A review of technical solutions and simulation approaches for ship collisions with lock gates

S. Ehlers*[1], H. Le Sourne[2], L. Buldgen[3], J. Ollero[4], C. Robertson[5] and P. Rigo[3]

Lock gates are frequently found at inland waterway locks and sea navigation locks. Entering a lock with a ship is a challenging manoeuvre, which can potentially lead to the ship colliding with the lock gate. Such collision may permanently damage the gate causing the lock operation to be disrupted and the ship transport to be delayed. Consequently, it is important to design for the possibility of a ship colliding with the lock gate to ensure its operability as well as the safety of the operation. In order to do so, a variety of recommendations and standards exist, which are however neither unified nor require the assessment of the lock under a ship collision on a mandatory basis. Therefore, this paper presents the current developments in assessment approaches for ship collisions with lock gates as well as current gate protection practices. The paper concludes with a recommendation of assessment approaches, which can be used to identify safe lock gate approach velocities in the case of existing locks or collision resistant structural layouts for new buildings of lock facilities.

Keywords: Steel lock gates, Numerical simulations, Collision mitigation

Introduction

Various national guidelines and design standards exist for the analysis and design of lock gates, but none specifically require the consideration of ship collision as a design criterion. Thus, a detailed, yet general, methodology to assess the lock gate in question under ship collision is not provided. Furthermore, quantitative measures or guidance for parameters relevant to the collision accident are scarce.

In Germany the design criteria are identified on a case-by-case basis and may include ship collision consideration. According to DIN 19704 and 19703 any collision against closure structures is to be prevented by installation of protection devices, where the kinetic energy to be absorbed is suggested to be in the range of 1–2 MN unless found to differ for the striking ship in question with a velocity ~ 1 m s^{1}. Eurocode 1, EN 1991-1-7: 2010-12 provides indicative values for ship collision within inland waterways for different ship sizes according to the European Conference of Ministers of Transport, and in seaways for oceangoing ships. The values given there are for collisions against rigid structures, where the collision energy is being absorbed solely by the deformation of the striking ship. Differing from the considerations above, sea navigation locks are commonly designed for a ship collision load of 300 kN. In these cases the upstream and downstream gates are of the same design and an additional gate is provided as a standby gate to cover for cases with significant damage. Owing to the large widths of sea navigation lock gates protection devices are not provided. In general, in the UK navigation lock gates are not specifically designed against collision loadings, with the exception being gates at naval dockyards. In France there are no particular standards for designing lock gates against ship collisions. Nevertheless, some recommendations concerning ship collisions on lock gates are published by a technical division of the French Ministry of Equipment called the Centre d'Etudes Techniques Maritimes et Fluviales (CETMEF) which are specifically addressed in the technical notice STC.VN no 97-01 (CETMEF 1997). A practical application of these recommendations can be found for the Seine–Nord Europe project, which will link the Seine and Scheldt rivers with a number of locks for efficient water-based transport with large ships. According to the RfP (Request for Proposals) published by the Panama Canal Authority ACP (Autoridad del Canal de Panamá) the following criteria had been established for the design of the lock gates in regard to ship collision: '...Lock gates shall be designed and constructed to be able to resist, when closed, the impact of a 160 000-ton displacement ship travelling at a speed of 1 knot without compromising their water tightness or the capability of being moved into their recesses. The contractor shall obtain the information on the ship's hull design that is required to correctly model the ship collision from either direction. In addition, impact from ships with displacements ranging from 75 000 to 160 000 tons shall be considered. Only minor, localised structural damage without loss of floatability shall be expected after a less-severe impact. Under the

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[1] Hamburg University of Technology (TUHH), Hamburg, Germany
[2] Mechanical Engineering Department, ICAM Nantes, France
[3] ANAST, University of Liege, Belgium
[4] INROS LACKNER AG, Bremen, Germany
[5] Independent Consultant, UK

*Corresponding author, email ehlers@tuhh.de

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impacted condition, the lock gate must be able to be fully floated and moved into its recess or be floated out of the lock chamber. Floating of the gates stabilised in their upright position shall still be possible after complete flooding of watertight zones because of local damage after a ship collision.' The U.S. Army Corps of Engineers published several engineering manuals (EM), such EM 1110-2-2105 and EM 1110-2-2703. Therein, depending on the lock gate type different collision loads and load cases are specified, including suggestions to, i.e. equip all mitre gates with a system of bumpers and fenders. In the Netherlands, ship collision is usually not considered as being a separate issue within gate design practice, but a part of the lock availability question.

Consequently, proper specifications and requirements concerning collision protection very much depend on the consequences that ship collision can have on the lock availability. The important questions in this context are:

What is the character and intensity of navigation traffic? The collision issue will be addressed differently for light recreation ships as compared to large cargo ships.

Are there one or more lock chambers at the location under consideration? If two or more parallel lock chambers exist, then losing one of them because of ship collision does not necessarily block the entire waterway.

Are there spare gates available? If yes and if a gate that suffers a collision can be replaced quickly, then the need for protection is less.

What are the economical, social or other costs of a lock being blocked because of ship collision?

For these reasons, there is no uniform national code or standard that considers ship collisions on lock gates. From a structural design perspective of the lock gate it is thus important to point out that the Eurocode 1 is not applicable here, because only rigid, i.e. non-energy absorbing, structures under ship collisions are considered, such as massive bridge piers.

Consequently, realistic analyses of lock gates under ship collision require computer-based numerical simulations. Therefore, this paper will identify the background needed to carry out a numerical ship collision simulation with a lock gate to allow for the analysis of the structural design of the lock gate. At first, common lock gate types are presented as well as possible gate protection systems followed by a design methodology section and available and recommended analysis approaches. In general, steel gates share many design aspects with ships, and the estimation of the collision resistance of ships is a fairly mature task using numerical methods, see for example, Paik (2007) and Ehlers (2010). By doing so, the following aspects shall be known and can be answered:

- What is the mass and hull form of the colliding ship?
- What should be the design speed(s) to be considered for collision?
- Is the collision from an up or down bound ship?
- What shape(s) of the ship in collision cause the most severe damage?
- What is the effect of added hydrodynamic mass?
- What level of damage can be accepted?
- How should the analysis be carried out, and how can such analysis be verified against real events?
- How can the design be implemented to deliver the required robustness and ductility levels?
- What are the recommended measures to prevent/minimise collision damage?
- What proportion of collision energy is dissipated in the ship and what proportion in the gate?
- What are (and what are not) the recommended repair methods and other practices after the collision?

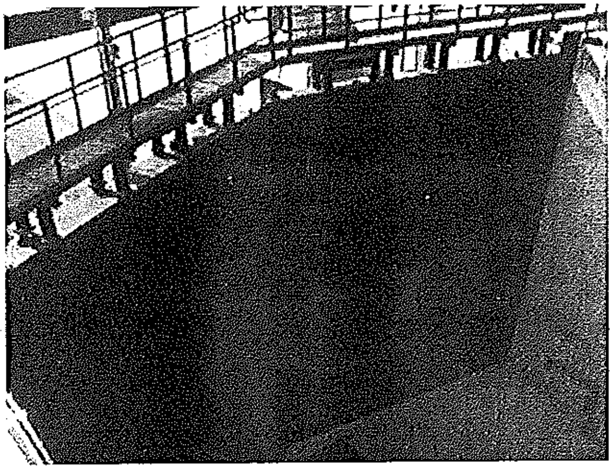
Obviously there are probabilistic issues within these aspects, which are beyond the scope of this article. The probability of a minor collision on a gate or approach structure, which causes no significant degradation of capability or performance, is relatively high for most lock gates or structures. However, the general probability of having a major collision which causes substantial damage and its potential consequences is much more complex to assess.

Types of gates

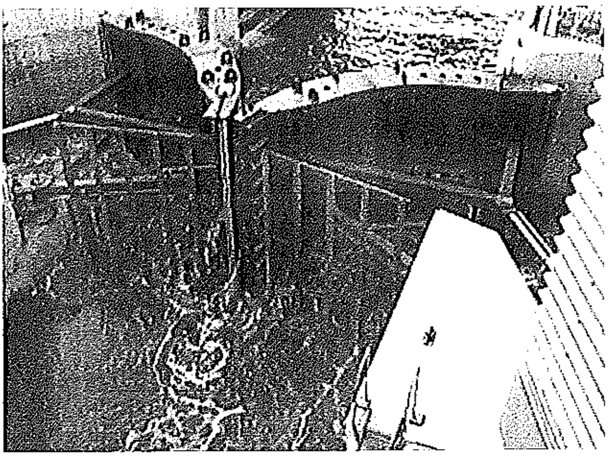
In general, functions of gate systems are diverse and they can range from closure structures of a navigation lock, harbour or shipyard dock to integral parts of water regulation and flood protection systems. For navigation locks it is useful to make a distinction between navigation locks for inland waterways with a typical width of 12·5–25 m and sea navigation locks reaching widths of up to 70 m. Two common examples of gate types are shown in Figs. 1 and 2, while a variety of types, i.e. gates with horizontal axis, such as floor-mounted flap gates or rising sector gates exist. Consequently, it is of utmost importance to assess the boundary conditions of the gate and their capacity for a consistent implementation into a numerical simulation.

Gate protection systems

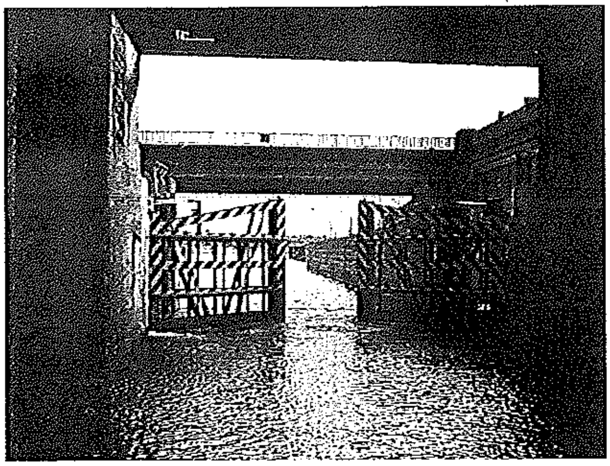
Damaging a lock gate to a state where the operability of the lock cannot be guaranteed must be avoided. One option is to install a separate energy absorbing protection system. The energy absorption is essential, because a rigid system may damage the approaching ship to a state where it sinks in the lock, causing the latter to be non-operable as well. The most common protection systems consist of cables (Fig. 3) or beams (Fig. 4), with an energy absorption capacity of 1–4 MJ. Another alternative to protect the gate from ship collisions in the upstream direction is the placement of an additional grillage, in the form of a mitre gate without plating, in front of the actual gate (Fig. 5).



1 Mitre gates (*Source*: INROS LACKNER AG)



2 Radial sector gates (lock gates in Cardiff, *Source*: PIANC Report no 106 – 2009)



5 Mitre grillage located in the downstream reach (lock at Bollène on the River Rhône)

3 Movable ship arrestor net next to a vertical lift gate during lifting, Bernhard Lock on the Amsterdam-Rhine Canal, The Netherlands (photo by R. Daniel)

4 Shock absorber beam II (Old Navigation Lock Wusterwitz/Germany, *Source*: INROS LACKNER AG)

Common to all these protection systems is the need to assess the required level of protection and in turn the capacity of the protection system against ship collision.

Elements of the design methodology

Collision scenario selection

The collision scenarios to be investigated in a lock gate analysis under ship collision must be selected with care because of the variety of possible operating conditions. Factors to be taken into account include: the ship types passing the lock; the existence of a gate protection system, the approach direction of the ship, i.e. upstream or downstream, the possibility of an oblique collision; the approach velocity and eventual approach velocity limitations; and the presence of other ships in the lock.

In order to perform a ship collision analysis on a lock gate, various parameters must be determined for the striking ship, the lock and the lock gate and the striking location. The required parameters for the striking ship are: displacement of the ship and corresponding draught; added mass of the water: generally, the added mass of a ship in its longitudinal direction can be assumed to be 20% of its displacement and must be added to the mass of the ship; the bow and bulb geometry; the bow and bulb scantlings and their material behaviour, if the bow is considered deformable; and the initial ship velocity before the collision. The required parameters for the lock and gate are: the geometry, scantlings and material behaviour of the lock gate; the boundary conditions between the gate and the lock structure and the percentage of the free water surface relative to the gate area. The required parameters for the contact area are: the striking location, angle and area; the friction coefficient between the bow of the striking ship and the gate, which may differ below and above the waterline.

Collision causes and consequences

The entry of a ship into a navigation lock is a difficult manoeuvre, which may lead to the ship colliding with the lock gate. Therefore, the eventual consequences of a ship colliding with a lock gate must be analysed, ranging from the ship sinking with potential loss of life to sudden downstream flooding if the gate fails. The causes of a ship colliding with a lock gate are manifold and Meinhold (2011) states that more than one-half of such collisions are because of human error. Potential causes of a ship colliding with a lock gate are: out draft conditions in the approach channel or excessive wind; pilot or mechanical failures when slowing the ship; operational failure of the control system for the lock; mechanical failure of the lock facilities; inappropriate mooring or other operational failure of the ship; failure of the mooring warps; and communication failure between the ship and lock operator.

In order to assess the associated risk, the probabilities of eventual consequences must be obtained as well as the particular function of the waterway. The design process should therefore include the ships' approach conditions in relation to layout of the lock.

The design methodology

The suggested design methodology to analyse a lock gate under a ship collision depends at first on whether this is to be done for an existing gate or for a new gate, e.g. in the conceptual design phase.

In the case of an existing gate, the aim of a ship collision analysis is usually to identify the critical collision velocity for a representative ship above which unacceptable gate damage will occur. Therefore, collision simulations are performed for several possible collision locations and possibly at a number of different collision angles.

In the case of a new gate, the aim of a ship collision analysis is to support the conceptual design by optimising the collision resistance of the gate, through geometry or scantlings or both. Further collision simulations are performed to validate the gate deformations and reaction forces for a representative ship and a range of possible collision scenarios.

The French Institute for Inland and Maritime Waterways (CETMEF) provides guidelines for the protection of lock gates against ship collision. The principal focus is the definition of collision scenarios, but useful information is also given on the provision of independent protection systems. The CETMEF guidelines define at first the collision scenario, both, for the downstream and upstream gate as follows:

For a ship moving upstream towards an upstream or downstream gate, the collision will occur at the bottom of the gate, where the gate is less vulnerable, because the hydrostatic pressure is acting in the opposite direction to the collision force, the hydrostatic pressure has no effect (downstream water level in the lock chamber) or has a favourable effect (upstream water level in the lock chamber). Such collision scenario in an upstream gate is fairly common, but because of the low velocity of a ship entering the lock chamber it is usually not critical and the collision scenario in a downstream gate is rare. For a ship moving downstream towards an upstream gate, the collision will occur on the top of the gate, which is the most vulnerable location, because the hydrostatic pressure has no effect (upstream water level in the lock chamber) or has an unfavourable effect (downstream water level in the lock chamber). Such scenario is however very rare unlike the scenario where the ship is moving downstream towards a downstream gate. Here the collision will occur at the top of the gate, being the most vulnerable location, because the hydrostatic pressure is acting in the same direction as the collision force.

Once the collision scenario is determined, the collision forces can be determined using either a detailed finite element simulation or, initially a simple estimation of the initial kinetic energy of the striking ship, which is given by

$$\mathrm{E} = c_m c_c c_s \frac{m_0 v_0^2}{2}$$

where v_0 is the initial velocity of the ship in the collision, ranging typically from 0·5 to 2 m s^1; m_0 is the mass of the striking ship and the coefficients c_m, c_c and c_s are introduced in the recommendations denoted by Les Recommandations pour le calcul aux états-limites des Ouvrages en Site Aquatique (ROSA) 2000 and published by CETMEF. The mass coefficient c_m accounts for hydrodynamic effects and the current practice is to set it to 1·2. However, it is directly influenced by the shape of the striking bow; hence, the ROSA recommendation provides refined formulae to assess it. The ship coefficient c_s accounts for the amount of energy that is dissipated through the deformations of the bow. Consequently, not all of the initial kinetic energy is absorbed by the gate in collision and therefore $c_\mathrm{s} \leqslant 1$. Thus, even though it depends on the relative stiffness between the striking vessel and the gate, CETMEF suggests to consider a rigid bow, and thus the coefficient c_s to be set to 1. The confinement coefficient c_c accounts for the additional pressure generated by the water confined between the ship and the lock. As a result, velocity of the striking ship is reduced before the collision and therefore $c_\mathrm{c} \leqslant 1$. The suggested value by CETMEF is $c_\mathrm{c} = 0{\cdot}8$. An accurate estimation of these parameters is however difficult. However, the most influential parameter in the estimation of the initial kinetic energy is the initial velocity, which must be obtained as accurately as possible, because it contributes with the power of 2. If statistical distribution of the initial velocity is available, then it is recommended to determine a characteristic value of v_0 associated to a probability of exceedance ranging from 10^{-4} to 10^{-3}.

In order to obtain the quasi-static collision force CETMEF uses the computed value of E in the Meier–Dörnberg formula. This formula is derived under the assumption that deformations are only occurring in the striking vessel. Denoting a as the total indentation of the bow under the collision, where according to Meier–Dörnberg, a is given by

$$a = \begin{cases} \sqrt{E/30} & \text{for a} < 0{\cdot}1\ \text{m} \\ -3{\cdot}65 + \sqrt{13{\cdot}32 + 1{\cdot}25E} & \text{for a} \geq 0{\cdot}1\ \text{m} \end{cases}$$

This value of the indentation may be used to obtain the corresponding quasi-static force, which is given by

$$F = \begin{cases} 60a & \text{for a} < 0{\cdot}1\ \text{m} \\ 6 + 1{\cdot}6(a - 0{\cdot}1) & \text{for a} \geq 0{\cdot}1\ \text{m} \end{cases}$$

This simple procedure was initially developed for the case of a collision between a ship and a quay wall. In this situation, the assumption of having a perfectly rigid striking structure in collision is more realistic. As a consequence, the procedure given above has to be applied judiciously for collision on lock gates.

The next step is to estimate the accepted level of damage of the lock gate during the collision, which mainly depends on the initial kinetic energy of the striking ship

$$E_0 = \frac{1}{2}(m + m_a)v_0^2$$

where v_0 is the initial velocity of the ship, m is its mass and m_a is the added mass of water associated with the ship. As a first approximation, m_a can be assumed to be equal to 20% of the mass of the ship. Therefore, the damage may be expected to be proportional to the mass and the square of the velocity of the colliding ship. In fact, during the collision process, it should be noted that the total initial kinetic energy E_0 will be dissipated principally through two processes: (a) minor energy absorption through plastic and deformations of the bow of the striking ship, which is usually stiffer than the gate, and (b) major energy absorption through elastic and plastic deformations of the gate structure.

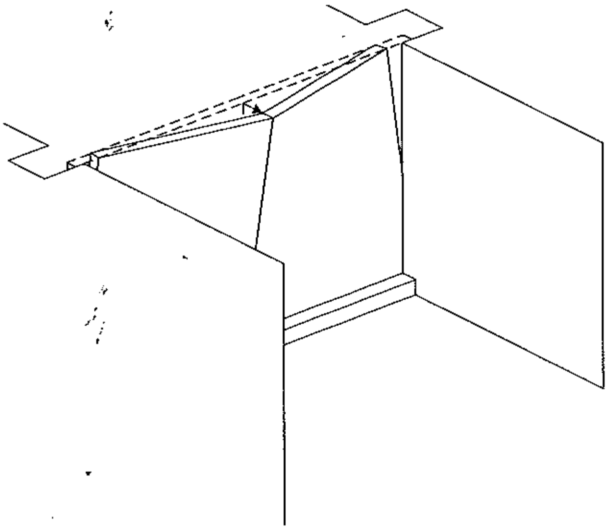
In general, it is not possible to give guidance on the level of damage that can be tolerated for a given lock gate, as it will be specific for the gate and project under consideration. However, some general considerations and examples may be given as follows:

Water tightness: Leakage will occur if the plating is punctured during a collision. Similarly, distortion of the gate may cause leakage at the supports (Fig. 6). Such leakage can be problematic if the ensuing flow prevents operation of the lock either directly or through grounding of the ship. Therefore, maintenance of adequate water tightness may be a determining criterion.

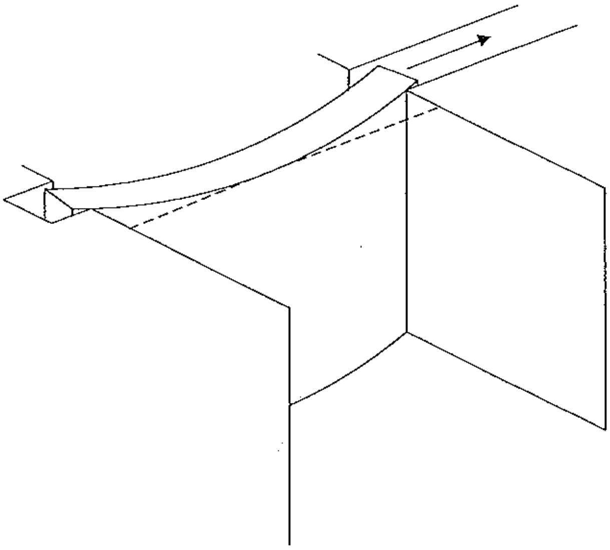
Operation of the lock: Damage to a gate can prevent its operation after the collision as shown in Fig. 7. Economic losses may then be significant especially for heavily trafficked waterways where the cost of repairing damage may be small in comparison to the overall economic loss. In this case, damage should be kept to a level preventing any loss of serviceability of the lock.

Overall stability: Collapse of the gate is generally not acceptable for a variety of reasons, notably for the adverse effects on safety of personnel operating the lock and the ship and the potential for flooding downstream to harm people and communities.

The guidance given above demonstrates the over-riding importance for gates to behave in a ductile manner. Further, if a gate is able to accommodate large deformations before becoming inoperable, then the kinetic energy of the collision will be absorbed by the structure in a safer and easier manner. However, deformation and damage levels must meet the criteria noted above. With these points in mind some general principles for achieving a ductile design are: the slenderness ratio of the main structural members forming the 'skeleton' of the gate must be kept low to avoid premature buckling, e.g. by use of compact sections; buckling of the stiffening elements should take place in a controlled fashion; the main structural members should be designed to develop plasticity over large areas. In particular, it is beneficial to form multiple plastic hinges in the 'skeleton' of the gate before a global mechanism develops; the secondary stiffening system should be designed to improve its energy dissipating capacity; and further the electro-mechanical devices supporting and operating the gate should be designed not to fail before the ductile capacity of the gate has been adequately mobilised.



6 Deformed gate after a collision causing leakage at supports



7 Deformed gate after a collision causing a retraction failure

Another allied feature that should be incorporated within the design is to provide the structure with an overall robustness. As it is not realistic to design a gate to be able to withstand a collision without damage, the structure should be able to keep its overall integrity without suffering disproportionate failure in comparison with the severity of the collision. To achieve this goal, alternative load paths with redundancy of some structural elements should be provided. Where this is not possible, e.g. at a hinge, consideration should be given to over-dimensioning the element to avoid a single component controlling the performance of the gate.

Analysis methods for ship collisions with lock gates

This chapter presents various methods for analysing the effects of ship collision on lock gates and identifies methodologies to assess collision withstand capacity. However, even for ship structures only a limited number of regulations exist which govern their collision resistance (Table 1). However, even though general concepts of Formal Safety Assessment (FSA) procedures exist, the corresponding mathematical models with the necessary precision and agreement are missing.

Table 1 Regulations for collision resistant structures

Regulation	Aim	Related references
KAISA No. 520	Collision resistance for ships with radiated fuels	Dodd and MacDonald (1960) Kitamura and Endo (2000)
Germanischer Lloyd COLL	Collision strengthening	GL rules (2004) Zhang *et al.* (2004)
ADNR Inland shipping	Carriage of gases	ADN rules (2005)
Det Norske Veritas	Carriage of compressed gases	DNV rules (2004a)
Det Norske Veritas	Collision with wind turbine	DNV -OS-J10115 (2004b)

This makes the decision chain questionable and open for debate (Pedersen 2010). Furthermore, a systematic assessment procedure that addresses the probability of occurrence, the structural consequences, the risk and possible acceptance criteria can be found in the offshore field, see, for example American Petroleum Institute (API 2000).

Nevertheless, this section identifies various analysis methods for simulation of ship collision on lock gates and summarises these methods. Furthermore, the simulation methods presented are concerned solely with the structural elements of the gate, i.e. supports are only considered as boundary conditions rather than being modelled discretely. In addition, methods to assess damage level against allowable damage criteria are included in the recommended procedures.

Methods to assess the probability of collision

The probability of a ship collision can be assessed with various methods (Otto, Pedersen, Samuelides and Sames 2002; Friis-Hansen and Cerup-Simonsen 2002; Montewka, Hinz, Kujala and Matusiak 2010). However, the major shortcoming of these methods is that they are based on statistical models, which may not predict future trends accurately. Additionally, the probability of collision or grounding is highly sensitive to human error and this area is subject to the highest level of uncertainty (Hänninen and Kujala 2009). Hence, even though the most cost-effective solution is to reduce the accident probability, the accident occurrence cannot be ruled out. In other words, even at low re-occurrence rates, the potential for such accidents remains and it is necessary for the structure, ship or gate, to withstand the collision within the accepted level of damage.

Empirical methods

Rigorous simulation of the structural mechanics of collision is computationally demanding. Therefore, several simplified analysis methods have been developed to assess the energy absorbed during a collision incident. Minorsky (1959) proposed the well-known simplified analysis method, in which the collision process is split into an external and an internal part. The central element of the external part is the evaluation of ship motions under the action of external hydrodynamic forces.

Analytical tools for ship-to-ship collisions

Ship-to-ship collisions can be analysed using non-linear finite element methods. However, this is time consuming and expensive and, at preliminary design stages, simplified analytical methods may be preferred. Buldgen, Le Sourne and Rigo (2012) reported some analytical procedures, which are currently available for assessing collisions between two ships. These methods typically assess the collision resistance as a sum of the resistance of individual members, namely girders, panels and intersection elements.

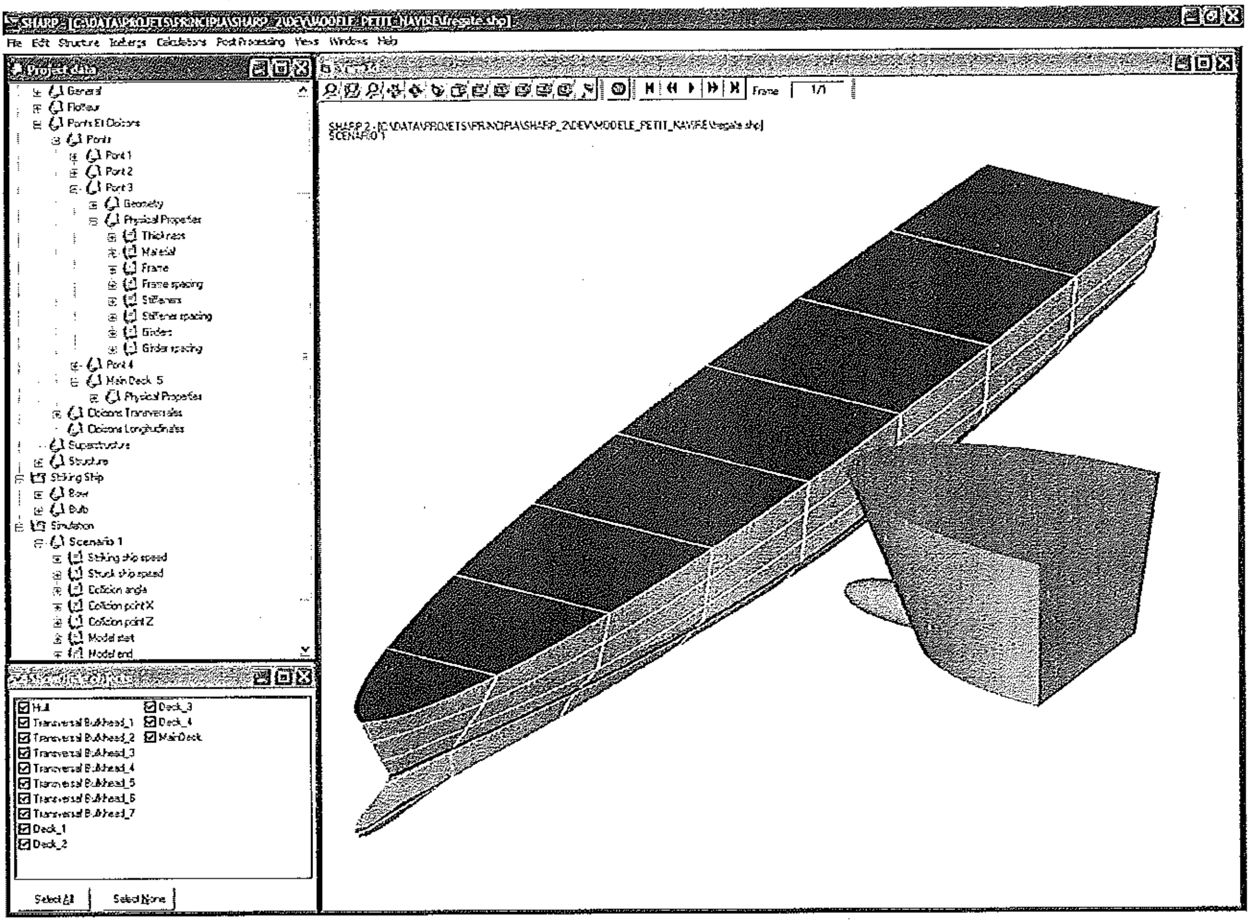
Hong and Amdahl (2008) summarised and compared the methods to estimate the crushing resistance by Wierzbicki and Culbertson-Driscoll (1995), Wang and Ohtsubo (1997), Simonsen (1997) and Zhang (1999). They also developed a refined expression to evaluate the ultimate crushing resistance of girders. The individual behaviour of ship side panels has been investigated in detail by Wang and Ohtsubo (1997), Wang (2002) and Zhang (1999), while the crushing resistance of the intersection between vertical and horizontal structural members has been analysed in detail by Amdahl (1983) and Zhang (1999).

Thus, certain methods are available for simplified assessment of ship-to-ship collisions. These can be implemented by modelling ship structures with very large elements using a limited number of nodal points. Using the literature referenced above, closed-form analytical formulations for the resistance of each member may be derived. Then, by combining the individual resistances properly, it is possible to obtain a global evaluation of the ability of a ship to withstand a collision with another vessel even under oblique collisions; see Buldgen *et al.* (2012).

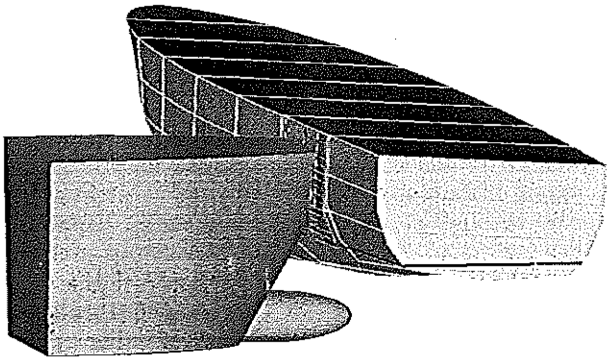
In these ship-to-ship collision analyses, the internal structural response must be coupled with the external dynamics of the collision to account for the global motions of the ship, while also taking into account the forces because of the surrounding water. However, there are very few tools available that completely couple the internal and external mechanics in this way. One of these, named SIMCOL (simplified collision model) was developed by Brown (2002). The results obtained by SIMCOL were compared successfully with time simulation results. Another coupled program is named Ship Hazardous Agression Research Program (SHARP) (see Figs. 8 and 9), which was developed by Le Sourne, Besnard, Cheylan and Buannic (2012). Both for the striking and the struck ship, SHARP uses a super-element method coupled to an adapted version of the 3D external dynamic MCOL, which is also implemented in the finite element code LS-DYNA.

Analytical methods for lock gates

The current literature does cover procedures to analyse collisions between two ships and this provides a basis for the development of analytical procedures for collisions with two main gate types. First, plane gates, which are made of single or double plating, reinforced by vertical and horizontal girders with one or more ballast tanks. Typical examples are mitre gates, flap gates, lifting and sliding gates. Second, curved gates which comprise



8 **Graphical user's interface of SHARP program (Le Sourne *et al.* 2012)**

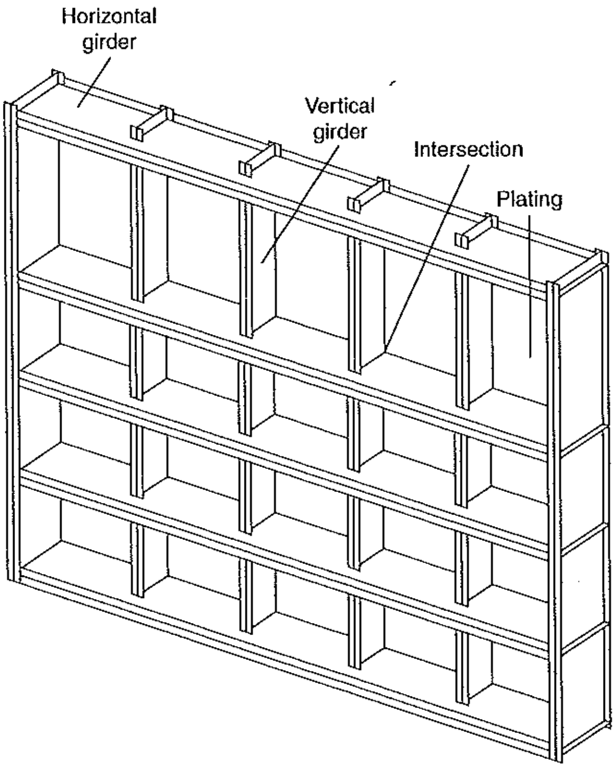


9 **Dry cargo vessel colliding with a passenger ship (Le Sourne *et al.* 2012)**

plating formed into an (usually circular) arc with a complex arrangement of stiffeners. Sector, segment and visor gates are typical examples.

The existing results developed for ship-to-ship collisions are not always adaptable to curved gates because of the differences in shape and stiffness. They are however applicable to all plane gates, as their structures are similar to ship structures. Basically, such gates may be seen as an assembly of three different structural components, namely plating, girders and intersections (see Fig. 10).

The plating provides the watertight skin and is made of stiffened panels to avoid buckling. For ballast tanks, double plating is required. Wang (2002); Wang and Ohtsubo (1995) and Zhang (2002) investigated ship collisions with such stiffened panels. In addition, Wang and Ohtsubo (1995); Zhang (2002); Wierzbicki (1995) and Zheng (1994) studied the resistance of metal



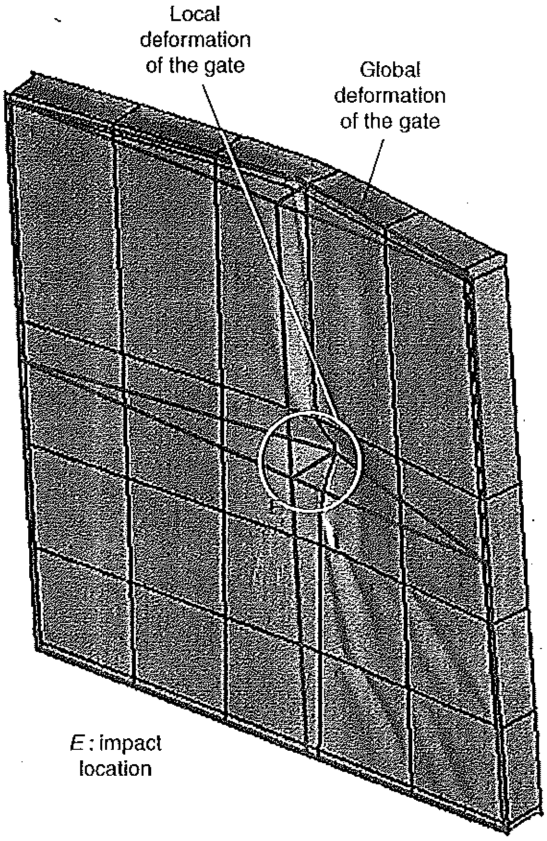
10 **Structural components of a lock gate**

plates after rupture, when subjected to tearing and cutting. The developments reported by Paik (2002), Cho and Lee (2009) and Ueda, Rashed and Paik (1995) constitute a very accurate basis for the assessment of stiffened panels under collision.

Girders are vertical or horizontal elements providing the principal support to the panels. Their behaviour under collision loads is globally elastoplastic, but contains also local phenomena, such as 'crushing'. Wierzbicki and Culbertson-Driscoll (1995), Wang and Ohtsubo (1997), Simonsen (1997), Zhang (1999), Hong and Amdahl (2008) studied the crushing resistance of these components theoretically and experimentally.

Intersections are located at the junction between vertical and horizontal girders. They, therefore, have X- or T-shaped cross-sections. Amdahl (1983) and Zhang (1999) studied their crushing resistance.

This brief literature review shows that certain results are available to assist with analytical approaches for the analysis of collisions between ships and gates. However, these are not sufficient as the behaviour of a gate in collision is not fully comparable in full to that of a colliding ship. Local crushing and plastic deformations in a gate are similar to those experienced by a ship impacted by with another ship. However, unlike a ship-to-ship collision, the collision energy is also likely to be dissipated through global bending deformation of the gate (see Fig. 11). The idea of decomposing the energy absorption into the two modes as illustrated in Fig. 11 was initially suggested by Le Sourne, Rodet and Clanet (2004). Subsequently, Le Sourne *et al.* (2004) and Buldgen *et al.* (2012) present estimations for the ship collision resistance of a lifting or sliding lock gate. They characterise the gate through boundary conditions, geometrical parameters (thickness, stiffener system, etc.) and various material properties. Further, they define the striking ship with a rigid bow shape, thus assuming a rigid ship, and the collision scenario through the relative position of the ship to the gate. For the *local mode*, they decompose the structure into large structural entities, called super-elements. Ueda and Rashed (1984) introduced this idea as the idealised structural unit method. Buldgen *et al.* (2012) extended this method to assess the local ship collision resistance of lifting and sliding gates. For the *global mode*, they evaluate the resistance by assuming that the gate experiences an overall bending deformation. With this assumption, the resisting force may be derived considering a simplified model of the structure representing this mechanism. Finally, they find the *total resistance* by combing the local and the global resistance assuming that for small values of penetration, the local mode is predominant. However, with increasing penetration of the gate, the global mode becomes predominant. The particular case of ship collisions against mitre gates was also investigated using super elements as reported in Buldgen, Le Sourne and Rigo (2013).

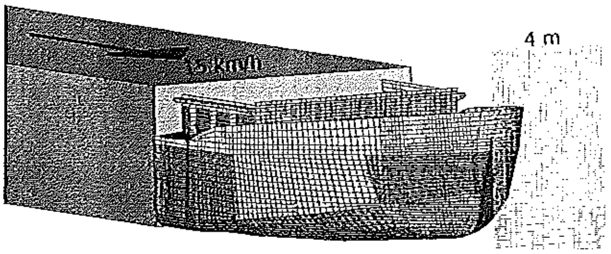


11 Local and global gate deformation modes according to Buldgen *et al.* (2012)

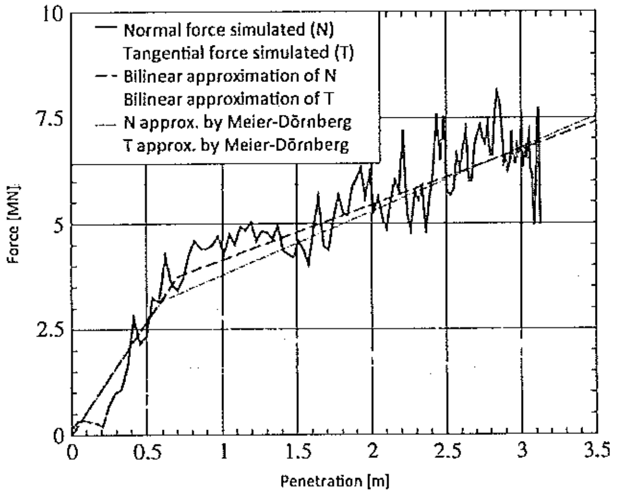
Quasi-static numerical approaches

Finite element-based analyses of ship collision simulations have been performed in many commercial codes, such as LS-DYNA, ABAQUS, and MSC/DYTRAN. Concerning ship and lock gate simulations, the Hamburg University of Technology (TUHH) carried out detailed collision simulations with the finite element method (see Fig. 12, Biehl and Kunz 2005) confirming the analytical work done by Meier-Dörnberg (1983) (see Fig. 13).

Common to such numerical simulations is the selection of a non-linear material behaviour in the form of a power law; see, for example, Alsos, Amdahl and Hopperstad (2009) and Zhang, Hauge, Ødegård and Thaulow (1999). The power law parameters can be obtained from standard tensile experiments; see Paik (2007) and Joun, Eom and Lee (2008). However, the required parameters are dependent on the chosen finite element length and this needs to be matched to obtain the true stress–strain relationship locally. For a given selected finite element length, agreement between the numerical simulation and the tensile experiment can be achieved by an iterative procedure, in which the stress–strain relationship, as represented by the power material law input to the simulation, is progressively adjusted until correspondence with the tensile experiment is achieved (Zhang *et al.* 1999; Huato and Roehr 2004). Because of the dependence noted above, this iterative procedure should be repeated for each element size to



12 Numerical model for the collision of an inland vessel's bow with a bridge pillar after Biehl and Kunz (2005)



13 Simulated force versus deformation characteristic and comparison to the assumptions of Meier-Dörnberg (1983) model for the collision of an inland vessel's bow with a bridge pillar after Biehl and Kunz (2005)

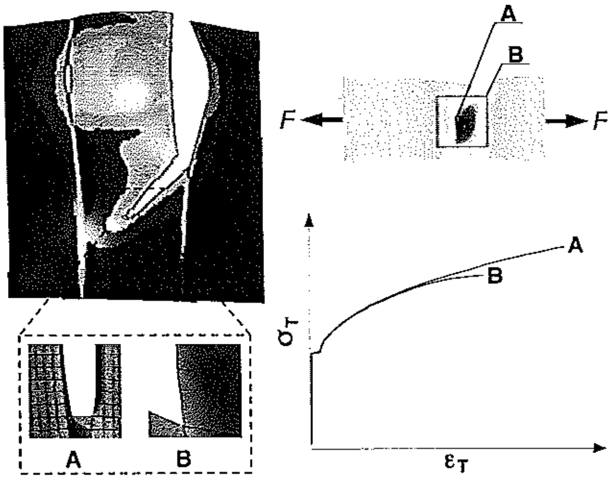
avoid incorrect representation of structural behaviour. It is worth emphasising the importance of implementing proper material relationships up to fracture, as these directly influence the accuracy of non-linear finite element models in collision and grounding simulations.

Furthermore, the determination of the stress–strain relationship is not sufficient as the failure strain, i.e. the end point of the stress versus strain curve, depends on the material relationship chosen. However, a significant amount of research has been conducted to describe criteria to determine the failure strain, for example, by Törnqvist (2003); Scharrer, Zhang and Egge (2002), Alsos, Hopperstad, Törnqvist and Amdahl (2008), and to present their applicability (Peschmann, Kulzep and Lehmann 2002; Tabri, Alsos, Broekhuijsen and Ehlers 2007; Alsos *et al.* 2009). However, all of these papers use a standard or modified power law to describe the material behaviour, and none of these papers identifies a clear relation between the local stress-strain relationship and the element length. Relationships to obtain an element length-dependent failure strain value are given by Peschmann (2001), Scharrer *et al.* (2002), Törnqvist (2003), Alsos *et al.* (2008) and Hogström, Ringsberg and Johnson (2009). These curve-fitting relationships, known as Barba's relationships, are obtained on the basis of experimental measurements. However, they define only the end point of the standard or modified power law. Hence, this adjustment of the element length with respect to the chosen local stress–strain relationship creates an inconsistency.

Therefore, Ehlers *et al.* (2008) carried out numerical collision simulations for three different large-scale structures using the finite element method with shell elements and LS-DYNA. as the solver. A comparison of three different failure criteria was presented for each of the structural models, which in turn were meshed with three different element sizes. The failure criteria adopted were those according to Germanischer Lloyd (Zhang, Egge and Bruhns 2004), Peschmann (2001) and Rice-Tracey and Cockcroft-Latham (Törnqvist 2003). All three criteria used the same power law material relationship. By this means Ehlers *et al.* (2008) showed that the resulting force and penetration predictions did not give good correspondence across the different element sizes – 25, 50, and 100 mm – when using the same failure criterion and material relationship. Furthermore, different failure criteria gave different results. Hence, Ehlers *et al.* (2008) concluded that the choice of an element length-dependent failure strain is not sufficient in its present form.

Therefore, Ehlers and Varsta (2009) presented a novel procedure to obtain the stress–strain relationship including failure strain with respect to the choice of element size using optical measurements. They introduced the strain reference length (measure A and B), which is a function of the discrete pixel recordings from the optical measurements and corresponds to the finite element length (Fig. 14). Furthermore, they verified their material relationship using tensile specimens, both experimentally and numerically. Moreover, Ehlers, Tabri, Romanoff and Varsta (2010) identified that a constant strain failure criterion suffices and that the strain rate sensitivity of the failure strain and ultimate tensile force is $<3\%$.

As a result, this material relationship shows a better convergence with different element sizes and prediction of the point of failure when compared with the standard power law results. Furthermore, Ehlers (2009a) and Ehlers (2009b) presented the validity of this material relation for circular plates, stiffened panels and complex geometries.



14 Symbolic element length-dependent true strain and stress relation until failure for numerical collision simulations (Ehlers 2009a)

Dynamic numerical approaches

In order to realistically assess the structural deformation, the distribution of energy between structural deformations and ship motions needs to be evaluated. Therefore, coupled dynamic collision simulations are the method of choice for a precise description of the entire collision process, as the full time histories of the motions and forces are thereby assessed. Motion-dependent forces, such as the hydrodynamic damping force arising from the interaction with the surrounding water, can be included in the analysis. However, as a result of the complexity, these simulation models are often reduced to include the motions in the horizontal plane only. Le Sourne, Donner, Besnier and Ferry (2001) formulated the external dynamics of collisions in a three-dimensional space and included all the major external forces through a subroutine MCOL implemented into LS-DYNA. The coupling between the ship motions and the structural deformations was carried out simultaneously with the help of structural analysis with the finite element method. Pill and Tabri (2009) presented a numerical model in LS-DYNA, where no additional subroutines are required. In their model, the mass and inertial properties of the ships, including the effect of the added mass, are described through a small number of mass points. They neglect the forces associated with the hydrodynamic damping and frictional resistance, because their inclusion is not straightforward and their share in the energy balance was found to be $<10\%$ of the total available energy (Tabri 2010). However, such coupled numerical simulations allow the precise estimation of structural damage in various collision scenarios under oblique angles and an eccentricity of the contact point. Additional formulations for the forces and the equations of motions are established for both colliding ships and solved in the time-domain with a specific analysis model (Petersen 1982; Tabri, Broekhuijsen, Matusiak and Varsta 2009) or with the finite element method (Le Sourne *et al.* 2004; Pill and Tabri 2009).

Physical models

This section presents experiments at various scales that have been undertaken to represent ship-to-ship collisions by means of a bow-shaped indenter colliding with a stiffened panel system and are thus applicable to the design of lock gates under ship collision.

Model-scale experiments: An extensive series of ship-to-ship experiments has been reported by Tabri, Määttänen and Ranta (2008). These performed a re-analysis at model scale of the full-scale experiments carried out by Nederlandse Organisatie voor toegepast-natuurwetenschappelijk onderzoek (TNO) see the subsequent section on full-scale experiments, and a principal concern was therefore to represent the steel structure adequately at model scale. This was achieved with special foam-like material. The experiments included additional motion components to investigate the influence of the collision scenario on force-penetration behaviour.

Large-scale experiments: Tautz, Schöttelndreyer, Fricke and Lehmann (2010) documents recent large-scale experiments of rigidly supported stiffened structures, i.e. ship side structures, in collision with rigid and deformable bow structures. These large-scale experiments provide a valuable baseline for validating and calibrating numerical simulations. They were funded by the German Federal Ministry of Economics and Technology under project number 03SX284B and undertaken at the Technical University of Hamburg Harburg within the research project ELKOS (this information should assist those wishing to gain access to existing test reports and results).

Full-scale experiments: TNO (the Dutch Institute for Applied Physical Research) carried out a series of full-scale collision experiments in the Netherlands to obtain data from real collisions on behalf of a Japanese, German and Dutch consortium of shipyards and a classification society. The main purpose of the tests was to investigate the performance of different ship side structures. The tests reported in Wevers and Vredeveldt (1999) are especially useful in providing verification data as all six motion components were measured for both ships. The tests also provided collision force and relative displacement time histories.

Summary of the presented analysis methods

This brief summary identifies which of the methodologies, described in detail above, are suitable for lock gate analyses under ship collision (see Table 2).

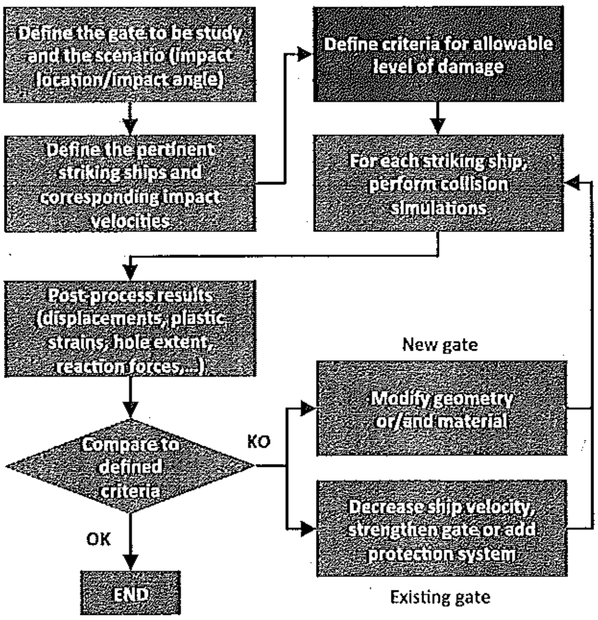
Summary and recommended assessment procedure

This paper generally recommends adopting, at least in parts, the CETMEF guidelines (CETMEF 1997, 2000) for the design of lock gates under ship collision. The main reason for this recommendation is that the CETMEF guidelines (CETMEF 1997, 2000) assume a collision model in which both the ship and the gate are considered to be deformable. This assumption represents the nature of ship collision with a lock gate better than the current Eurocode 1 approach.

Additionally, this paper presented a variety of available approaches to assess the energy absorption of a lock gate and ship during a collision. Further, the most important aspects to be considered during such assessment are discussed. As a result, the recommended assessment procedure for analysing collisions between a lock gate and one or several striking ships is illustrated by the flow chart in Fig. 15. The general procedure presented in this flow chart starts with the definition of the gate characteristics, the collision scenario and the criteria giving the allowable level of damage. This is followed by simulations for each collision scenario, post-processing of the results and finally drawing conclusions for new or existing gates as appropriate. Suggested criteria for the allowable level of lock gate damage are presented in Table 3. This procedure can be used to design a gate to withstand a given collision or to define a safe approach velocity for a given ship.

Table 2 Evaluation of different approaches

	Analysis effort		Results		
Methods	Modelling	Computation	Energy	Loads	Stress
Analytical methods	Least in volume, large in expertise	Least, special programmes required, often unavailable	Yes	partially	yes
Numerical methods – quasi-static approaches	Moderate in volume and expertise	Moderate, specialist programmes required and available	Partially	partially	yes
Numerical methods – dynamic approaches	Extensive in volume and expertise	Time consuming and expensive. Extensive and dedicated software required	Yes	yes	yes



15 **Recommended assessment procedure for analysing collisions between a lock gate and one or several striking ships**

Table 3 **Suggested criteria for the allowable level of lock gate damage**

Level of damage	Loss of watertightness	Loss of operability	Loss of overall stability
Lock gate type			
Single plating lock gate	Perforation, location and extent of the holes	Local and/or global transverse displacement of the gate	Extent of the plastic mechanism
Double plating lock gate	Double perforation and position/ extension of the holes	Localand/or global transversal displacement of the gate, Perforation of a submerged ballast tank	Extent of the plastic mechanism
Mitre gate	Transverse displacement of the leaves	Transverse displacement of the leaves, plastic deformation of the hinges	Repture of the hinges
Curved gate	Perforation, location and extent of the holes	Local and/or global transverse displacement of the gate, Plastic deformation of the rotation axis	Extent of the plastic mechanism, repture of the rotation axis

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