also be noted that the impact duration is such that damping effects can conservatively be neglected in the analysis. Once the load history is defined, the structural demands can be calculated by means of a full model, either considering or ignoring damping effects.

For the analysis of flexible protection structures, which may be designed to undergo plastic deformations to absorb the kinetic energy of the flotilla, the dynamic response of the structure is accounted for by means of a simplified model consisting of a piecewise linear (i.e., nonlinear) spring (Pinto et al. 2013).

Implementation

The dynamic barge-collision analysis is performed by means of a numerical integration scheme of the equations of motion of the full barge-structure system. The initial conditions of the system consist of the initial velocity and position of the barge flotilla, as well as the initial velocity and location of the bridge pier (assumed to be in an at-rest condition at the beginning of the impact). For the numerical

Table 1. Lashing Properties

Wire type	Diameter (cm)	Elastic modulus (GPa)	Nominal area (cm^2)	Nominal resistance (kN)		Failure deformation (%)	
				New	Used	New	Used
6×19	2.22	96	2.39	308	246	6	5
	2.54		3.1	399	319		

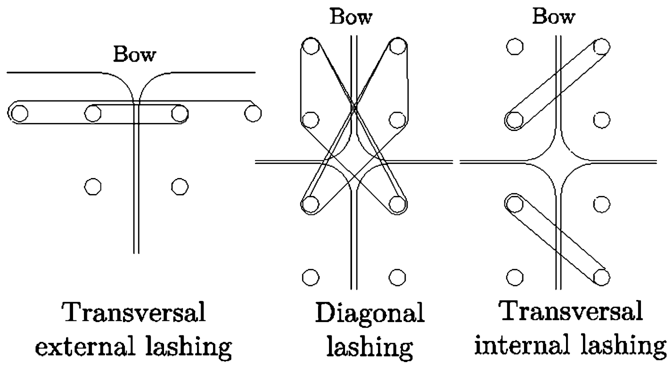

Fig. 4. Standard layout of lashings

integration scheme, a fixed time step is defined, and an explicit two-step integration method is followed (Bathe 1982)

$$u_{n+1} = 2u_n - u_{n-1} + \frac{\Delta t^2}{m} F_n \tag{1}$$

where u_{n+1}, u_n, and u_{n-1} = position of a particular degree of freedom in the next, current, and previous time steps, respectively; Δt = adopted time step; m = mass of the degree of freedom; and F_n = resultant force applied in this degree of freedom in the current time step. For stability reasons, the adopted time step must not exceed one-half of the shorter vibration period of the system

$$\Delta t \leq \frac{\pi}{\omega_{\max}} \tag{2}$$

where $\omega_{\max}$ = highest frequency of the system, approximately $\omega_{\max} = 50$ rad/s. However, to improve accuracy a much smaller time step ($\Delta t = 0.005$ s) is adopted in the analyses presented in this paper.

Validation of Proposed Model

To validate the proposed method, a comparison is made with an example case presented by Harik et al. (2008a). This example evaluates the symmetric impact of a 15-barge flotilla (plus tow boat) traveling at 3 knots against a 2-m-wide, flat pier. The pier is modeled as a cantilever beam with two concentrated masses ($M_1 = 190$ tons and $M_2 = 850$ tons) and superstructure translational and rotational stiffness ($k_x = 143 \times 10^6$ N/m and $k_\theta = 15.3 \times 10^9$ N, respectively). The pier bending stiffness is EI $= 33 \times 10^9$ N/m^2, and the distance between the impact point and fixed end is $L_1 = 8$ m, whereas the distance between the impact point and superstructure is $L_2 = 12$ m. Masses of individual barges and the towboat are $m_b = 1{,}720$ tons and $m_t = 700$ tons, respectively. The barge bow-crushing relation is adopted from Harik et al. (2008a) for a flat, 2-m-wide pier.

Figs. 5(a and b) shows the load history and kinetic energy of an individual barge, where it is seen that there is very good agreement between the proposed model and that of Harik et al. (2008a).

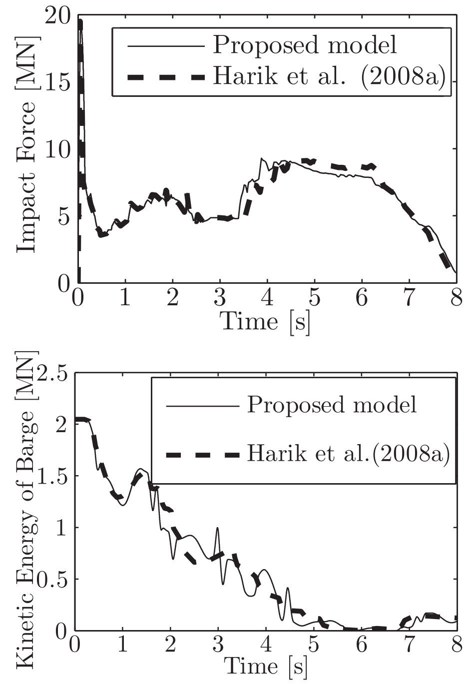

Fig. 5. Proposed method versus that of Harik et al. (2008a)

Parametric Study

A parametric study is carried out by means of the proposed model to analyze the influence of adjacent barge columns for head-on, symmetric impacts. The influence of the following parameters is considered in this study: lashing configuration, number of barge columns, number of barges along the length of the flotilla, friction coefficient between barges, initial velocity, and yield force of the barge bow. The ranges for the parameters considered in this study are summarized in Tables 2 and 3. A single barge bow is considered to come into contact with the bridge pier for three- and five-column flotillas, whereas two barge bows were considered to determine the total impact force for four- and six-column flotillas (Fig. 1).

The combination of the parameters considered in the study yield a total of 3,600 analysis cases. Each of these cases was analyzed by means of the proposed model, where two types of behavior were identified: either the adjacent barge columns break away during the collision process, or the flotilla remains as a unit.

To quantify the influence of the adjacent barge columns on the effective impulse, an influence coefficient is defined as follows:

$$C_I = \frac{I}{P} = \frac{(V_i - V_f) M_a}{V_i M_c} \tag{3}$$

where C_I = influence coefficient; I = impulse given by the adjacent barge columns (which may break away from the tow); P = initial momentum of the impacting barge columns; V_i and V_f = initial and final velocity of adjacent barge columns, respectively; and M_c and M_a = impacting and adjacent column masses, respectively.

According to this definition, the load history of a head-on multicolumn barge flotilla can be estimated in a simplified manner considering a single degree of freedom, representative of the barge flotilla, with an equivalent mass given by

$$M_e = M_c(1 + C_I) \tag{4}$$

where M_e = equivalent mass; C_I = influence coefficient defined in Eq. (3); and M_c = mass of the impacting column for three- and five-barge column impacts, and the two center barge columns for four- and six-column impacts.

This way, the total impulse of the barge flotilla (i.e., sum of impulse given by central and adjacent barge columns) is equal to the impulse given by a single degree of freedom with the equivalent mass definition

$$M_e C_I = M_c(1 + C_I)V_i = M_c V_i + M_a(V_i - V_f) \tag{5}$$

Table 2. Values Considered in Parametric Study

Parameter	Considered values
Initial velocity V_i (m/s)	1, 2, 3, 4, and 5
Friction coefficient μ	0.2, 0.35, and 0.5
Number of flotilla columns C	3, 4, 5, and 6
Number of barges in length of flotilla R	2, 3, 4, and 5
Lashing configuration	Weak, medium, and robust
Total yield load of barge bows (MN)	7, 12, 17, 22, and 27 (for three- and five-column flotilla) 14, 18, 22, 26, and 30 (for four- and six-column flotilla)

Table 3. Lashing Configuration Considered in Parametric Study

Lashing configuration	Number of lashing sections: Transversal external	Transversal internal	Diagonal	Condition
Weak	2	1	2	Used
Medium	3	2	3	Used
Robust	4	3	4	New

Note: Data from Arroyo and Ebeling (2005); see Fig. 3.

The influence coefficient was determined for all cases of the parametric study, and a regression was made with the following equation:

$$S_I = \exp\left(a_I R + b_I V_i + c_I \mu + d_I F_y + e_I\right) \tag{6}$$

where S_I = separation index; R = number of barges along the length of the flotilla; V_i = initial velocity in meters per second; μ = friction coefficient; F_y = barge bow yield force in MN; and a_I, b_I, c_I, d_I, and e_I = parameters fitted to the MDF model results (Table 4).

By comparing the proposed separation index with two reference values, situations where the tow breaks away or it remains as a unit can be identified with a reasonable degree of accuracy. However, it should be pointed out that about 8% of the analysis cases considered remain uncertain. A worst-case condition is assumed for these cases in the proposed method.

Considering only the analysis cases where adjacent barge columns break away from the tow, a regression was made by means of the following equation:

$$C_I = \exp\left(a_c R + b_c V_i + c_c \mu + d_c F_y + e_c\right) \tag{7}$$

where the parameters are identical to the ones used in the separation index defined in Eq. (6); and a_c, b_c, c_c, d_c, and e_c = fitting constants given in Table 5. The regression shows good agreement with the MDF model results, yielding a coefficient of determination $p^2 = 0.94$. Hence, a simplified analysis procedure, based on the proposed MDF method, is schematically summarized in Fig. 6.

Example Case

An example case is considered where a comparison of the impact load history of a multicolumn barge flotilla is made between the results obtained by means of the proposed simplified procedure and those of the MDF model. The comparison considers results obtained for the full mass of the flotilla (i.e., barge columns do not break away, rigid flotilla) and for the impacting column mass only (i.e., neglecting the influence of adjacent barge columns). A 3 × 3 barge flotilla impacting a 4-m-wide, rigid, flat pier is considered with an initial velocity of 2 m/s, a 0.35 steel/steel friction coefficient, and a standard lashing configuration.

A comparison of load histories is shown in Fig. 7, where the influence of adjacent barge columns can be observed by comparing Curve A, which results from an analysis that neglects the contribution of adjacent columns, and Curve B, which considers energy transfer by lashings and contact phenomena among columns. It can

Table 4. Separation Index Parameters

Number of flotilla columns	Lashing configuration	Separation index parameters: a_I	b_I (s/m)	c_I	d_I (1/MN)	e_I	Reference values: Lower limit L_l	Upper limit L_u
3	Weak	2.151	−0.022	−0.001	−0.504	−6.428	1	1
	Medium	0.418	−0.039	0.643	−0.105	−0.468	0.87	1.04
	Robust	0.340	−0.037	0.319	−0.032	−0.441	0.94	1.28
4	Weak	—	—	—	—	—	Separation in all cases	
	Medium	0.666	−0.057	0.830	−0.104	−1.750	0.43	0.55
	Robust	0.386	−0.039	0.222	−0.019	−1.337	0.5	0.7
5	Weak	2.790	−0.017	16.270	−0.622	−16.260	1	1
	Medium	0.480	−0.027	0.525	−0.167	0.287	1.82	1.9
	Robust	0.430	−0.030	0.448	−0.048	−0.142	1.75	2.3
6	Weak	—	—	—	—	—	Separation in all cases	
	Medium	0.942	−0.045	1.932	−0.220	−1.496	0.9	0.9
	Robust	0.586	−0.036	0.659	−0.042	−1.470	0.77	1.33

Table 5. Coefficients of Influence Parameters

Number of flotilla columns	Lashing configuration	Coefficients of influence parameters a_c	b_c(s/m)	c_c	d_c (1/MN)	e_c	Fit R^2
3	Weak	0.286	−0.433	1.214	−0.073	−1.727	0.917
	Medium	0.370	−0.386	1.137	−0.059	−1.368	0.956
	Robust	0.550	−0.284	0.982	−0.054	−1.338	0.913
4	Weak	0.267	−0.442	1.076	−0.044	−2.324	0.961
	Medium	0.417	−0.406	1.242	−0.056	−1.727	0.958
	Robust	0.593	−0.315	1.272	−0.049	−1.737	0.97
5	Weak	0.332	−0.444	0.957	−0.078	−1.739	0.923
	Medium	0.420	−0.425	1.497	−0.080	−1.232	0.922
	Robust	0.653	−0.356	1.559	−0.098	−0.812	0.873
6	Weak	0.246	−0.442	1.010	−0.039	−2.344	0.961
	Medium	0.382	−0.453	1.120	−0.059	−1.486	0.952
	Robust	0.577	−0.367	1.182	−0.055	−1.471	0.956

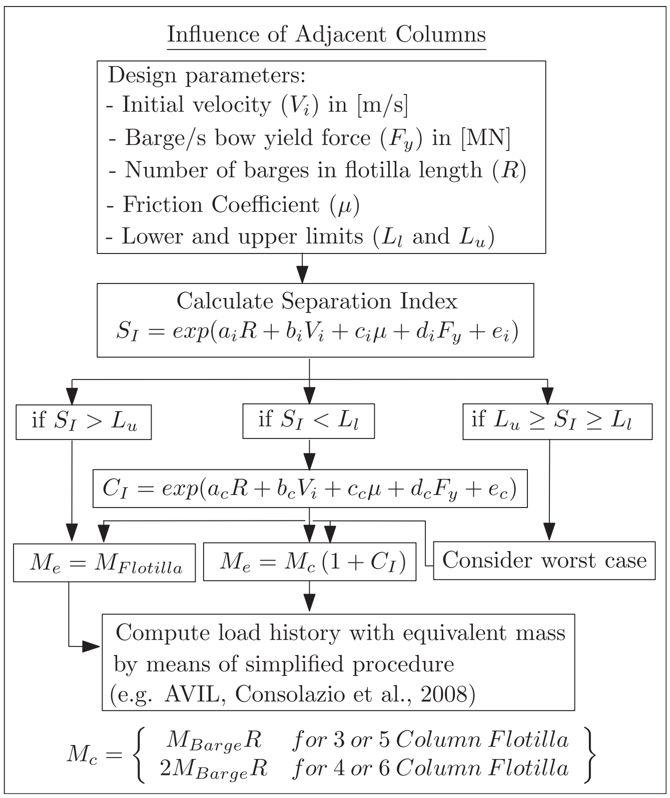

Fig. 6. Flowchart for determination of adjacent columns influence on impact

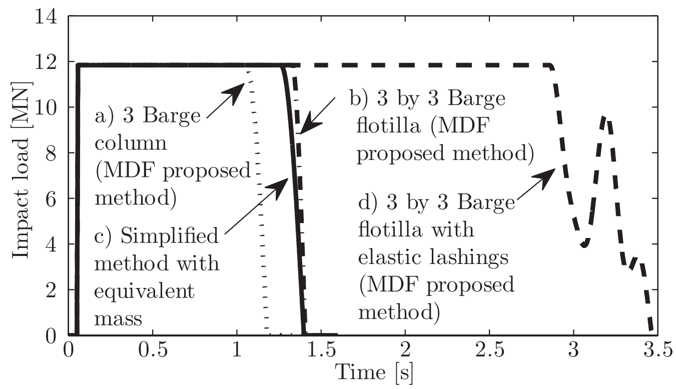

Fig. 7. Load history of a 3 × 3 barge flotilla impacting a 4-m-wide pier at 2 m/s

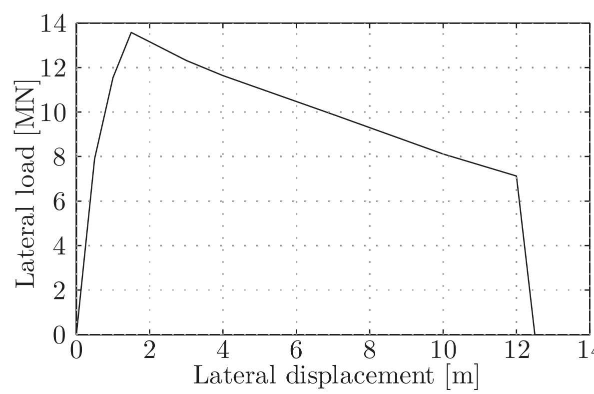

Fig. 8. Pushover analysis of protection structure of the General Belgrano bridge

be seen that the proposed simplified procedure (Curve C) represents with a reasonable degree of accuracy the contribution of the adjacent barge columns. Moreover, it can be seen that for this case the impulse given by the barge flotilla to the impacted structure is overestimated if the failure of the lashings is not considered (Curve D). For this example case, the proposed MDF model shows that barges adjacent to the impacting columns lose contact and drift away once the lashings have failed. In this analysis, the coefficient of influence yields $C_I = 0.21$, meaning that the effect of the adjacent barge columns is a 21% increase in the impulse effectively transferred to the impacted structure by the column that comes into contact with the bridge pier.

If a pier width of 2 m is considered, the yield load of the barge bow would be smaller. Hence, for the same initial velocity, lashing configuration, and friction coefficient, the flotilla would have remained as a unit during the collision. In that case, the whole mass of the flotilla would have to be considered to be acting on the bridge pier.

Oblique Flotilla Impacts

In certain design situations, the analysis of oblique impacts may be warranted, e.g., a barge flotilla that may collide at an oblique angle or in an off-center manner or if the impacted structure has beveled sides. In these situations, the proposed 2D MDF model is more representative than the 1D model. As a particular application of the 2D MDF model, the impact of a barge flotilla against a protection structure downstream of the main pier of the General Belgrano bridge [over the Paraná River, Argentina (Pinto et al. 2008, 2013)] is analyzed. The considered flotilla consists of a 3×3 barge group with an initial velocity of $3.3\,\mathrm{m/s}$. The protection structures, currently under construction for this bridge, are wedge-shaped to deflect the impacting barge columns and therefore reduce the energy absorbed during the impact compared with a flat configuration. The yield loads of the central and lateral barge bows were determined considering impacts against a 2-m-wide object and an oblique impact (45°) against a flat wall, respectively. According to Consolazio et al. (2008, 2010b), the yield loads for the center and lateral columns under these assumptions are 8.4 and 12.1 MN, respectively.

Fig. 8 shows the lateral pushover analysis of the protection structure, which has a 1,584-t rigid cap. Figs. 9 and 10 show the load histories and energy absorption by the protection structure for this case obtained by means of the 1D MDF model (Harik et al. 2008a) and the 2D model proposed in this paper.

It can be seen that the proposed 2D model is able to account for the oblique impact of the adjacent barge columns that occurs once they break away from the impacting column, whereas the elastic 1D model only represents the impact of the center row. The load history computed by means of the proposed model shows a peak value of 31.5 MN attributable to the combined impact of both center and adjacent barge columns projected along the longitudinal direction: $8.4\ \mathrm{MN} + 2 \times 12.1\,\mathrm{MN}\cos(45° - \phi) = 31.5\,\mathrm{MN}$, where ϕ is the steel-to-concrete friction angle [$\tan(\phi) = 0.5$]. Because of this, the absorbed energy by the protection structure computed by the proposed model (10.7 MN·m) is higher than the absorbed energy computed by the 1D model (6.3 MN·m). Thus, in this case, the 1D MDF model yields an unconservative estimation of the energy effectively absorbed by the protection structure. It is also noticed that the residual kinetic energy of the flotilla computed by means of the proposed model (31.2 MN·m) is higher than the kinetic energy evaluated by means of the 1D model (0.8 MN·m). Fig. 11 shows the 2D barge flotilla impact behavior.

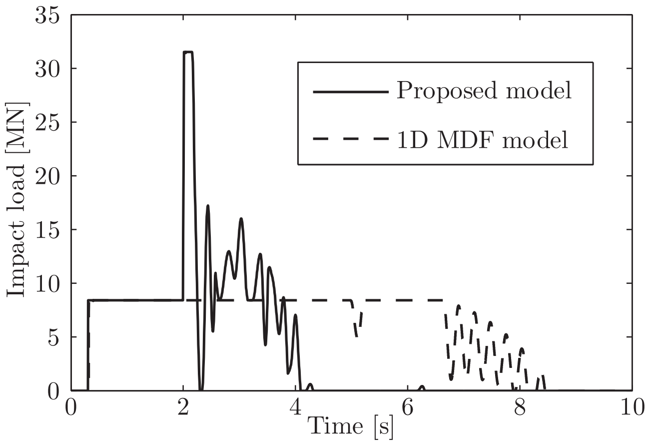

Fig. 9. Load history obtained by 1D MDF model versus proposed model

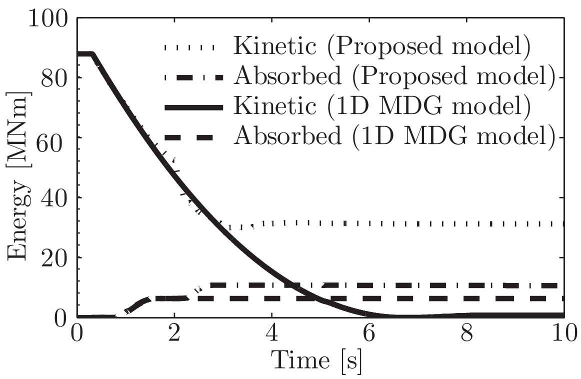

Fig. 10. Kinetic energy of barge flotilla and energy absorbed by protection structure of the General Belgrano bridge

Conclusions

This paper presents a 2D MDF model for the analysis of barge collisions against bridge piers, considering the nonlinear behavior of bow, lashings, and contact between adjacent barges. The model has been validated against results published by other authors, which consider more simplified assumptions regarding barge behavior. This model is a generalization of a 1D model proposed by Harik et al. (2008a) and allows the analysis of barge flotilla impacts in a more general manner, as it allows nonsymmetrical and oblique impact analysis.

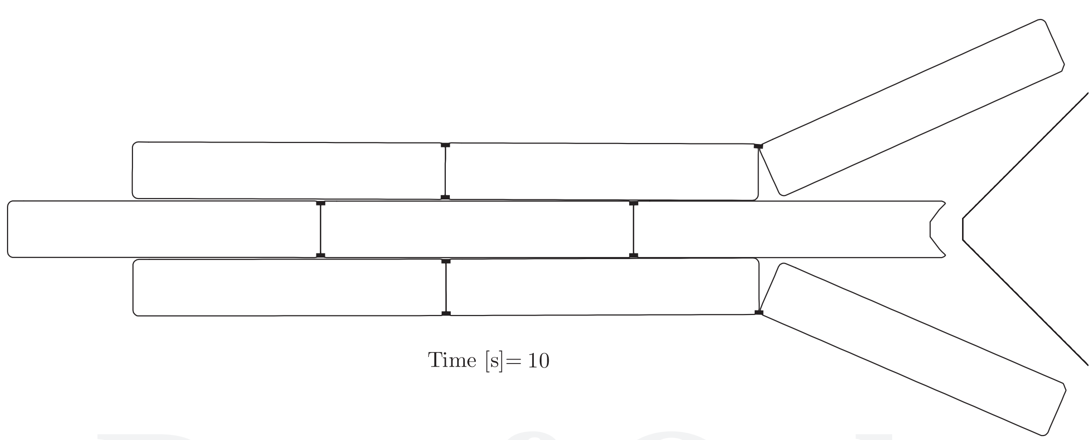

Fig. 11. Configuration of barge flotilla after collision evaluated by means of 2D MDF model

A parametric study considering a set of typical parameters encountered in bridge design was carried out by means of the proposed 2D model. On the basis of the parametric study, a simplified procedure that allows the evaluation of the influence of adjacent barge columns through the definition of an equivalent mass is proposed. The impact load history can be more accurately computed by means of existing single degree of freedom methods and the equivalent mass definition proposed in this paper.

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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

There are no queries in this article.