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ORIGINAL ARTICLE

Finite element simulation of barge impact into a rigid wall

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Abstract The forces and locations of inland barge impacts currently control the design specifications for lock walls. This has resulted in a significant increase in the final construction costs of these walls. Thus, the loads from barge impacts on lock approach walls become an important evaluation and/or design factor when working toward reducing construction costs.

Many approaches have been developed in order to obtain these impact loads. In general, collision mechanics for floating units is classified into, external mechanics and internal mechanics. In external mechanics, analytical approaches are used to determine the absorbed energy acting on the vessel from the collision, while in internal mechanics analytical approaches are used to determine the ability of the ship's structure to withstand the absorbed energy. Due to the difficulty and the highly expected cost to perform model testing and impact data for validation, finite element simulation provides an alternative tool for physical validation. In this study, a simulation of barge impact to a rigid wall is presented using the explicit nonlinear finite element code LS-DYNA3D. A conventional fine mesh finite element barge model is created. Impact results are obtained at two different speeds in order to show the consequence of barge and wall damage.

1. Introduction

Ship impacts against bridges although very unlikely happen, Fig. 1. Nevertheless, history shows that this type of accident has happened quite regularly. Scheer [1] lists bridge failures caused by ship impacts since 1850 as shown in Fig. 2. Larsen [2] gives a list of serious ship accidents including bridge failures due to ship impact, Fig. 3. The data show a peak in the number of impacts at the end of the 1970s and the beginning of the 1980s. After that, the number of impacts declined. Unfortunately, since the beginning of the 1990s, the number of ship impacts against bridges has risen again, especially in some areas of Germany.

The fact that bridge failures due to ship impact can lead to serious consequences, including massive fatalities, is illustrated in Table 1. Two examples of recent ship impacts are given: a ship impacted against a highway bridge in China in 2007, yielding to the collapse of the bridge; and a ship impact in Krems, Austria, in 2005 resulted in the pier moving more than 2 m Simandl et al. [3].

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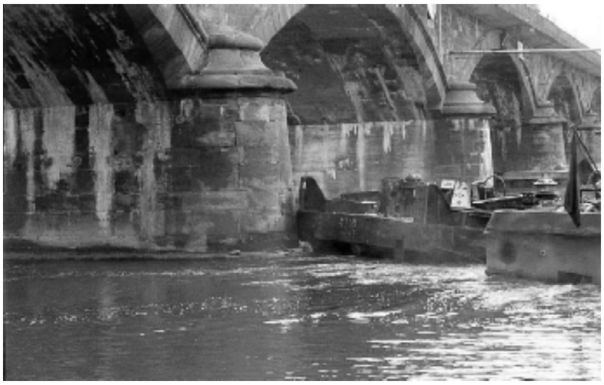

Figure 1 Ship impact against bridge.

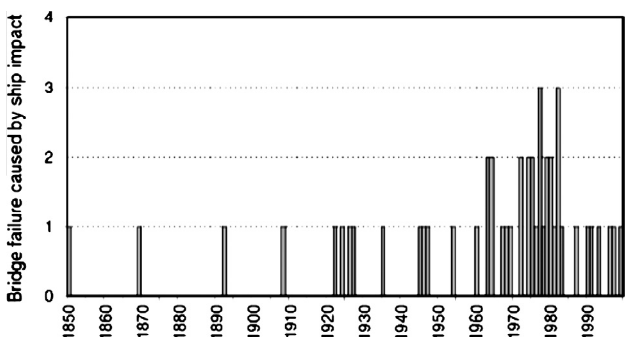

Figure 2 Number of bridge failures caused by ship impacts [1].

The development of the number of accidents, both for Germany and for the area controlled by the Würzburg Department of Highways and Bridges are given by Stede and Kunz [4,5]. Additional information on ship collisions with bridges is given by Van Manen and Frandsen [6]. Unfortunately, no data for the Egyptian river authority are available.

The high variability and complexity of damage behavior in ship collision precludes the ability to predict the exact behavior of the vessels during the collision event. However, as with most complex systems, various simplifications and assumptions based upon general behavior collected from multiple events can be made yielding a less complex and definable system.

2. Ship collision mechanics

The collision analysis approaches are classified into the following categories:

1. External mechanics.
2. Internal mechanics.
3. Simulation approach that couples the internal and external mechanics.

2.1. External mechanics

The external ship accident mechanics is dealing with the rigid-body global motion of the structures involved under the accidental actions.

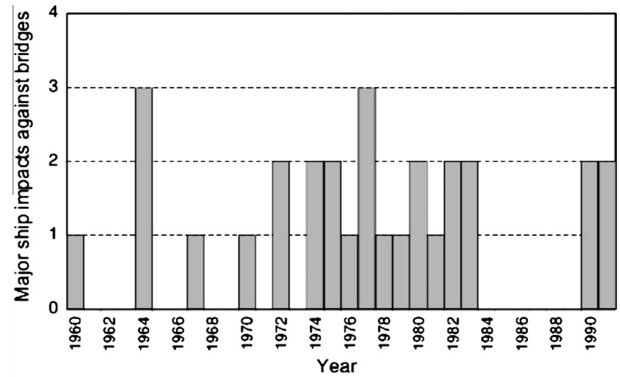

Figure 3 Major ship impacts against bridges [2].

The external sub-model calculates the ship dynamics in collision. Different models have been developed from different assumptions and for different purposes.

The simplest is the one-dimensional approach (striking ship surge, struck ship sway) proposed by Minorsky [8]. Damage [9] adds an additional degree of freedom (struck ship yaw) and is more suitable for strikes away from the center of gravity of the struck ship. More sophisticated models consider three degrees of freedom (surge, sway and yaw), as in Hutchison [10].

2.2. Internal mechanics

The internal ship accident mechanics includes evaluation of the structural failure response of the involved ships during the accident. The internal mechanics of collisions are quite complex, deformations many times larger than the structural thickness may take place, and the major part of energy dissipation takes place in inelastic straining. The inelastic straining tends to take place in relatively localized regions. The analysis methods of internal mechanisms can be categorized into four groups:

1. Simple formulae.
2. Simplified analytical approach.
3. Experimental method.
4. Finite Element Methods (FEMs) which is divided into:
   (A) Simplified FEM.
   (B) Nonlinear FEM.

The analysis methods advantages and disadvantages are summarized in Table 2 [11]. This study focuses on the finite element method.

2.3. The simulation approach that couples the internal and external mechanics

The procedure of simulation approach as shown in Fig. 4 is consisting of external and internal collision mechanics. The aim of external collision mechanics analysis is to identify the loss of initial kinetic energy during ship collisions, while the object of internal collision mechanics analysis is to identify the structural crashworthiness involving yielding, crushing, and rupture in terms of collision forces versus penetration relationship as a striking body penetrates a struck structure.

Table 1 Examples of bridge failure caused by ship impact Mastaglio [7].

Bridge and location	Year	Fatalities
Severn River Railways Bridge, UK	1960	5
Lake Ponchartain, USA	1964	6
Sidney Lanier Bridge, USA	1972	10
Lake Ponchartain Bridge, USA	1974	3
Tasman Bridge, Australia	1975	15
Pass Manchac bridge, USA	1976	1
Tjorn Bridge, Sweden	1980	8
Sunshine skyway Bridge, USA	1980	35
Lorrain Pipeline Bridge, France	1982	7
Sentosa aerial Tramway, China	1983	7
Volga River Railroad Bridge, Russia	1983	176
Claiborn Avenue Bridge, USA	1993	1
CSX/Amtrak Railroad Bridge, USA	1993	47
Port Isabel, USA	2001	8
Webber-Falls, USA	2002	12
Highway Bridge between Foshan and Heshan, China	2007	>9

Table 2 Comparison between the analysis methods of internal ship mechanics.

Methods		Analysis efforts		Results		
		Modeling (%)	Computation	Energy	Loads	Stress
Simple formulae		10–20	10–20%, hand calculation	√		
Simplified analytical approach		20–40	20–40%, hand calculation	√	√	
Experimental method		40–60	40–60%	√	√	√
FEM	Simplified FEM approach	40–60	40–60%, special programs	√	√	
	Nonlinear FEM simulation	60–100	60–100%, expensive software	√	√	√

This approach relies on the solution of final velocities of struck and striking ships by an external model. This uncoupled solution requires significant simplifying assumptions, and/or restricting degrees of freedom of the system Paik and Park [12]. In addition, this analysis can be made in the time domain with a fully coupled time-stepping solution. Starting with the initial external condition, impact forces are calculated based on internal structural mechanics at each time step and applied to the struck ship.

3. Finite element methods

3.1. Simplified FEM

Paik and Pederson [13] used the idealized structural unit method (ISUM) as a nonlinear analysis tool for collision problems. This approach often combines the analytical approach models for crushing, tearing and yielding behavior of structural component, and the ordinary finite element technique. To determine these forces the outer and the inner side shell plates around the colliding zone of the struck ship are modeled by membrane tension triangular/rectangular plates units with a stiffness matrix formulated by considering the rupture behavior. Transverse webs and side stringers that connect the outer and the inner hulls are modeled by rectangular plate units, which are formulated by taking into account yielding, crushing and rupture. The striking ship was modeled as a rigid body. Dynamics effects were considered by including the influence of strain-rate sensitivity material model. The computing cost and modeling efforts of analysis are reasonably small, while the accuracy is not lost. This technique has the advantages of FEM in modeling the interaction between structures involved, and the merits of simplified analytical methods in dealing with complex damage behavior. Since the rapid advance in computer hardware and nonlinear FEM codes, the simplified FEM has been rarely used nowadays.

3.2. Nonlinear FEM

Recent advances in computer and calculation algorithms have made nonlinear finite element analysis an available tool for assessing the internal mechanics of ship collisions.

Two types of FE methodologies, implicit and explicit techniques, are relevant. Implicit methodologies solve systems of equations, and the calculation cost depends largely on the equation solver and the computer capacity, especially memory resources. Implicit methodologies based codes include ABAQUS/STANDARD, ANSYS, MARC and NASTRAN. However explicit systems do not require equation solving. Equilibrium is solved in the element level, which requires very small time step to comply with stability required for equation solving. Explicit methodologies based computer codes include ABAQUS/EXPLICIT, DYTRANS, LS-DYNA, PAM-CRASH and RADIOSS [14].

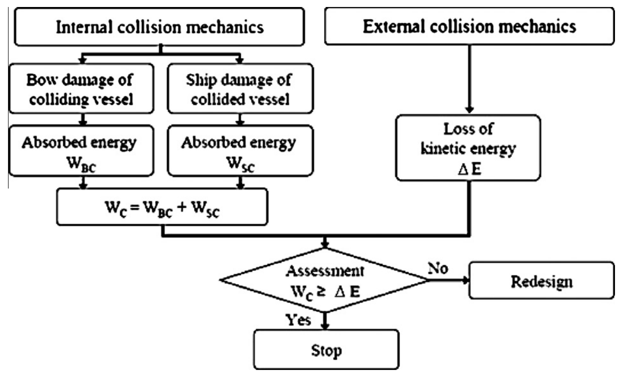

Figure 4 Procedure for the coupling of external and internal ship mechanics.

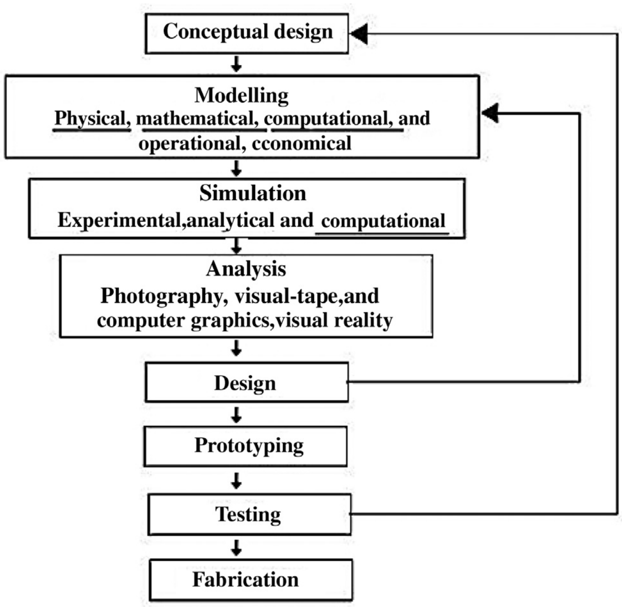

Figure 5 Process leading to fabrication of advanced engineering system [14].

4. Simulation approach using finite element method

The Finite Element Method (FEM) has developed into a key indispensable technology in the modeling and simulation of advanced engineering systems in various fields like housing, transportation, communications, and so on. In building such advanced engineering systems, engineers and designers go through a sophisticated process of modeling, simulation, visualization, analysis, designing, prototyping, testing, and lastly, fabrication. Note that much work is involved before the fabrication of the final product or system. This is to ensure the workability of the finished product, as well as for cost effectiveness. The process is illustrated as a flowchart [15] in Fig. 5.

4.1. Computational modeling using the FEM

The behavior of a phenomenon in a system depends upon the geometry or domain of the system, the property of the material or medium, and the boundary, initial and loading conditions. For an engineering system, the geometry or domain can be very complex. Furthermore, the boundary and initial conditions can also be complicated. It is therefore, in general, very difficult to solve the governing differential equation via analytical means. In practice, most of the problems are solved using numerical methods. Among these, the methods of domain discretization championed by the FEM are the most popular, due to its practicality and versatility.

The procedure of computational modeling using the FEM broadly consists of four steps:

1. Modeling of the geometry.
2. Meshing (discretization).
3. Specification of material property.
4. Specification of boundary, initial and loading conditions.

The procedure is fully presented through the application of barge impact to a rigid wall.

5. Finite element simulation of barge impact to a rigid wall

In the present study, a simulation approach is carried out in order to emulate the barge impact to a rigid wall. This can help to understand the mechanism of the impact and to determine the barge response under this impact. To be extremely accurate, the water could be modeled discretely as a fluid body surrounding the barge. However, this would be extremely time consuming and computationally intensive. In the meantime, the approach can compensate the highly expected cost of carrying out an experiment for such simulation. The simulation is carried out using LSDYNA finite element simulation software. The basic procedures of modeling in LSDYNA [16] are as follows:

- Create a model using the FEMB pre-processor.
- Run the LSDYNA collision simulation using the model.
- Use the post- and/or graph-processor to obtain/review the simulation results.

The development of simulation for a barge impact with a rigid wall at two different velocities is presented. The model is developed using FEMB and analyzed using LSDYNA solver. The model summary is:

(1) A barge striking a rigid wall at a velocity of 3 knots.
(2) A barge striking a rigid wall at a velocity of 5 knots.

Table 3 Barge particulars.

Length overall	60 m	Depth, molded	6 m	Light Weight	1428 T
Length between perpendiculars	60 m	Design draft	4.6 m	Light KG	2.40 m
Breadth, molded	18 m	Maximum design speed	5 knots	Light LCG	27 m fwd AP

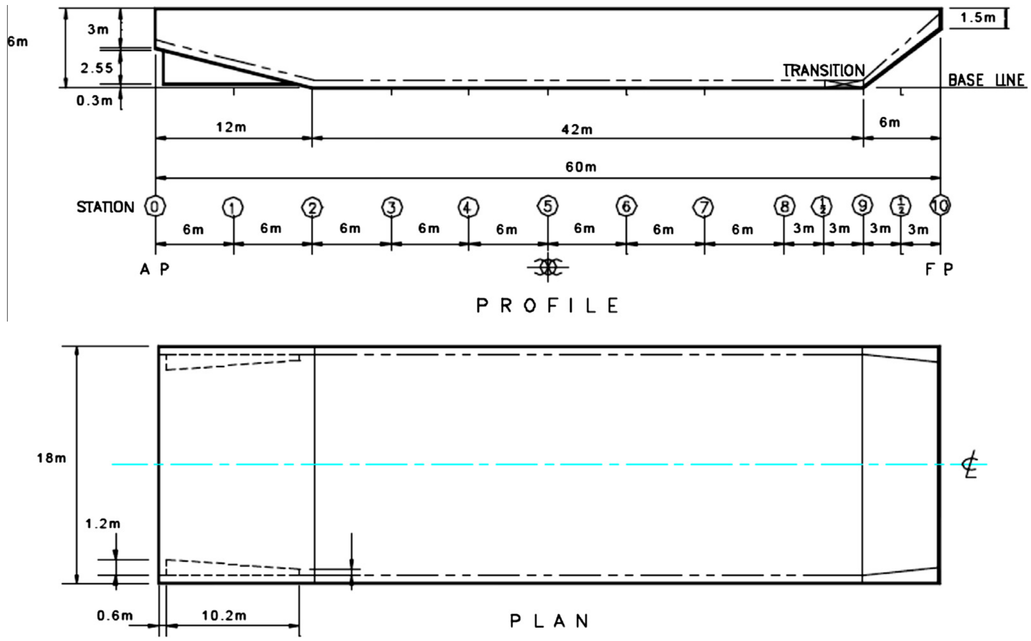

Figure 6 Hull definition.

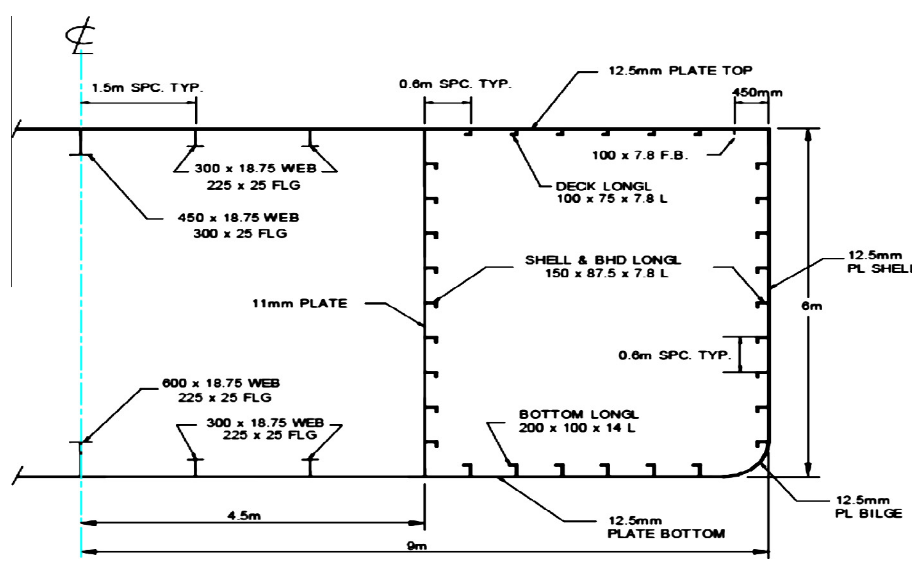

Figure 7 Midship section before smearing.

The barge is assumed to strike normal to the wall (worst case scenario).

5.1. Barge particulars

An actual barge is considered. The barge particulars are shown in Table 3.

5.2. Hull definition

The barge hull and dimensions are presented in Fig. 6.

5.3. Barge material

The material properties of the barge are as follows:

ABS steel grade AH32	
Mass density:	7.850 kg/m^3
Young's modulus:	2.09 × 1011 Pa
Poison ratio:	0.3
Yield strength:	3.55E + 08 Pa

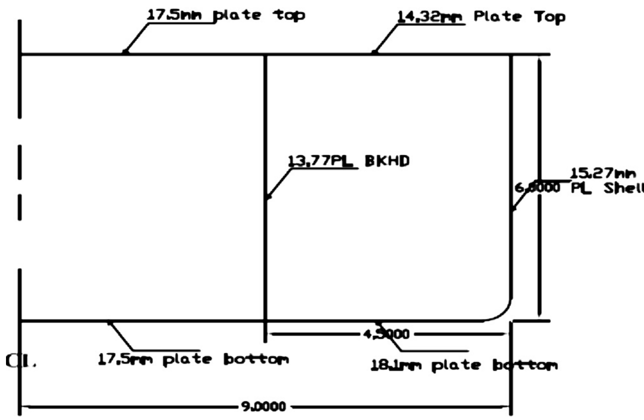

Figure 8 Midship section after smearing.

5.4. Structural section

Fig. 7 shows the midship section for the barge under study before smearing. The barge model involves smearing the longitudinal stiffeners and girders into the plates.

In order to reduce computational time and to allow the use of a larger shell element mesh in the bow and cargo section models, plate stiffeners, flanges, and structural holes are smeared into plate panels. The traditional smearing method provides equivalent tensile strength under longitudinal tension loading using area smearing. The equivalent plate thickness, T_t, is calculated using the following equations of smearing [17]. Fig. 8 shows the midship section after the smearing of the longitudinal stiffeners and girders into the plates.

$$T_t = \frac{N_s(A_f + A_w) + A_p}{B} \quad (1)$$

where T_t is the equivalent plate thickness, N_s is the number of stiffeners and A_f, A_w and A_p are the stiffener flange, web and plate sectional areas, and B is the plate span.

5.5. Barge modeling

The modeled barge and the rigid wall are shown in Fig. 9 after exporting from the FEMB.

5.6. Modeling material properties

Material type 20 (rigid) is used to model the rigid wall. All parts in the striking barge use material type 3 (kinematic/isotropic elastic plastic). The material properties are as follows:

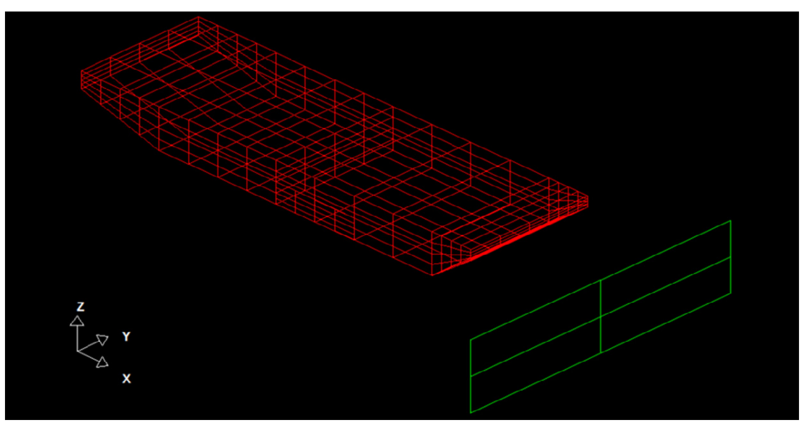

Figure 9 Barge and rigid wall developed in the FEMB.

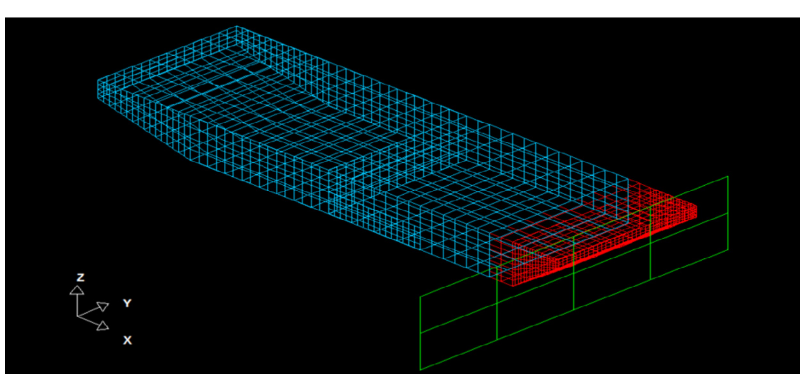

Figure 10 Mesh size.

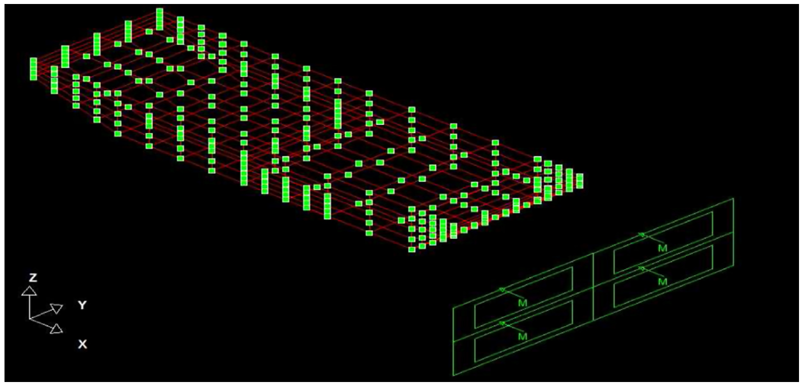

Figure 11 Interface between the barge and the rigid wall.

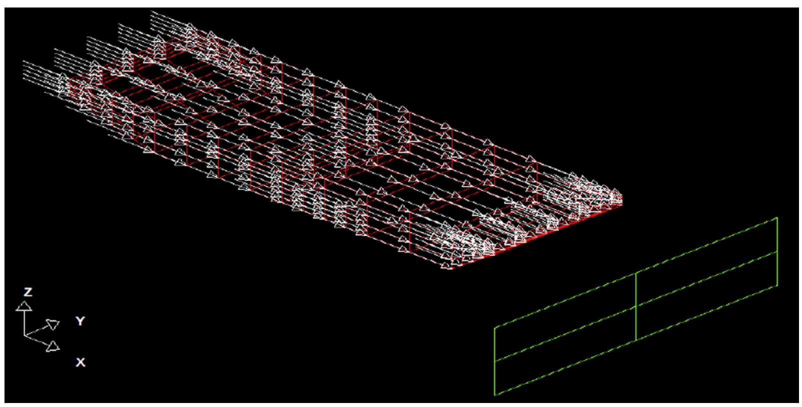

Figure 12 Barge velocities toward the rigid wall.

1. RIGID (Wall)

Material type:	20 (Rigid)
Mass density:	7.85×10^3 kg/m^3
Young's modulus:	2.09×10^{11} Pa
Poisson's ratio:	0.3

2. DEFORMABLE (Barge)

Material type:	3 (Kinematic/Isotropic Elastic Plastic)
Mass density:	7.85×10^3 kg/m^3
Young's modulus:	2.09×10^{11} Pa
Poisson's ratio:	0.3
Yield stress:	4.57×10^8 Pa

5.7. Element properties

Belytschko–Tsay shell elements are used for the rigid wall and the barge plating. 1624 elements are used.

5.8. Meshing

Mesh size used is 0.4 m in the bow portion while a larger mesh size of 0.8 m used in the aft portion as shown in Fig. 10.

5.9. Interface

Contact type 5 (nodes to surfaces) are used for this case study as shown in Fig. 11. The rigid wall is assigned master surfaces elements and the striking barge nodes are assigned slave nodes. One surface of the interface is identified as a master surface and the other as a slave. Each surface is defined by a set of three or four node quadrilateral segments, called master and slave segments, on which the nodes of the slave and master surfaces, respectively, must slide. The surface which is more coarsely zoned should be chosen as the master surface. When using the one-way slide surface with rigid materials, the rigid material should be chosen as the master surface.

5.10. Initial conditions

The striking barge modeled is used, for both cases only the velocity assigned to it is changed from 3 Knots to 5 Knots, Fig. 12.

6. Results and comparisons

After modeling using FEMB, the created model is imported to the LS-DYNA solver to create the analysis file, and then

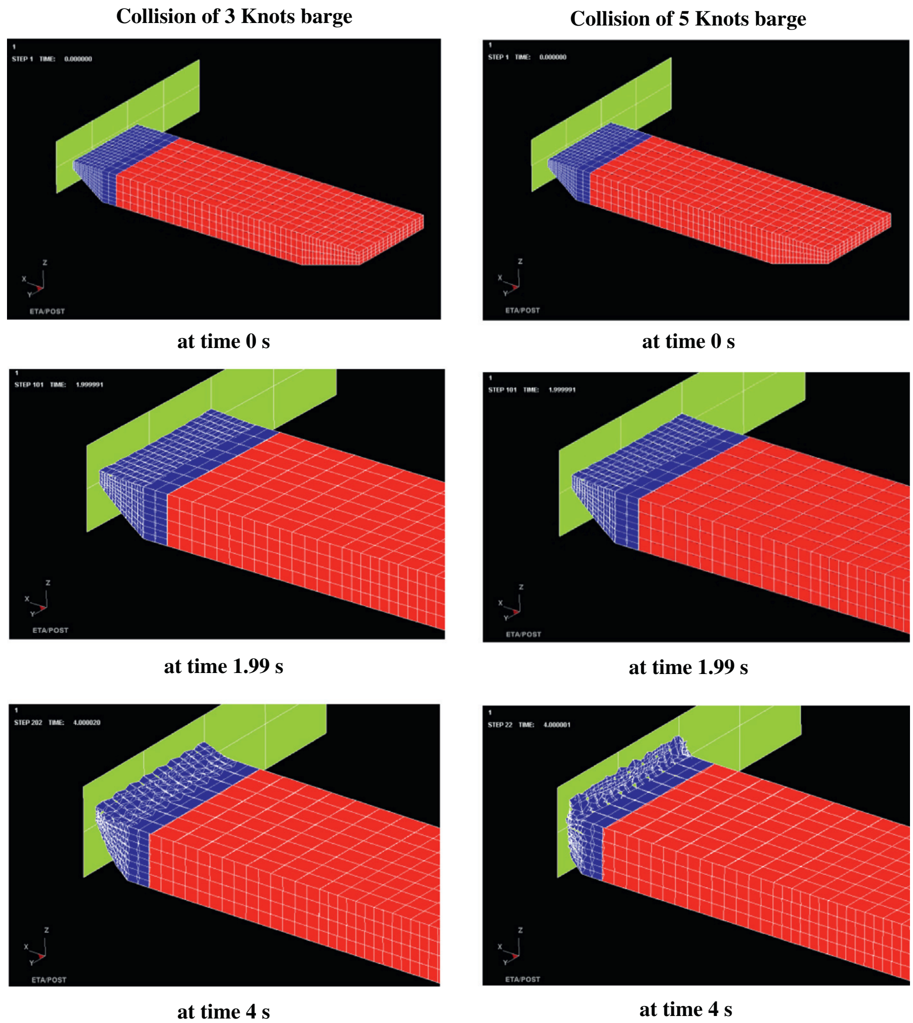

Figure 13 Collision damage for both cases.

through the POST-GL module, the simulation of the results can be shown for both cases as shown in Fig. 13. It is obvious that at the end of the collision the damage extent of the 5 knots collision is more than that of the 3 knots collision. At an intermediate time 1.99 s the damage is almost the same.

6.1. Stresses contours

POST-GL module can also be used to view the normal stress distribution along the model at any time during the collision as shown in Fig. 14.

At the beginning of the contact it is observed that for the barge with 3 knots speed has normal stress values at the corners higher than that of the bow and decrease toward the middle while for the barge with 5 knots speed the normal stresses values are higher at the corners and the middle portion.

At the end of the contact the results show that for the barge with 3 knots speed the stresses values at the corners are still higher than those at the middle portion. While the stresses values of the 5 knots barge has lower values at the end due to the failure of the bow plates.

6.2. Von Mises stresses

If the "Von Mises stress" exceeds the yield stress, then the material is considered to be at the failure condition. The Von Mises stress distribution may be viewed from the POST-GL module, and the values can be determined along the barge at any time of the collision.

6.3. Kinetic energy

The chart in Fig. 15 shows the kinetic energy versus time for the 3 and 5 knots barge striking the rigid wall. At the 3 knots velocity the KE starts at 1.35E + 8 (N.m.) at the time of collision (1.3 s) and decreases after that until it reaches zero the (barge stops). At 5 knots velocity the KE starts at 3.9E + 08 (N.m.) at the time of collision (0.88 s) and decreases after that until it reaches zero (the barge stops).

6.4. Absorbed energy

According to the internal absorbed energy versus time for the 3 and 5 knots barge striking the rigid wall, the 3 knots velocity

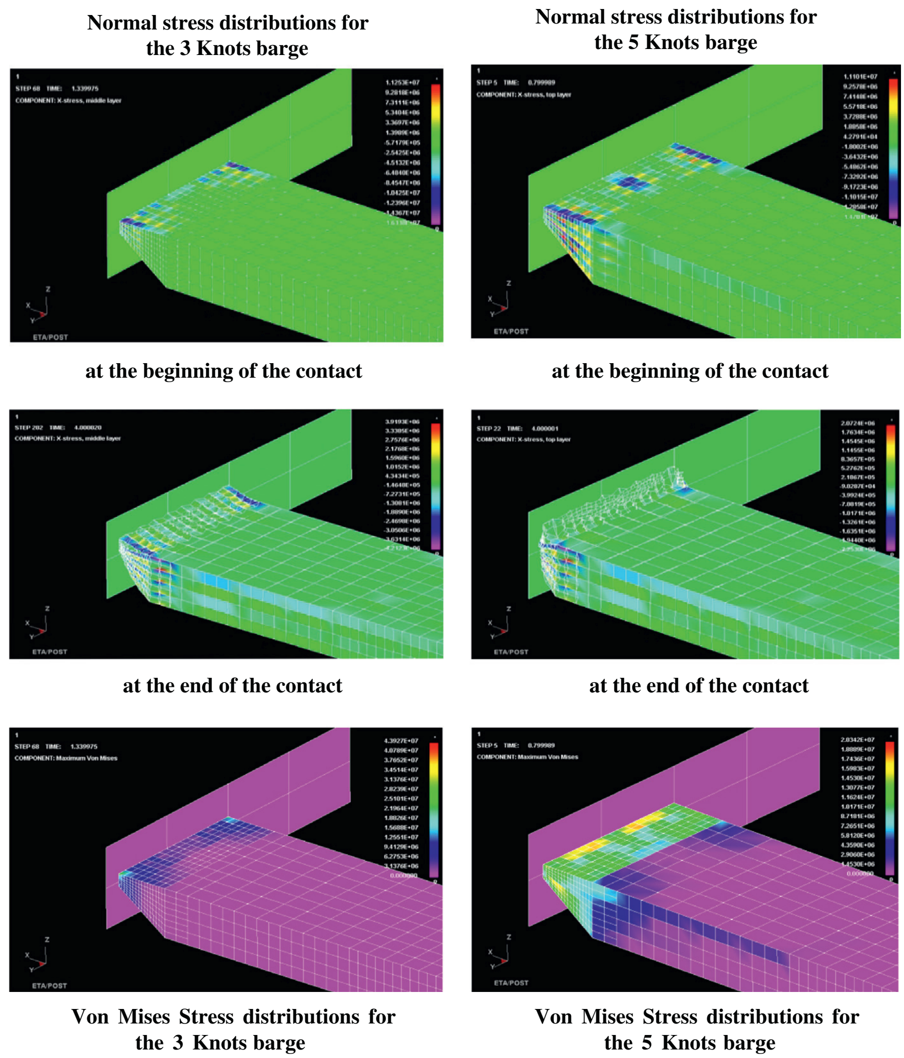

Figure 14 Normal stresses distribution for both cases.

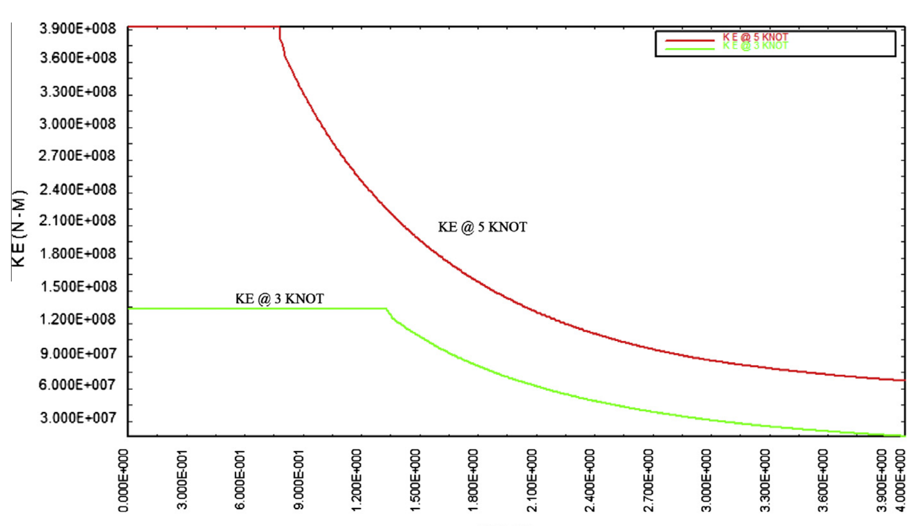

Figure 15 Kinetic energy versus time.

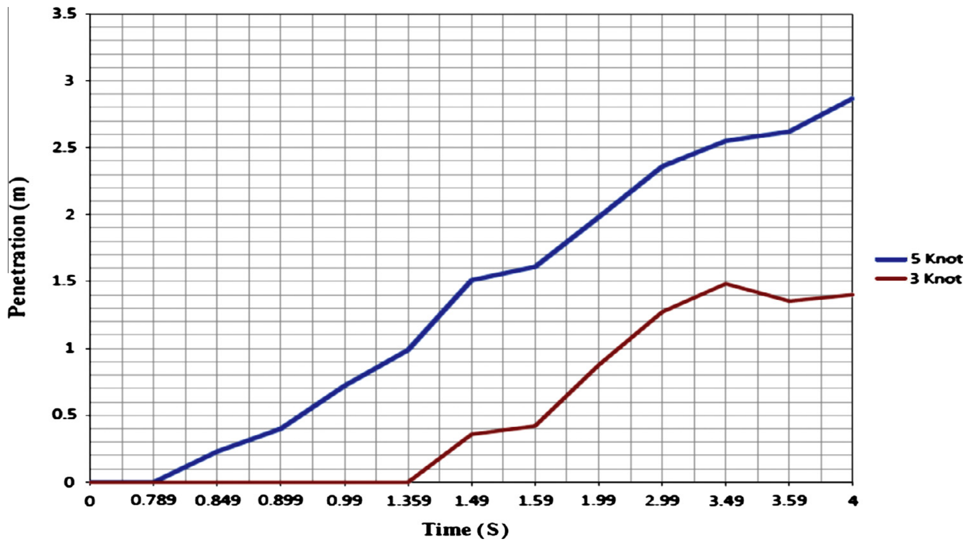

Figure 16 Penetration versus time.

the absorbed energy was zero until the time of collision (1.3 s), it increased instantaneously to 2.8E + 5 and started to decrease immediately until it reached zero at the end of the collision. While, the 5 knots velocity the absorbed energy was zero until the time of collision (0.8 s), it increased instantaneously to 8.65E + 5 and started to decrease immediately until it reached zero at the end of the collision.

6.5. Penetration curve

Fig. 16 represents the penetration versus time curves for the two speeds and shows that the maximum penetration at the end of the collision for the 3 knot barge is 1.4 m and for the 5 knots barge is 2.8 m.

7. Conclusions

Due to the importance of determining loads due to ship impacts against bridges or lock walls, direct and simple methods are developed in order to determine the internal and external ship mechanics, however these methods are not accurate enough to assist in developing new regulations. The recent advances in computer and calculations algorithms have made the nonlinear finite element analysis an available tool for assessing the internal and external ship collision mechanics. FEM is the most descriptive and accurate method from all methods developed to determine the internal and external ship collision mechanics. However the FEM software requires very high capability computers in order to obtain accurate results, which makes this method an expensive method. For this reason, an adequate simplification has been made for a barge model. As a result of the barge modeled earlier, the maximum damage extent of the barge with a velocity of 5 knots is 2.8 m limiting it to the forepeak compartment. The obtained results should be validated using real case(s). More concerns have to be raised toward more investigations of ship collision accidents, especially for the Nile barges and collisions in the Egyptian ports, to establish new regulations for building river bridges foundations and limiting ship collision consequences for better environment protection.

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