Paper 9, part B - Lock gates ship impact

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ABSTRACT: This paper presents an overview of the state of art of ship impact analysis on lock gates. First, the different kinds of analysis are presented, which are: empirical approach, analytical-rational approach, and finite element methods performed with quasi-static analysis or dynamic analysis. A discussion on the hypothesis and the calculus time required by each method is carried out with a view to clarify the state-of-practice for engineers. Then, a quasi-static analysis by finite elements modeling a ship impact is performed on the specific case of a new lock gate designed in Belgium for the "Seine-Escaut Est" project. The results suggest some design recommendations to provide a ductile behavior and so impact strength for the gate structure.

1 INTRODUCTION

At the beginning of a new project, design recommendations for the ship impact load case are hard to find, while there obviously are decisive decisions to take. First of all, the "vessel impact" must be defined in terms of ship weight and speed. Then, a decision must be taken on whether the gate must have sufficient impact strength or protective measures must be designed in order to prevent the ship from impacting the gate. In the first case, the analysis to perform to design the gate structure has to be decided.

2 SPECIFICATIONS

2.1 *Vessel impact design criterion*

The ship weight and speed to take into account for designing the gate structure or the protective device have to be defined by the client. Of course, this "vessel impact" has to be consistent with the project. For instance, the design &build request for proposals for the third set of locks of the Panama Canal explicitly adopted a "vessel impact" of 160 000 t with a speed of 0.5 m/s (PIANC, 2009), which is consistent with the design ship and the expected ship velocities in the lock.

2.2 *Protective measures VS gate designed to sustain ship impact*

Both solutions have to be compared on economical basis. In Germany, the downstream side is generally equipped with a protection system (on the chamber side). This protection system can't be very stiff because it must avoid destroying the ship, since a sinking ship will result in a long downtime period for the lock (PIANC, 2009).

2.3 *Ship impact analysis*

If the gate has to serve as a ship stopping device, an analysis of the ship impact must be performed on the gate structure. Different kinds of analysis are possible. The decision depends notably on the importance of the project and the time and money that can be spent on this analysis.

3 SHIP IMPACT ANALYSIS: STATE OF ART

3.1 *Empirical approach*

These methods are based on empirical data and practice experience. They offer a very simple way to evaluate an order of magnitude of the impact strength of a lock gate but their simplicity does not allow to reflect correctly the phenomenon of an impact. They can only be used as a rule of thumb. Always more detailed analysis must be performed (see here after).

3.2 *Analytical-rational approach*

Analytical models can represent simple cases of impact with a good accuracy. Some hypothesis have to be made on the strain state of the gate but numerical studies with uniform gate structures have highlighted the ways of dissipating energy that should be considered, i.e. a local deformation of structure elements in the vicinity of the impact and a global bending around plastic hinge lines (Le Sourne et al., 2004). The principal assumption in analytical analysis is that the totality of the energy brought by the ship is dissipated by the gate. Various numerical studies have validated this assumption (Le Sourne et al., 2004).

Those models do not take into account phenomenon's of instability that could appear during the rotation of the plastic hinge lines, considering the global plastic failure mechanism. Such instabilities could reduce the structure capacity for energy dissipation.

However, such models, if they are correctly applied, can be seen as very effective and time-saver for gate structure with plane geometry.

3.3 *FEM, quasi-static analysis*

Finite elements methods can be used to analyze the ship impact. As dynamic effects are usually not significant for lock gate, a quasi-static analysis can be seen as sufficient to model the impact. One possible method is to consider the bow of the ship as perfectly stiff and so to apply a quasi-static load on the gate structure until equalization of the strain energy of the gate with the initial kinetic energy brought by the ship.

The approximations of this method are that the totality of the energy is dissipated by the gate; there is no dynamic effect and no evolution of the contact between the bow and the gate. Nevertheless, this kind of analysis gives good results when a dynamic analysis can't be performed.

3.4 *FEM, dynamic analysis*

Such analysis allows modeling the deformable bow of the ship so that giving an initial position and speed, the contact between the bow and the gate can be considered. Moreover, dynamic effects are taken into account. This is unfortunately highly time consuming method –main disadvantage.

Using this method for few study cases can offer reference results to validate assumptions made in analytical models or quasi-static finite elements methods.

4 ONE EXAMPLE: SEINE-ESCAUT EST

A quasi-static analysis by finite elements using the FINELG software (de Ville de Goyet, 1994) has been performed on a lock gate designed for the "Seine-Escaut Est" project in Belgium, which includes the upgrading of 4 locks. The dimensions of the gate are 13.7 m length and 13.6 m height. The design ship is a 2400 t barge. The lock gate is first elastically designed with the LBR-5 lock gate optimization software (Rigo, 1999) considering the hydrostatic load cases. The total weight of the gate is 51.4 t.

4.1 *Ship impact analysis*

Three scenarios of impact are studied:

1. The ship impacts the gate at upstream water level (U.W.L.), but the hydrostatic loads are neglected.
2. The ship impacts the gate at U.W.L. while the hydrostatic service loads are already applied to the gate
3. The ship impacts the gate at downstream water level (D.W.L.).

The analysis of the first scenario applied on the initially optimized structure shows a fragile behavior of the gate. The gate structure has a low capacity for dissipating energy (max. 80 kJ). Here, it should be noted that the gate was elastically designed to resist to hydrostatic loads. Consequently, the slenderness ratio of the stiffened panel respects Hugues' criteria for T-elements (Hugues, 1995), which fit with the Eurocode class-3 of cross sections. It explains why the collapse appears very early by buckling of the frame when the gate is impacted by a ship.

After reinforcing the gate to obtain class-1 cross sections for the frames and girders, the observed behavior of the gate structure is very ductile (Fig. 1). Instability phenomenon's are avoided and the gate is able to develop a global plastic failure mechanism and to dissipate until 2 MJ. However, the total weight is gone up from 51.4 t to 68.7 t (+34%).

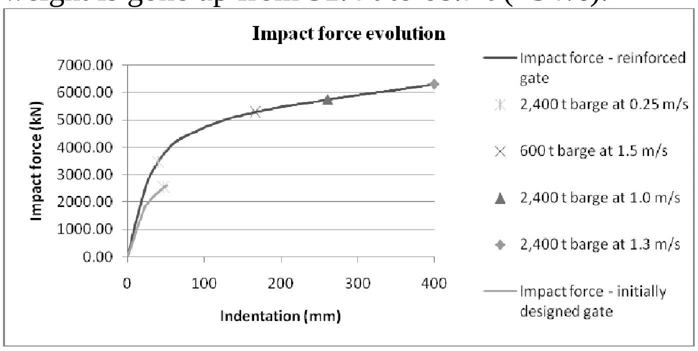

Figure 1. Impact force evolution for a U.W.L. impact

When taking into account the hydrostatic load, the global behavior of the gate structure is identical but the structure is more deformable. The reason is that the gate is already submitted to a stress field.

The gate structure is more fragile for a downstream side impact compared with an upstream side impact, the stiffness being much higher and the collapse arising suddenly for an impact of energy in the order of 450 kJ (Fig. 2). The strain pattern in the gate at the collapse stage shows that there were strain concentrations in the impact zone, mainly in the frame in contact with the barge bow. This strain peak is due to the small ratio between the transverse and longitudinal stiffness in this zone, which prevented the propagation of yielding and thus the development of a global plastic failure mechanism (Fig. 3).

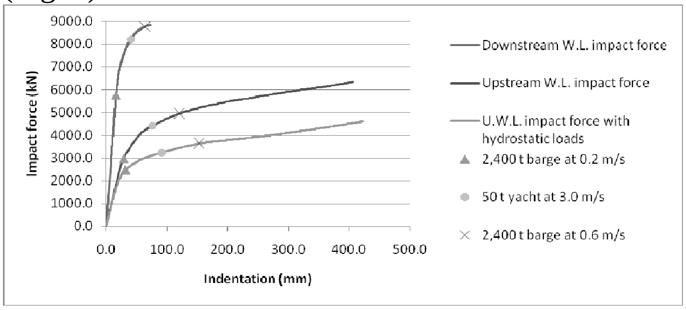

Figure 2. Impact force evolution for different impact cases.

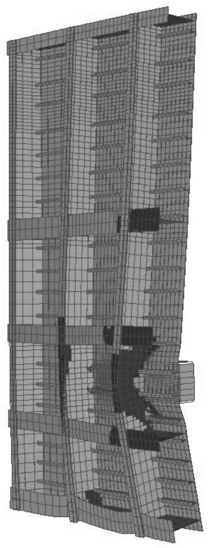

Figure 3. Yielding at the collapse stage, D.W.L. impact.

4.2 *Conclusion*

In this considered example, the aim was to design a gate able to resist the ship impact by itself. To provide the gate a good capacity for dissipating energy, it is necessary to provide a ductile behavior for the gate structure, i.e. to avoid instability phenomenon and to allow the gate forming a global plastic failure mechanism. Ductility of the elements can be achieved by using EN class-1 cross sections. Ductility of the structure requires a good propagation of yielding, which can be achieved by an adequate design of the stiffness ratios in the potential impact zones.

Nowadays, it becomes a current practice to perform an elastic design and optimization of the lock gates considering hydrostatic load cases. However, the gate impact analysis may force the designer to increase the dimensions (cross section) of the frames and the girders of the optimum solution to obtain class-1 cross sections.

Consequently for design purpose the main recommendation is to implement in the optimization software a new constraint that consists in using only class-1 cross sections for the frames and the girders. It would permit to obtain optimized solutions considering impact strength. Then, this solution should be compared in term of cost with the elastic optimum solution coupled with protective measures against ship impact.

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Lock Gate and Ship Impact

- Report n°106, 2009 -

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Lock Gate and Ship Impact

Part A: LOCK GATES – INNOVATIVE CONCEPTS

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Part B: SHIP IMPACT

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LOCK GATES – INNOVATIVE CONCEPTS

1. - LOAD AND STRENGTH ASSESSMENT

Load and strength are linked when structural engineers design lock gates and valves, first at the early design stage (to assess weight and cost) and later at the final design stage (construction drawings).

Nowadays most difficult issues issues concern :

➔ Seismic effect on lock gate

- additional loads (external and internal)
- behavior during gate motion
-

➔ Ship collision on lock gates

The challenge for the next years is to identify relevant and cost/effective specifications and requirements.

LOCK GATES – INNOVATIVE CONCEPTS

2. - MECHANİCAL PARTS: SEALS, BEARİNGS, HYDRAULİC CYLİNDERS, OPERATİNG EQUİPMENT

The main points about the mechanical parts (see Table 1 in Report):

- The key points to consider during the design of mechanical parts is the Gate Operation.
- Operating machinery is critical locks equipment because this equipment is subjected to intensive operation.
- Lock availability depend mainly on the machinery performance and reliability.

LOCK GATES – INNOVATIVE CONCEPTS

2. - MECHANİCAL PARTS: SEALS, BEARİNGS, HYDRAULİC CYLİNDERS, OPERATİNG EQUİPMENT

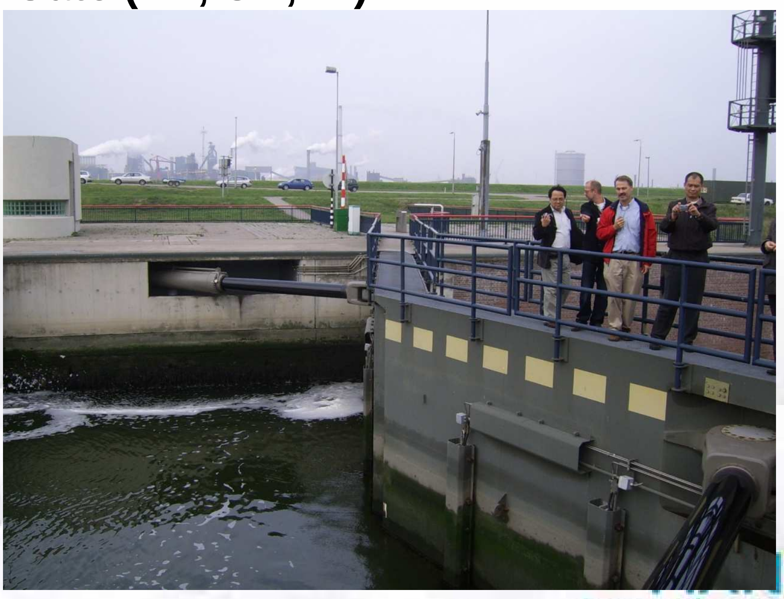
Electromechanical actuators, using a capsulated threaded pin (Germany)

Mitre gate at Uelzen II

3- NEW INNOVATIVE GATE CONCEPTS

a- Folded Plate for gates (Germany) – see previous page

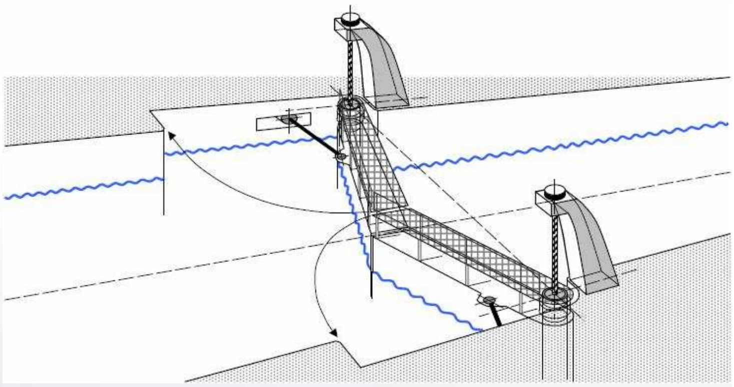
b- Reversed Mitre Gate (NL, UK, …)



Reverse Mitre Gate (IJmuiden-NL)

NEW INNOVATIVE GATE CONCEPTS

c- Suspended Mitre Gates (NL)

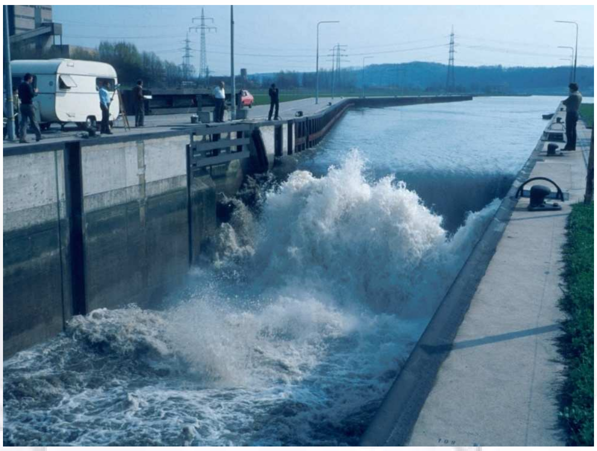


Suspended Mitre Gate

Mitre gates supported only at their top hinges

NEW INNOVATIVE GATE CONCEPTS

d- Rotary Segment Lock Gate (horizontal axis) - Germany



Lisdorf Lock – Flood discharge through the lock

NEW INNOVATIVE GATE CONCEPTS

e- *Vertical-axis Sector Gates (Germany, Finland, Japan, …)*

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NEW INNOVATIVE GATE CONCEPTS

f) **COMPOSITE LOCK GATES**

CETMEF (France) ➔ vertical lift arch gate with composite materials.

RWS - the "Spieringsluis" ➔ high strength synthetic composite material to reduce the higher maintenance costs of wooden or steel gates.

Main advantages of composite arch gates are:

- **No corrosion;**
- **Good resistance to aging in damp environment;**
- **Finishing paint useless, ➔ reducing maintenance costs;**
- **Lightness, easing transportation and fitting of the gate;**
- **Lightness reducing purchasing and maintenance of machinery;**

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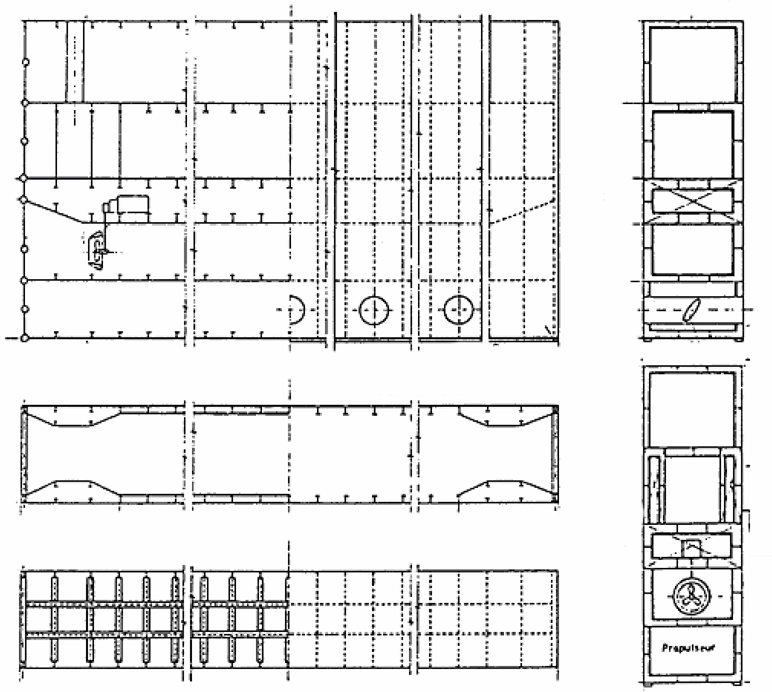
NEW INNOVATIVE GATE CONCEPTS

g) Self-propelled floating lock gates

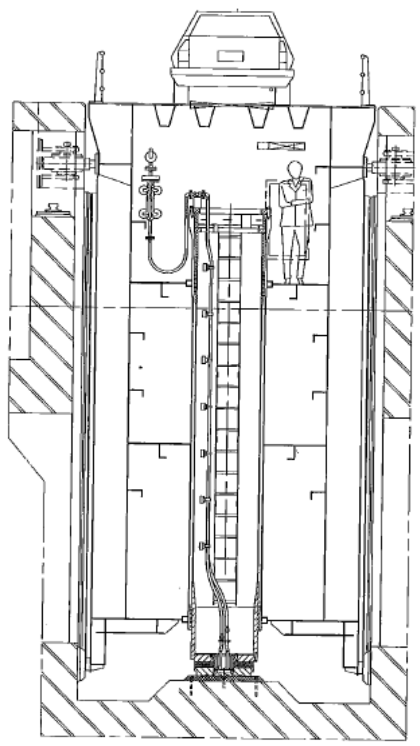


Maritime locks
➔ Cost savings

ANAST -ULG

NEW INNOVATIVE GATE CONCEPTS

h- Sliding gate – Hydrojet (NL)

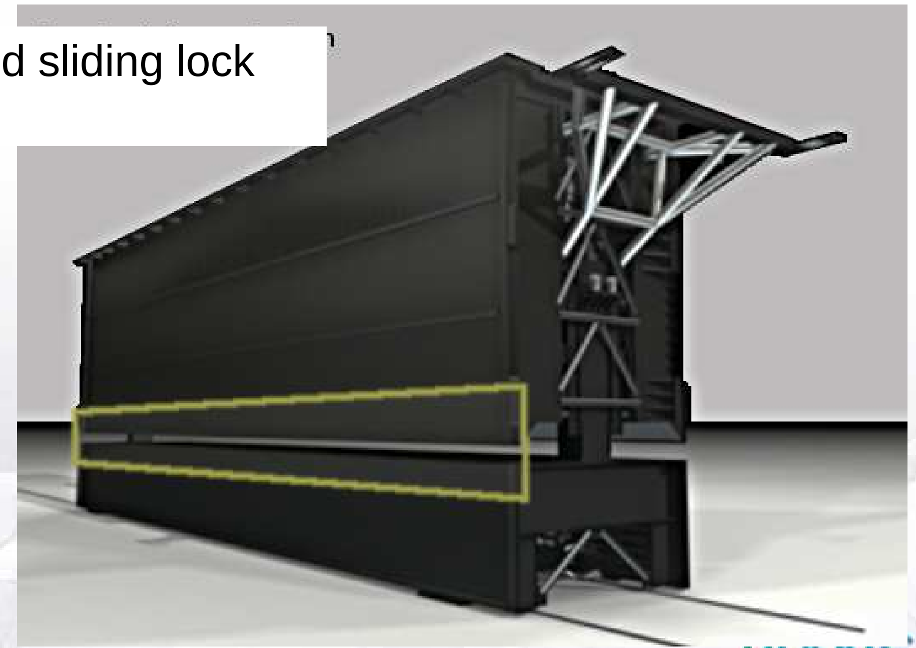


Hydrojet
Oranje lock (NL)

NEW INNOVATIVE GATE CONCEPTS

i) Rolling gates with integrated filling/emptying system

Kaiser lifting and sliding lock gate



LOCK GATES – INNOVATIVE CONCEPTS

4. – GATE TIGHTNESS, LININGS and SEALS

➔ ***The "come back" of sliding gates/valves***

In the Netherland, Germany, Panama, etc.

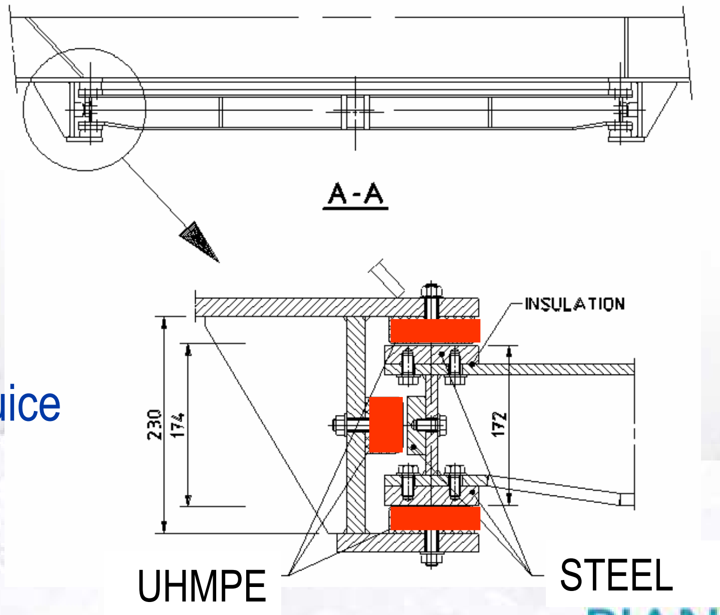
UHMPE *(ultra-high molecular weight polyethylene)*
is nowadays considered a reliable teachnology and a very durable material to be used for sliding gate and lock filling and emptying valves.

LOCK GATES – INNOVATIVE CONCEPTS

5. – VALVES for FILLING/EMPTYING SYSTEM

Use of UHMPE

UHMPE sliding Gate sluice (Naviduct, NL)



LOCK GATES – INNOVATIVE CONCEPTS

5. – VALVES for FILLING/EMPTYING SYSTEM

➔ USE of UHMPE (ultra-high molecular weight polyethylene)

Sliding lift gate with UHMPE is based on a high mechanical performance sliding material with a low friction coefficient.

The material provides both guiding and sealing functions.

UHMWPE has the following characteristics:

- **low friction coefficient (< 0.2);**
- **low wear index (wear < 4 mm in 35 years – working life);**
- **maximum stress (6 N/mm²)**

UHMPE is nearly a standard solution for such contacts in the modern Dutch vertical lift gate sluices e.g. see as the valves of the Naviduct Enkhuizen (NL)

LOCK GATES – INNOVATIVE CONCEPTS

6. – CORROSION : PREVENTION and PROTECTION

a) In the last decade, costs associated with maintenance of infrastructure have increased dramatically due to the development of more stringent environmental regulations.

b) Durability and economic maintainability are both directly proportional to corrosion preventive measures taken.

c) Corrosion prevention of metal, which should be considered at the design stage, must not be confused with corrosion protection, which is regarded as an other item to consider but at the building stage.

LOCK GATES – INNOVATIVE CONCEPTS

7. – GATE EQUIPEMENT

Magnetic automatic innovative mooring systems

Magnetic Mooring System at KaiserLock (*Cavotec Ltd*)

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Part b: Ship Impact

- Report n°106, 2009 -

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Plan

1. **Introduction**
2. **Ship impact analysis: state of art**
   a) Empirical approach
   b) Analytical-Rational approach
   c) FEM, quasi-static analysis
   d) FEM, dynamic analysis
3. **One example: “Seine-Escaut Est”**
4. **Conclusion**

Introduction

New project: recommendations?

1. **Define a "vessel impact" design criterion (ship weight and speed)**
   Panama canal:
   - 160,000 t
   - 0.5 m/s
   - With no loss of water tightness and the global resistance
     => consistent with the project

2. **Protective measures VS gate designed to sustain ship impact**

WG29 – LOCK GATE AND SHIP IMPACT

Introduction

3. **Gate = ship stopping device**
   Structure must combine sufficient <u>flexibility</u> with sufficient <u>load bearing capacity</u> to successfully <u>absorb the kinetic energy</u>

Analysis to perform to design the gate structure?

a) Empirical approach
b) Analytical-Rational approach
c) FEM, quasi-static analysis
d) FEM, dynamic analysis

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State of art: empirical approach

- Methods based on empirical data and practice experience
- Very simple way to evaluate an order of magnitude
- Use it as a rule of thumb

  → more detailed analysis must be performed

WG29 – LOCK GATE AND SHIP IMPACT

State of art: analytical approach

Analytical models (Le Sourne)

Hypothesis – Approximations:

- Analytical model → simplifications
- Totality of the energy dissipated by the gate
- No change in the contact
- No dynamic effect (vibrations, ...)

Numerical studies have validated these assumptions for simple cases

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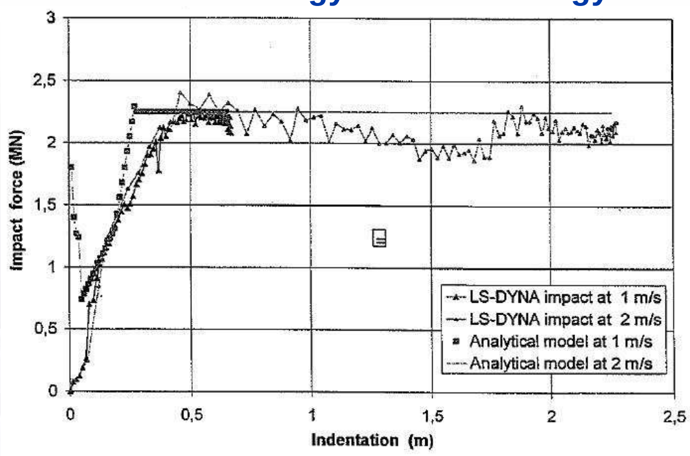
State of art: analytical approach

The impact force – indentation relationship can be obtained

Kinetic energy ↔ Strain energy



Impact forces comparison (Le Sourne) – Dynamic analysis VS analytical model

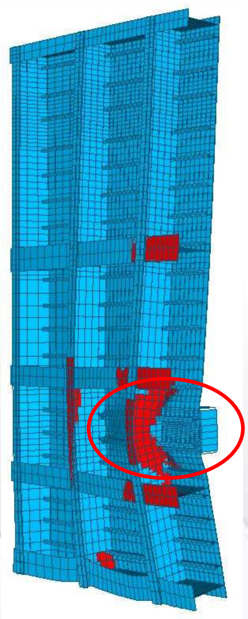
FEM, quasi-static analysis

Finite Elements Methods
Neglect the dynamic effects → quasi-static analysis

One possibility:
Simple model of the bow of the ship
→ ex: perfectly stiff rectangular element

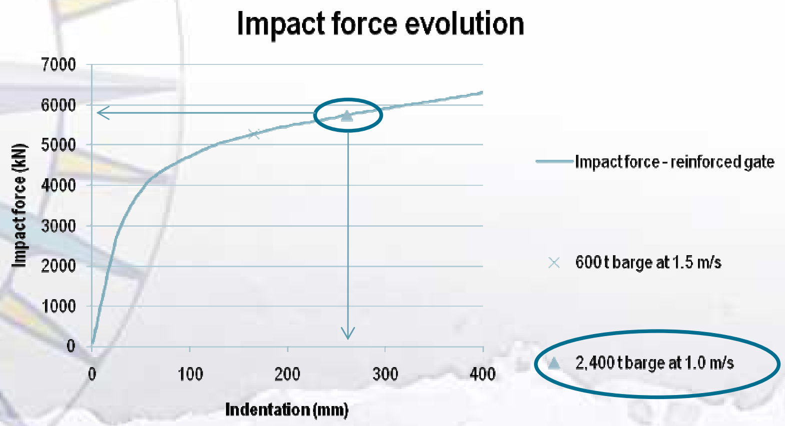
No evolution of the contact
between the bow and the gate

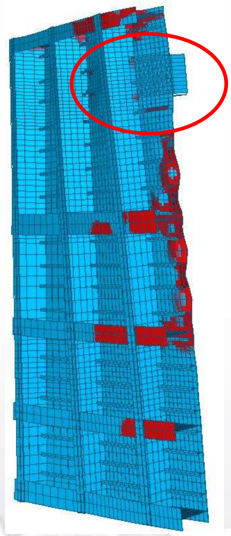
Load *Fimpact* on the bow increased
until equalization of the energies



Lock gate simply supported on three sides

FEM, quasi-static analysis





⇒ *Indentation 26 cm and impact force 5,75 MN (energy: 1,20 MJ)*

WG29 – LOCK GATE AND SHIP IMPACT

FEM, dynamic analysis

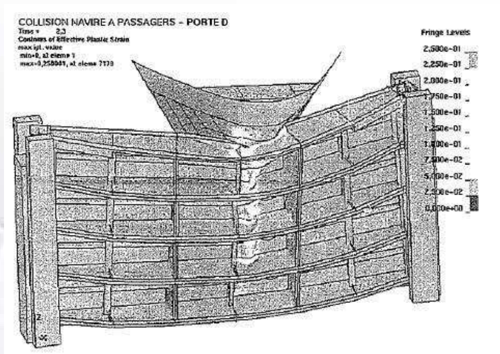
LS-DYNA

✓ **Possibility of modeling the deformable bow of the ship**

⇒ **Giving an initial position and speed, the contact can be considered**

✓ **Dynamic effects taken into account**

... But highly time-consuming



Passenger ship impact: effective plastic strains at t=2,3 sec.

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Which analysis perform?

Empirical: gives an order of magnitude of the impact strength

Analytical: very effective and time-saver for gate structure with plane geometry but must be correctly applied (assumptions to validate)

FEM, quasi-static: gives good results when a dynamic analysis can't be performed

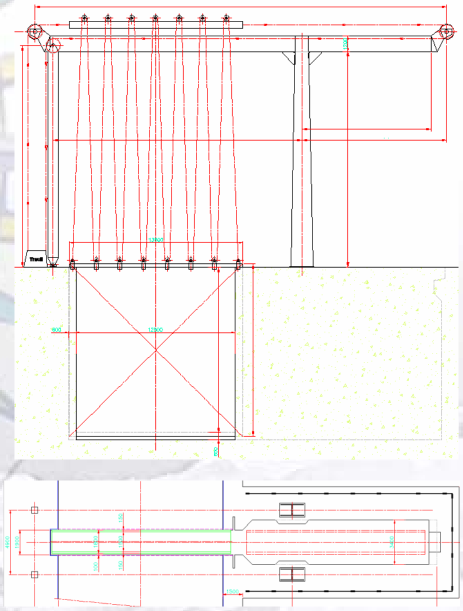
FEM, dynamic: accurate but time consuming. Using it for few cases can offer reference results to validate assumptions made in other methods

One example: "Seine-Escaut Est"

Lock gate designed for the "Seine-Escaut Est project" in Belgium

Downstream lock gates: length 13.7 m ; height 13.6 m
Gates suspended and manoeuvred by lateral movement

One example: "Seine-Escaut Est"



First, optimization of the structure considering hydrostatic load cases

→ Elastic design

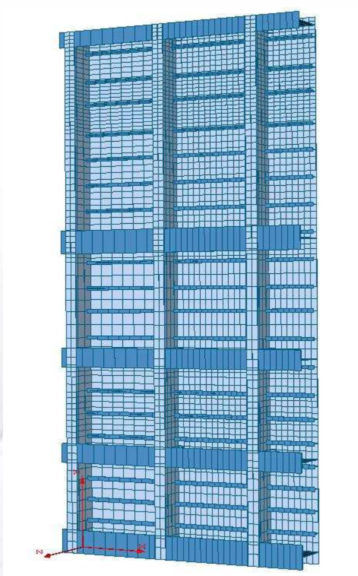
Total weight: 51.4 t

WG29 – LOCK GATE AND SHIP IMPACT

One example: "Seine-Escaut Est"

Then, analysis of the ship impact

It was decided to perform a FEM quasi-static analysis using the *FINELG* software



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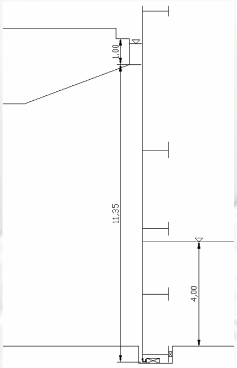
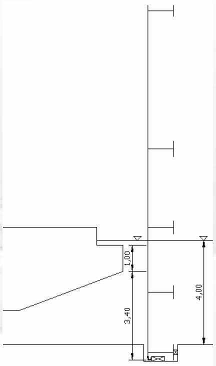
FEM, quasi-static analysis – example

Analysis of 3 scenarios

1. Upstream water level (U.W.L.) without any hydrostatic load
2. Upstream water level with hydrostatic service load (7.50 m)
3. Downstream water level (D.W.L.) without any hydrostatic load

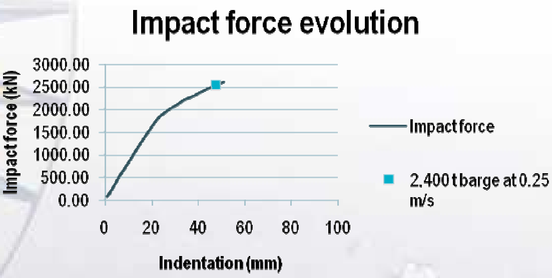


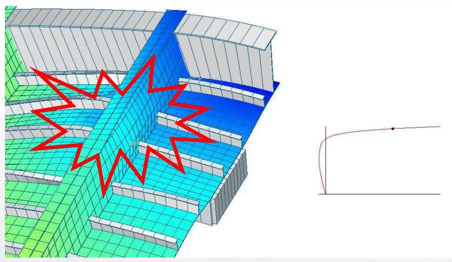


FEM, quasi-static analysis – example

U.W.L. with the initially optimized structure

Low thickness of the frames and girders (slenderness ratio: Hugues' criteria for T-elements)





⇒ Buckling of the central frame

⇒ Fragile behavior – sudden collapse – low capacity for energy dissipation

⇒ Choice of reinforcing the structure

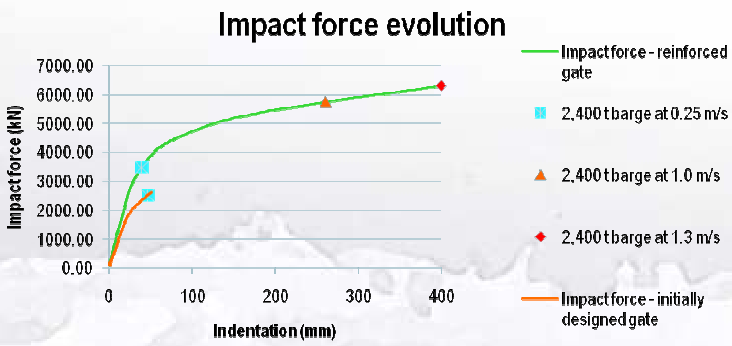
WG29 – LOCK GATE AND SHIP IMPACT

FEM, quasi-static analysis – example

Reinforcing the structure

Aim: avoid instability phenomenon – increase ductility

Dimensions of frames and girders increased (slenderness ratio: EN class 1)
Total weight: 51.4 t → 68.7 t (+34%)



⇒ **By using class-1 sections for frames and girders, we improve the gate behaviour in case of ship impact**

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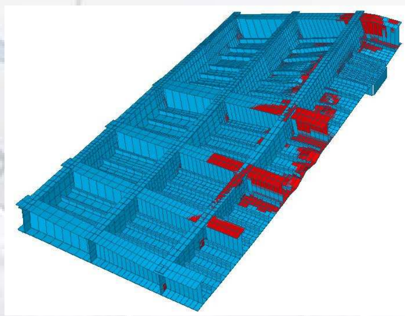
FEM, quasi-static analysis – example

Reinforced gate

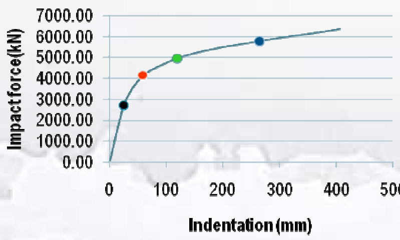
Ductile behaviour – very significant capacity for energy dissipation

Initially optimized structure: 0,08 MJ
Reinforced structure: 2 MJ (i.e. a 2,400 t barge at 1.3 m/s)

Global plastic failure mechanism



Yielding at the collapse stage (amplified x6)



Apparition of successive plastic hinges in the girders

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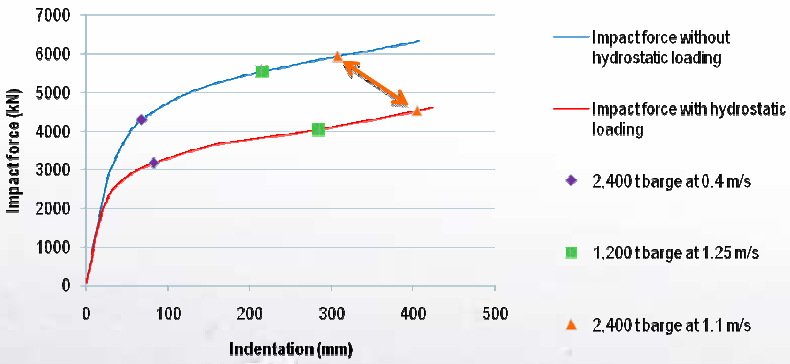
FEM, quasi-static analysis – example

U.W.L., taking into account the hydrostatic loads



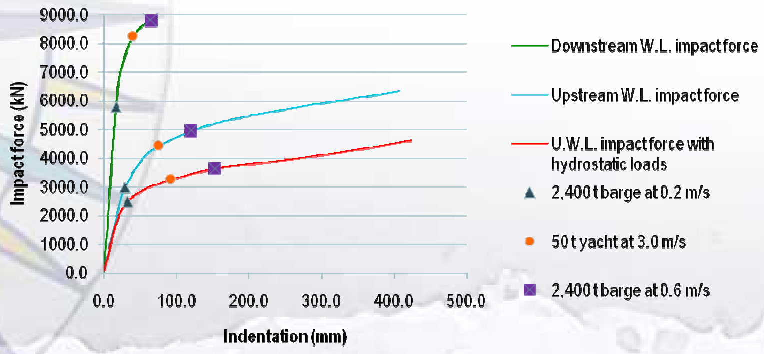
The global behaviour of the gate is identical but the structure is more deformable because previously submitted to a stress field

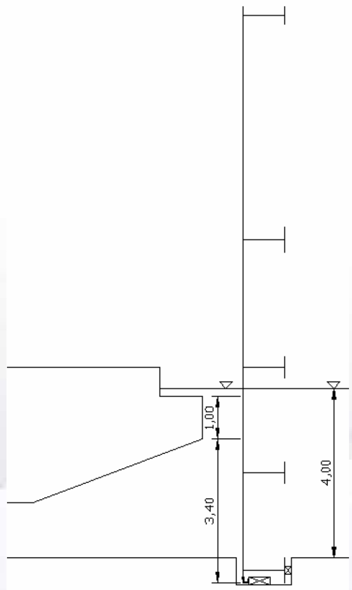
⇒ Neglecting the hydrostatic load leads to underestimate the deformation and the yielding of the structure – but overestimate the impact force

FEM, quasi-static analysis – example

Impact at downstream water level

Highly stiffened impact zone





⇒ Very different behaviour of the gate (fragile) because of the impact zone

FEM, quasi-static analysis – example

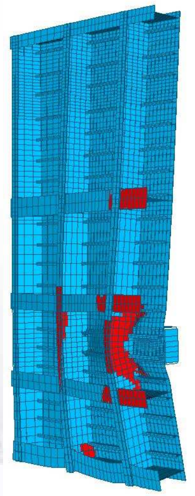
Strain concentration in the impact zone leads to a fragile, sudden collapse

Transverse stiffness << Longitudinal stiffness

⇒ **No propagation of yielding**

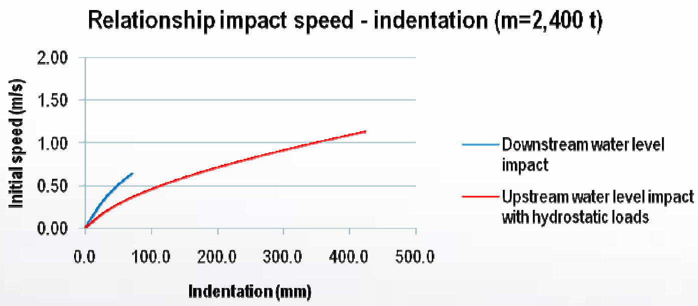
⇒ **No global plastic failure mechanism**

⇒ **Collapse for a small indentation and low energy dissipation (0,5 MJ)**



FEM, quasi-static analysis – example

Results



Impact of a 1,200 t barge at 0.8 m/s (384 kJ)	U.W.L. without hydrostatic loads	U.W.L. with hydrostatic loads	D.W.L.
Impact force	4,845 kN	3,550 kN	8,706 kN
Indentation (only due to the impact)	11.1 cm	13.9 cm	5.9 cm
Number of plastic hinges in frames and girders	2 girders	3 girders	1 frame

FEM, quasi-static analysis – example

Conclusion:

1. Aim: to design a gate able to resist the ship impact by itself
2. To dissipate energy, it needs ductility (avoid instability)
3. Ductility of the elements can be achieved by using EN class-1 cross sections (increasing dimensions of frames and girders)
4. Ductility of the gate requires a good propagation of yielding, which can be achieved by a good design of the stiffness ratios in the potential impact zones

WG29 – LOCK GATE AND SHIP IMPACT

FEM, quasi-static analysis – example

- Lock gates: elastic design considering hydrostatic loading
- Impact analysis: increase the dimensions of the frames and girders
- Recommendation: new constraint in the optimization software to obtain optimized solutions considering impact strength
- Then, comparison (cost): reinforced solution VS elastic optimum solution coupled with protective measures against ship impact

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Thank you

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