Paper 54 - Review of existing solutions and presentation of a simplified method for the crashworthiness of lock gates

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ABSTRACT: This paper presents a review of existing solutions to analyze lock gates subjected to vessel collisions. In the first part of this article, a brief review of national and international guidelines is performed. Some examples of existing protection devices are also provided. The second part of this paper is devoted to the presentation of a simplified analytical method that could be used to quickly evaluate the impact resistance of plane lock gates. To validate this new approach, some comparisons with finite element simulations are presented.

1 INTRODUCTION

Ship travelling on inland waterways or entering a sea port usually have to pass through lock structures. This is a quite challenging manoeuvre that can lead to collisions with the gate. Due to the large mass of the striking vessel in spite of the low velocity, the kinetic energy involved in the accident is such that the structure may be severely damaged. In this case, the lock operation may be disrupted and the navigation interrupted. Unfortunately, it is possible that these situations will appear more frequently in the future, because the waterborne transport is constantly increasing since 1995.

For social and economic reasons, it is of prior importance to ensure a continuous operability for the lock gate. Although some recommendations are already available in international standards, there is no harmonized procedure to guide engineers in developing crashworthy structures. As a contribution to fill this gap, the first part of this paper presents a short state of the art that summarizes important design approaches regarding ship collisions and gate protection devices.

Apart from these international standards, another way for engineers to evaluate the impact resistance of lock gate is to carry out direct simulations using the finite element method. Unfortunately, such first-principle-based approach is not always suited for the pre-design of a new structure. Indeed, building the finite element model, running the simulations and post-processing the results is typically very time demanding. This is particularly true if an iterative process is required to perform a structural optimization.

Similarly, if an existing lock gate has to be quickly assessed against ship collisions, performing finite element analyses is not always appropriate. Furthermore, the cost of such studies may be also an important drawback, particularly for public administrations that are in charge of inland waterways.

In the attempt to overcome the previous difficulties, the second part of this paper presents a simplified methodology that allows for a rapid estimation of the impact resistance. This approach uses analytical developments that are based on the theory of plasticity. As a matter of illustration, the results of this simplified method are compared to those obtained with the finite element software LS-DYNA.

2 REVIEW OF EXISTING PRACTICE

There is no uniform international standard that considers ship collisions on lock gates, mainly because the requirements and specifications are different for each situation. Indeed, designing lock gates against collisions requires investigating many different aspects such as [1]:

- The intensity of the navigation traffic: as the collision probability is quite low on waterways that are rarely used, it is not necessarily required to consider impact in the design.
- The character of the traffic: collisions have to be more carefully considered if cargo may be involved for example.

- The economical consequences: if the gate is too severely damaged, in addition to the repair cost, the interruption of the traffic may also lead to non negligible consequences.

Integrating all previous points in a uniform procedure has not been done so far and would be a quite laborious task. Furthermore, in addition to the points mentioned above, the design process should also include some probabilistic aspects [2]]. Indeed, the probability of minor collisions causing small damages to the lock is known to be quite high, but assessing the probability of having major collisions with more severe consequences is not straightforward. Unfortunately, all these issues are only partly taken into account in the list of important reference hereafter.

2.1 *Design procedure of Eurocode 1*

Collisions are scarcely treated in Eurocode 1 (EN 1991-1-7) and there is no clear recommendation for lock gates. Some indications are given for the design of massive structures that may be regarded as perfectly rigid during the impact, such as bridge piers. Some formulae and tables are available to calculate equivalent static forces that could be integrated in the design.

Excepted for minor collisions involving very small vessels, Eurocode 1 should not be applied to calculate lock gates because the structure may not be seen as rigid. The impact causes damages to the gate and the vessel, which means that the energy is dissipated by both of them. Obviously, this contradicts the assumptions of Eurocode 1.

2.2 *Design procedure in Germany*

For inland navigation locks, the German philosophy (DIN 19704 and DIN 19703) is to prevent collisions by protection devices, such as cables for example (see section 3). These devices should be capable to absorb a kinetic energy within a range of $1\ MJ$ to $2\ MJ$. Alternatively, this recommendation can be circumvented for any particular case by considering the energy of a suitable design vessel with a velocity of $1\ m/s$.

Regarding sea navigation locks, due to the large width of the chamber, using protection devices is not always possible. In this case, an impact load of $300\ kN$ should be considered. Furthermore, the upstream and downstream gates should have the same design and a standby additional gate should be provided in case of major damages.

2.3 *Design procedure in Panama*

Vessel collisions have been considered for the new set of locks in the Panama Canal through requirements published by the ACP (Panama Canal Authority). Two situations have to be analyzed [3]:

- The closed gates should be designed to resist an impact by a vessel with a mass of 160000 tons and an initial velocity of 1 knot. For this scenario, the watertightness and the capability of retracting the gates in their recesses have to be preserved.
- Less severe impact from vessels with displacements ranging from 75000 to 160000 tons should also be considered. For these situations, only minor damages are expected, such that *"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 stabilized in their upright position shall still be possible after complete flooding of watertight zones due to local damage after a ship collision"* [3].

2.4 *Design procedure in the United States*

In the United States, some recommendations are available from the US Army Corps of Engineers (EM 1110-2-2105 and EM 1110-2-2703). In these references, the impact force and the design procedure vary according to the type of lock gate (mitre, sector or lifting gates for example). Different values of equivalent static loads are proposed with their application points. These ones can be used within the load resistance factor method (LRFD) or the allowable stress design (ASD) recommended for the calculation of steel structures (EM 1110-2-2105).

In addition to the previous points, other practical information is also provided by the US Army Corps of Engineers, such as protecting mitre gates with bumpers and fenders for example.

2.5 *Design procedure in France*

The French Institute for Inland and Maritime Waterways (CETMEF) has provided some useful guidelines [4] that can be used to evaluate the striking forces during a collision on a lock gate. According to these recommendations, the most critical scenario is the case of a ship moving downstream and colliding with the downstream gate of the lock. For this configuration, the initial kinetic energy can be evaluated by:

$$E = C_m C_c C_s \frac{M_0 V_0^2}{2}$$

where M_0 and V_0 denote the mass and the velocity of the vessel. C_m is a coefficient introduced to account for the mass of water that is also displaced during the motion of the ship ($C_m \sim 1.2$). C_s is a coefficient smaller than unity that accounts for the energy dissipated by the deformation of the bow. It is mainly influenced by the stiffness difference between the ship and the gate (taking $C_s = 1$ is conservative). Finally, C_c is a coefficient used to model the loss of velocity due to the piston effect ($C_c \sim 0.8$).

Once the total energy E that has to be dissipated is evaluated, some formulae are available to calculate the quasi-static force F that has to be applied on the gate. According to the magnitude of F, we have:

- If $F < 6\,MN$: $F = 60\sqrt{E/30}$
- If $F \geq 6\,MN$: $F = 1.6 \cdot \sqrt{13.32 + 1.25E}$

Unfortunately, this simple procedure was initially developed for collisions on quay walls with the assumption of having a perfectly rigid structure, which is not necessarily realistic for lock gates.

3 EXAMPLES OF PROTECTION DEVICES

One of the most simple protection systems against vessel impact is to attach some wooden beams directly to the structure. Alternatively, neoprene can also be used due to its better resilient properties. Such devices are expected to act as dampers because a non-negligible amount of the collision energy can be dissipated through their potentially high deformation capacities.

Unfortunately, it is clear that the previous solutions are only suitable in case of minor impacts. Consequently, if more severe scenarios could be expected, another option is to use protection systems that are placed before the gate. Some examples are discussed below [1]:

- In Figure 1 a floating mobile barrier is placed before the curved gate in order to prevent collisions from ship entering into the chamber. The barrier moves vertically as the water level increases inside the lock. Once the maximal level is reached, the barrier is retracted to leave the passage free for navigation.
- In Figure 2 the gate is protected by an additional grillage that has a structure similar to a mitre gate but without the plating. It is maneuvered by two hydraulic jacks and prevents ship from entering into the chamber before the gate has been totally opened.
- In Figure 3 a shock-absorbing beam is placed before the mitre gate. A similar idea is shown in Figure 4 where a cable is used to stop the vessel travelling with a too high velocity near the lock entrance. Of course, instead of using only one cable, a network of horizontal cables can also be used.

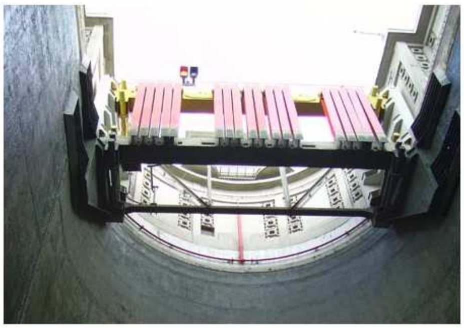

Figure 1: Floating mobile barrier

Figure 2: Protection grillage

Figure 3: Shock-absorbing beam

Figure 4: Cable

4 SIMPLIFIED ANALYTICAL METHOD

From all the international recommendations mentioned in section 2, it appears that none of them is entirely satisfactory, because they are mainly based on the assumption of a rigid structure. Consequently, another way for engineers to evaluate the collision resistance of a lock gate is to use finite element simulations. Unfortunately, such an approach is not always suitable, because it may be too time-demanding. In order to fill this gap, this section presents a new simplified method according to [8] that allows for a rapid estimation of the collision resistance of plane lock gates.

4.1 *Deformation sequence*

In this simplified approach, it is conservatively assumed that the striking vessel is perfectly rigid, which implies that its initial kinetic energy has to be entirely dissipated by the deformation of the gate. In order to establish an analytical procedure, it is assumed that the gate may deform in two different manners during the impact (Figure 5):

- The local deforming mode (1), which is associated to a localized indentation of the striking vessel. During this process, the major part of the structure is not affected by the impact and the penetration of the vessel is mainly allowed by the crushing of some elements in a confined area.
- The global deforming mode (2), which is associated to an overall deformation of the gate. In this case, the striking vessel continues to move forward by imposing displacements on the entire gate.

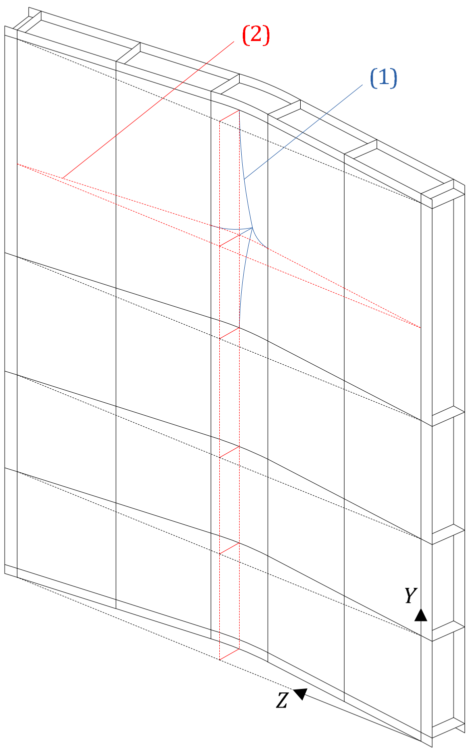

Figure 5: Local and global deforming modes

At the beginning of the collision process, it is clear that the gate will be affected in a quite small region, which means that the local mode is first activated. Nevertheless, a larger part of the structure will be progressively involved, which implies that there should be a switch from the local to the global behavior. It is therefore required to detect when this transition is likely to take place.

To do so, for a given penetration δ of the striking vessel, the resistance is calculated in both the local and the global deforming modes, which leads to P_{loc} and P_{glob}. These values are then combined according to the following rules (Figure 6):

If $P_{loc} < P_{glob}$: Local deforming mode: $\begin{cases} \delta < \delta_t \\ P = P_{loc} \end{cases}$

If $P_{loc} = P_{glob}$: Transition: $\begin{cases} \delta = \delta_t \\ P_{glob} = P_{loc} \end{cases}$

If $P_{loc} > P_{glob}$: Global deforming mode: $\begin{cases} \delta > \delta_t \\ P = P_{glob} \end{cases}$

where δ_t is the particular value of the penetration δ corresponding to the transition between the local and global behaviours. This procedure is presented in Figure 6, from which it transpires that the analytical derivation of P may be achieved by solving two different problems consisting in finding closed-form solutions for P_{loc} and P_{glob}.

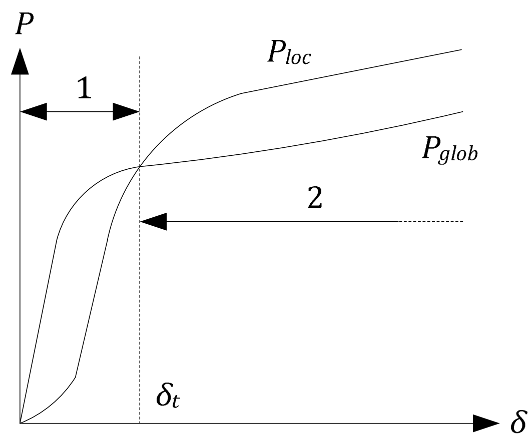

Figure 6: Combination of the local and global resistances

4.2 *Derivation of the local resistance*

To calculate the local resistance P_{loc}, the gate is divided into a set of N large structural entities called super-elements. Each of them is characterized by a law giving its individual resistance P_i as a function of the penetration δ. In the case of plane lock gates with a single plating, four different types of super-elements are required. They are briefly described hereafter and depicted in Figure 7:

- Type A: this type of super-element is used to represent plating elements bounded by two vertical frames and two horizontal girders. They are modeled as a simply supported plate submitted to an out-of-plane impact load. In this case, the resistance is mainly provided through the development of tensile membrane forces.

- Type B: this type of super-element is used to model portions of vertical frames limited by two horizontal girders. For such elements, it is worth noting that the collision may not appear on one of their intersection. In other words, they are always impacted somewhere between the two delimiting horizontal girders (otherwise they have to be treated as a type C element). During the collision, these components are submitted to a successive folding process.
- Type C: this type of super-element is introduced to treat impacts occurring on the intersection between horizontal girders and vertical frames. They are supposed to be crushed axially, which also requires the development of successive folds.
- *Type D:* type D is the same as type B but is this time applicable to portions of horizontal girders bounded by two vertical frames. Here again, the impact may not take place on their extremities.

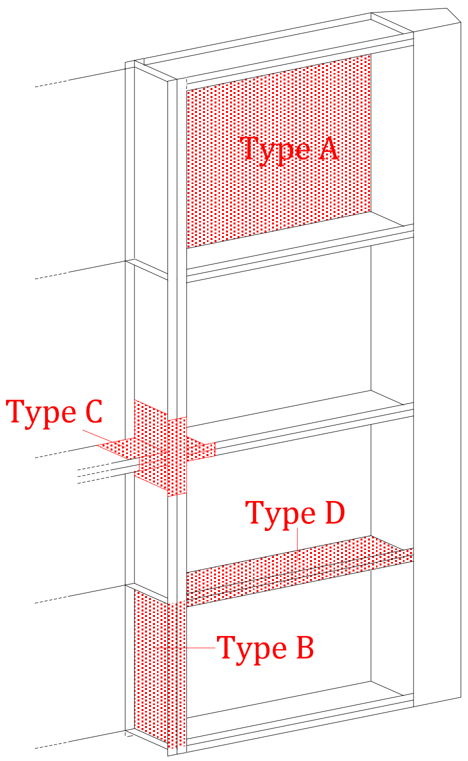

Figure 7: The four different types of super-elements

For each of the four different types introduced above, by applying the upper-bound method, it is possible to derive analytical formulations relating the resistance of the super-element to the indentation δ. For conciseness, these calculations are not detailed in this paper, but more information can be found in references [5] to [8]. By doing so, each of the N super-elements constituting the gate is characterized as being of type A, B, C or D and its individual resistances P_i may be evaluated by an analytical formula. Finally, to evaluate the local resistance P_{loc}, the two following hypotheses are postulated:

- A super-element remains inactive (i.e. $P_i = 0$) as long as it is not in contact with the striking bow.
- The super-elements are assumed to be decoupled, so they do not influence each others during the impact.

With these assumptions, the local resistance P_{loc} may be simply obtained by summing all the individual contributions coming from the N super-elements, i.e.:

$$P_{loc} = \sum_{i=1}^{N} P_i(\delta)$$

This last equation provides an estimation of the resistance associated to the localized crushing of the gate near the contact area. The next step is now to perform a similar derivation for the global mode.

4.3 *Derivation of the global resistance*

The resistance P_{glob} in the global mode is derived under the hypothesis that the gate is forced into an overall motion, where the bending effects are preponderant (Figure 8). During such a movement, it is clear that the main contribution to the resistance is coming from the horizontal girders and not really from the vertical frames because these latter mainly follows the bending motion without dissipating a large amount of energy.

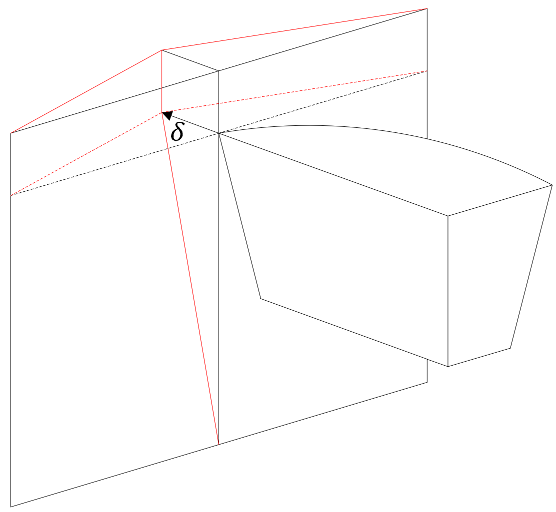

Figure 8: Global bending motion of the gate

As a consequence, if the structure is reinforced by M horizontal girders, it may be seen as a set of M independant simply-supported beams. These ones are bent in their plane and submitted to an individual displacement δ_k (Figure 9) that may be related to the ship penetration δ through simple analytical relations.

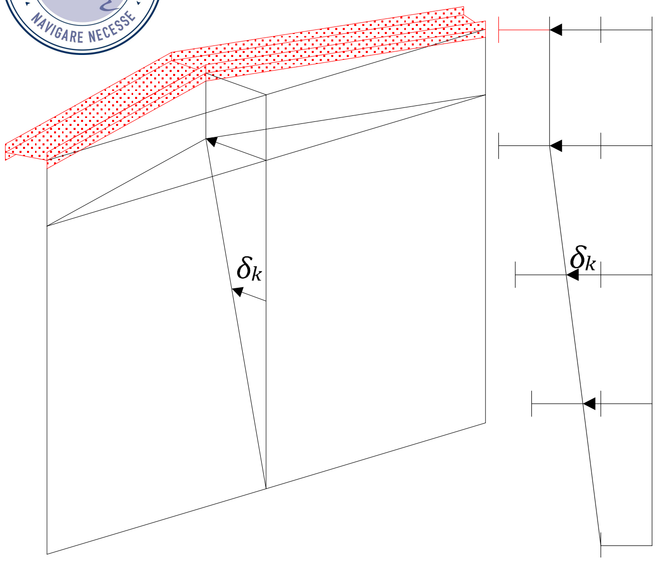

Figure 9: Beam model and displacement field during the global deforming mode

Of course, during this overall motion, each of the M girders opposes an individual resistance P_k, which can be simply evaluated by using the classical beam theory in the elastic and plastic regimes. For conciseness, the analytical derivation of P_k will not be presented here but more information can be found in [8]. Here again, the global resistance P_{glob} is calculated by summing all the individual contributions P_k:

$$P_{glob}(\delta) = \sum_{k=1}^{M} P_k(\delta)$$

Finally, it appears that P_{loc} and P_{glob} can be evaluated by the closed-form expressions given in sections 4.2 and 4.3 respectively. These solutions may then be combined in accordance with the rules presented in section 4.1 to find an approximation of the gate resistance P.

4.4 *Numerical validation*

To validate the analytical approach detailed here above, it is now applied to the lock gate depicted in Figure 10. This gate has five horizontal girders and six vertical frames. Smaller stiffeners of rectangular cross-section regularly reinforce the plating. The gate is made of mild steel, with a Young modulus of $210\ GPa$ and a yield stress of $235\ MPa$. The aim is to compare the analytical prediction P calculated in section 4.1 with numerical solutions obtained by simulating the collision with the LS-DYNA software. As a matter of illustration, two different vessels will be considered:

- A conventional bow having a parabolic shape without bulb (Figure 11).
- A river barge with a more rectangular shape (Figure 12).

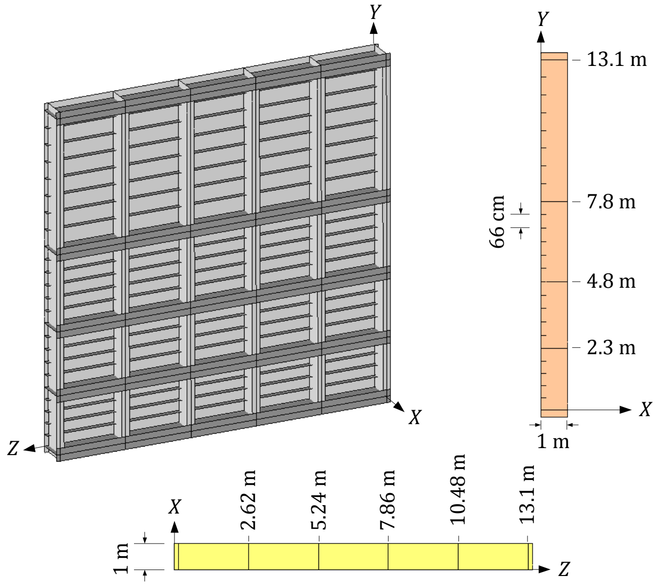

Figure 10: Lock gate used for validation

The two striking ships are perfectly rigid. They have a total mass of 4000 tons and an initial velocity of $2\ m/s$, which corresponds to a kinetic energy of $8\ MJ$. The simulations are stopped when this energy has been entirely dissipated by the deformation of the gate.

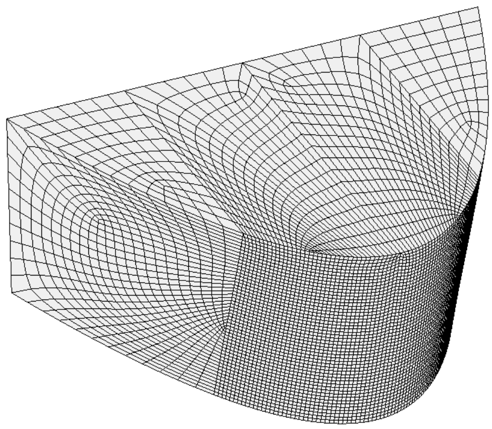

Figure 11: Conventional bow

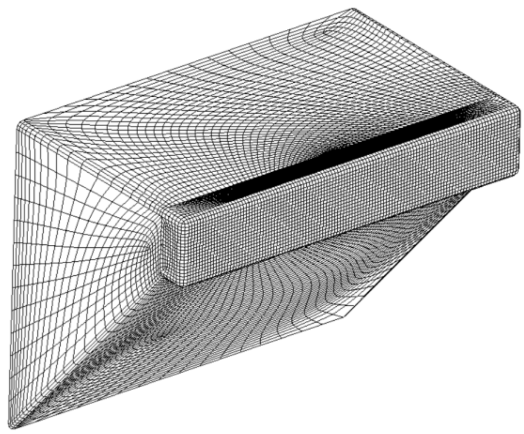

Figure 12: River barge

The resistance obtained by the present simplified approach is compared to the numerical solutions of LS-DYNA on Figure 13 for a conventional bow and on Figure 14 for a river barge. As it can be seen, the agreement between the two curves is satisfactory. Apart from the examples presented in this paper, many other validations have been performed. In each case, the maximal penetration of the striking vessel predicted by the analytical method has been found to be conservative and in an acceptable agreement with the finite-element results. Such observations show that it is possible to quickly approximate the impact resistance of a lock gate without having to resort to numerical simulations.

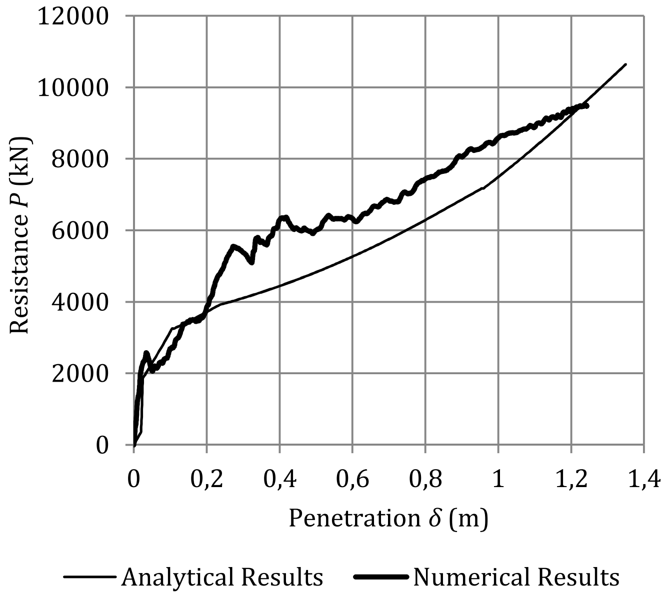

Figure 13: Numerical and analytical results for an impact by a conventional bow

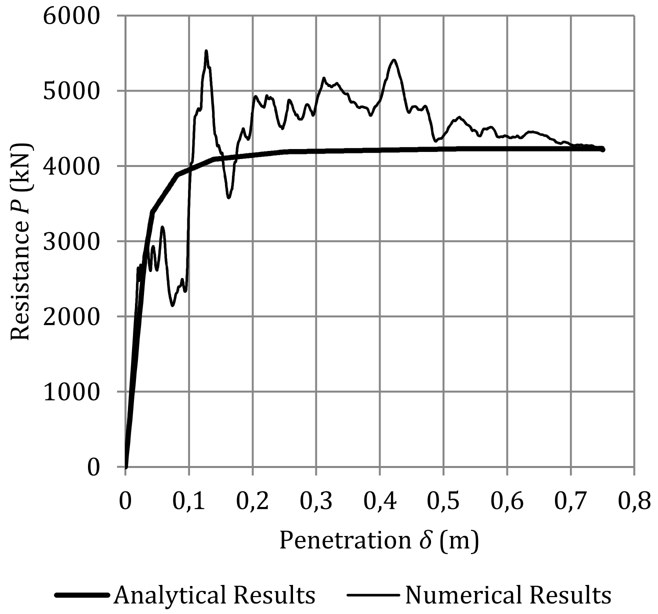

Figure 14: Numerical and analytical results for an impact by a river barge

5 CONCLUSION

In this paper, a review of the existing practice is performed regarding vessel impacts on lock gates. From this brief overview, it can be seen that the methods used in national or international standards are quite different, which means that there is no uniform guideline for the design of lock gates against collisions. Furthermore, most of the available methods involve the derivation of a quasi-static force that is calculated under the assumption of a perfectly rigid structure, which is not necessarily realistic for lock gates.

In order to circumvent this difficulty, an option is to design protection systems to avoid severe damages to the gate. This approach is widely used in Germany and some examples of protection devices are listed in this paper.

Alternatively, another option to study the impact resistance of lock gate is to perform finite element simulations. Unfortunately, doing so may be time-consuming because building the model, running the simulations and post-processing the results is a quite long process. To avoid this difficulty, a simplified analytical method is also presented in this paper.

In this approach, the derivation of the resistance is based on the idea that the gate exhibits two different successive behaviours. At the beginning of the collision, a local deforming mode is postulated, which means that there is only a localized crushing of some components near the impact point. However, when the ship moves forward, there is a switch from this local behaviour to a global one, involving an overall bending of the entire gate. During the first phase, the analytical derivation is based on the super-element method. To do so, the structure is divided into large entities, each of them being characterized by a closed-form relation giving its individual contribution to the local resistance. This one is then simply obtained by considering all the activated super-elements. During the second phase, the gate is assimilated to a set of horizontal beams that are simply bent between the two lock walls. Doing so provides an estimation of the global resistance. As a matter of validation, the results provided by the simplified method are compared to numerical solutions of the LS-DYNA software, from which a quite satisfactory agreement is observed.

As a final comment, it is worth emphasizing that using this simplified method or another approach recommended in national or international guidelines should be restricted to the early design stage of a lock gate. Indeed, these methods are too approximate to provide accurate results that could be valuable at a final design stage, for which the use of finite element simulations is still recommended for the most critical scenarios.

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