University of Liege
Department ArGEnCO

De Paepe – Willems Award

Optimization and analysis of lock gates in the framework of the "Seine-Scheldt-East" waterway upgrading

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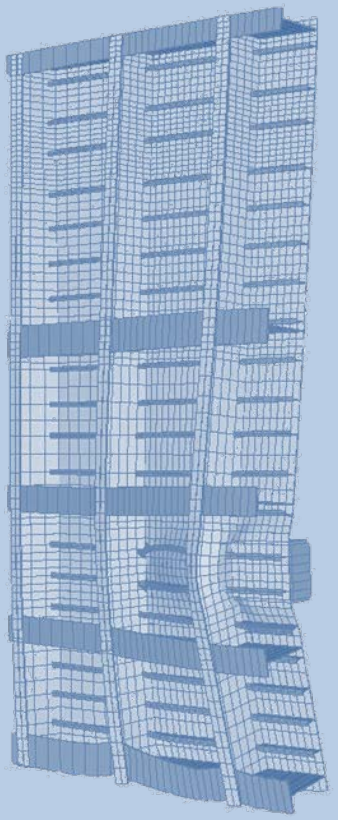
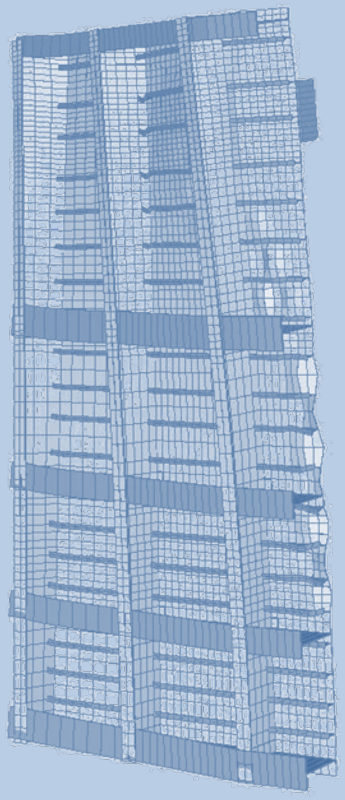
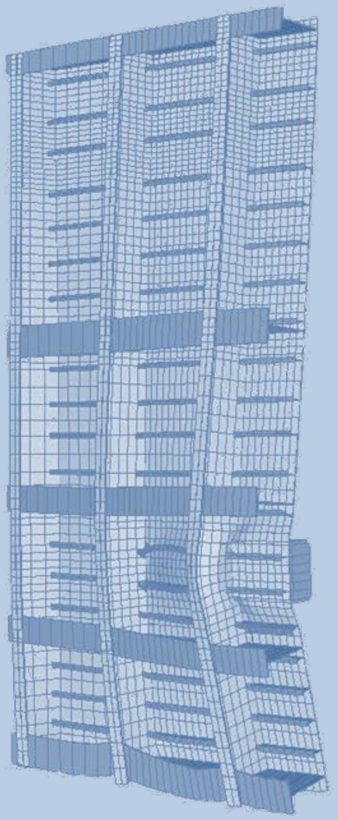


PLAN

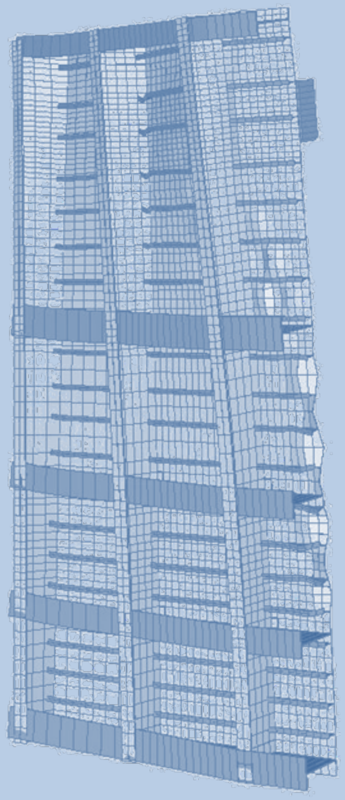


Plan

1. **Introduction**
2. **Design & Optimization of the lock gate**
3. **Finite Element Model (FEM)**
4. **Ship impact**
5. **Ship impact results**
6. **Conclusion**



Introduction



Introduction

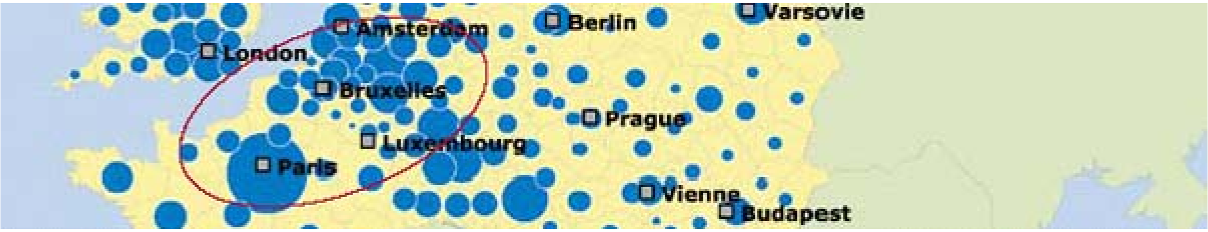
“Seine-Scheldt-East” project

“Seine-Nord Europe” canal connecting the Seine river to the European waterway network

- ✓ Northern Europe
- ✓ Rhin-Main-Danube to Black Sea
- ✓ Le Havre, Rouen with Dunkerque, Anvers, Rotterdam

“Seine-Scheldt-East” project

Important zone in terms of population (EUROSTAT 2003)

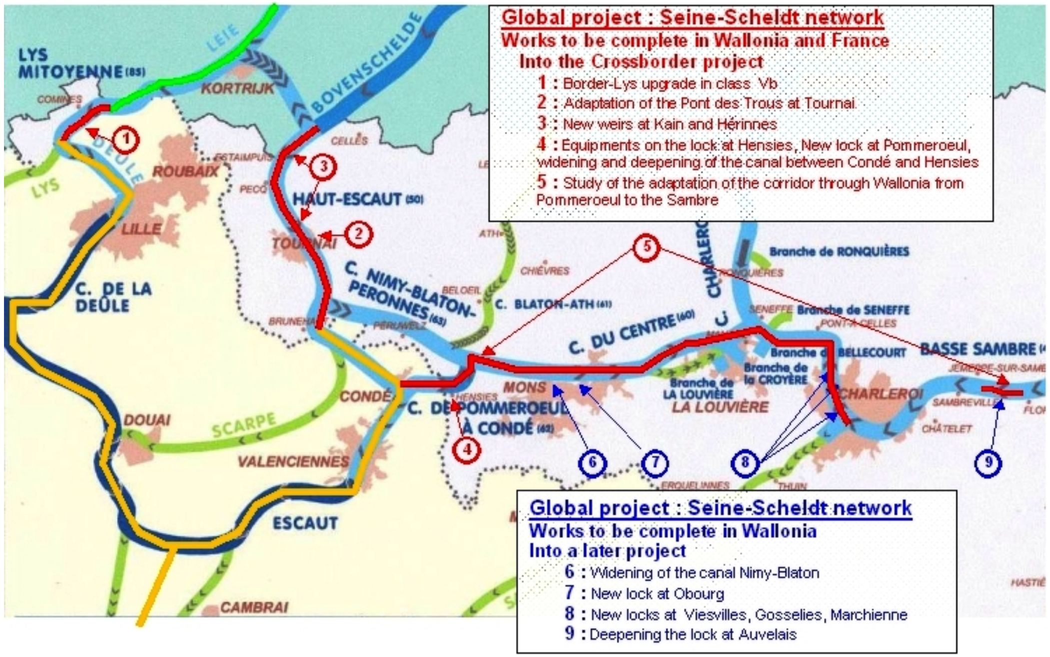


Important zone in terms of GDP (EUROSTAT 2003)

"Seine-Scheldt-East" project

4 new locks planned by the Walloon Region

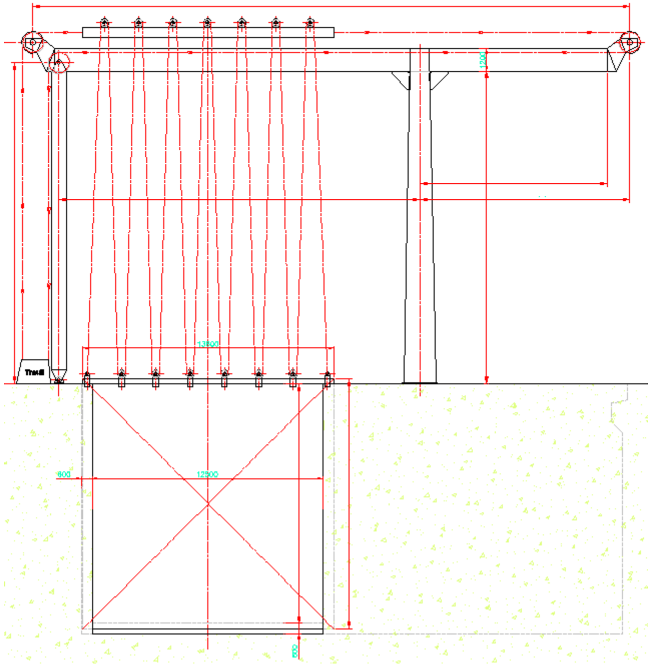
- ✓ Connecting the Scheldt and the Meuse rivers
- ✓ Marchienne-au-Pont, Gosselies, Viesville and Obourg
- ✓ Class Va in Europe (2000 tons)
- ✓ Lock 112,5 m x 12,5 m

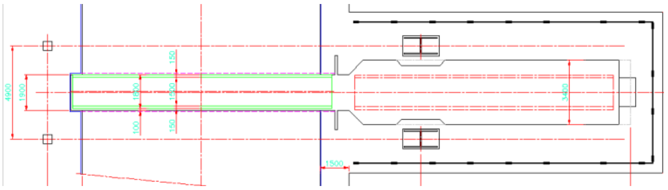


Global project : Seine-Scheldt network
Works to be complete in Wallonia and France
Into the Crossborder project
1 : Border-Lys upgrade in class Vb
2 : Adaptation of the Pont des Trous at Tournai
3 : New weirs at Kain and Hérinnes
4 : Equipments on the lock at Hensies, New lock at Pommeroeul, widening and deepening of the canal between Condé and Hensies
5 : Study of the adaptation of the corridor through Wallonia from Pommeroeul to the Sambre

Global project : Seine-Scheldt network
Works to be complete in Wallonia
Into a later project
6 : Widening of the canal Nimy-Blaton
7 : New lock at Obourg
8 : New locks at Viesvilles, Gosselies, Marchienne
9 : Deepening the lock at Auvelais

Analysis of the downstream gates of the four new locks





Decisions from the basic preliminary design:

- ✓ Gates suspended and manoeuvred by lateral movement
- ✓ Standardization → focus on one gate

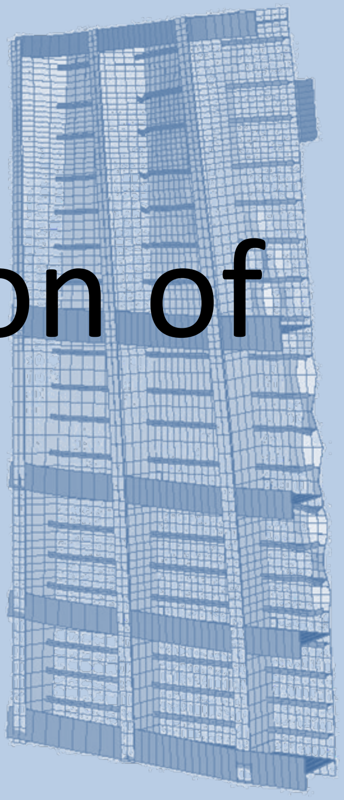
Dimensions

- Length: 13,70 m
- Height: 13,60 m
- Width: 1,00 m < l < 1,80 m

To be determined

- ✓ Width
- ✓ Use of waterproof compartment
- ✓ Gate structure (elements, thicknesses, …)

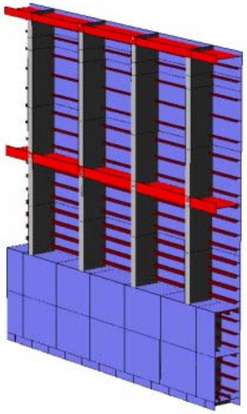
Design & Optimization of the lock gate



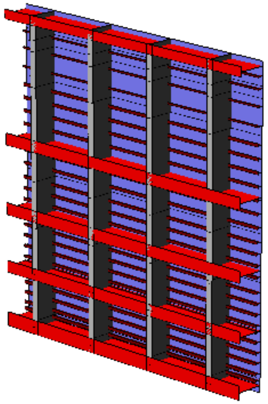
Design & Optimization

Analysis of 4 different models

- 2 models with additional waterproof compartment and different gate widths



- 2 models without waterproof compartment, with different gate widths



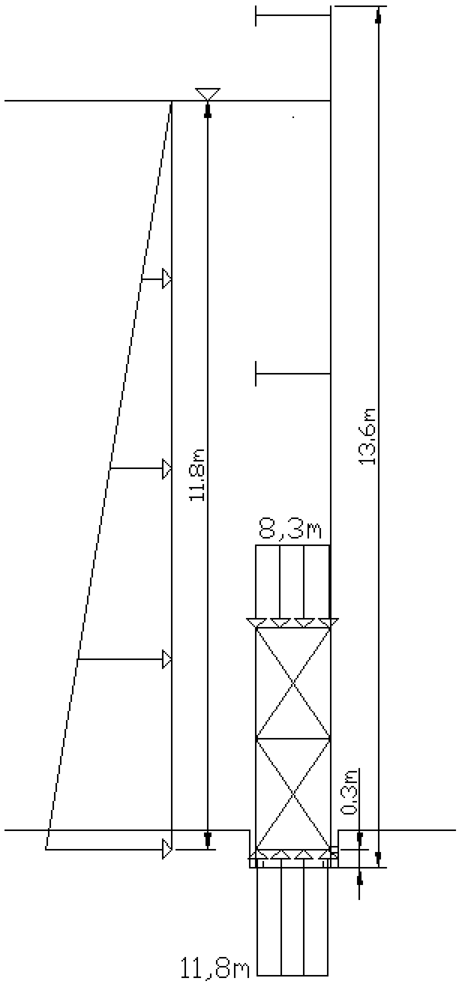
Design & Optimization

Optimization (weight, cost) of the structure considering hydrostatic load cases

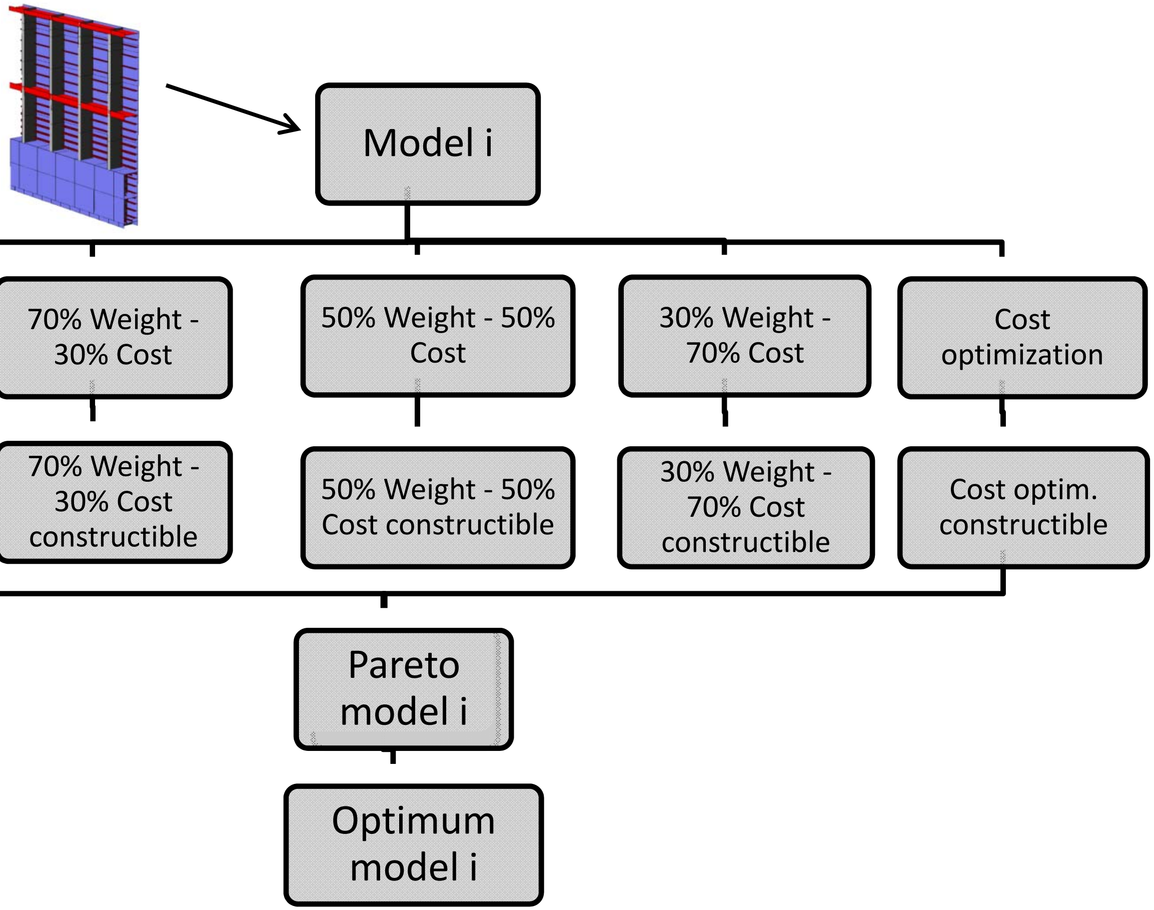
→ Elastic design σ < 176 Mpa

Slenderness ratio of reinforcement elements (frames, girders, stiffeners) adapted to avoid instabilities (Hugues criteria)

Exceptional hydrostatic load case: downstream section of the canal empty



Optimization process in successive stages using the LBR5 software (Ph. Rigo, Ulg)



Model i

Weight optimization

70% Weight - 30% Cost

50% Weight - 50% Cost

30% Weight - 70% Cost

Cost optimization

Weight optim. constructible

70% Weight - 30% Cost constructible

50% Weight - 50% Cost constructible

30% Weight - 70% Cost constructible

Cost optim. constructible

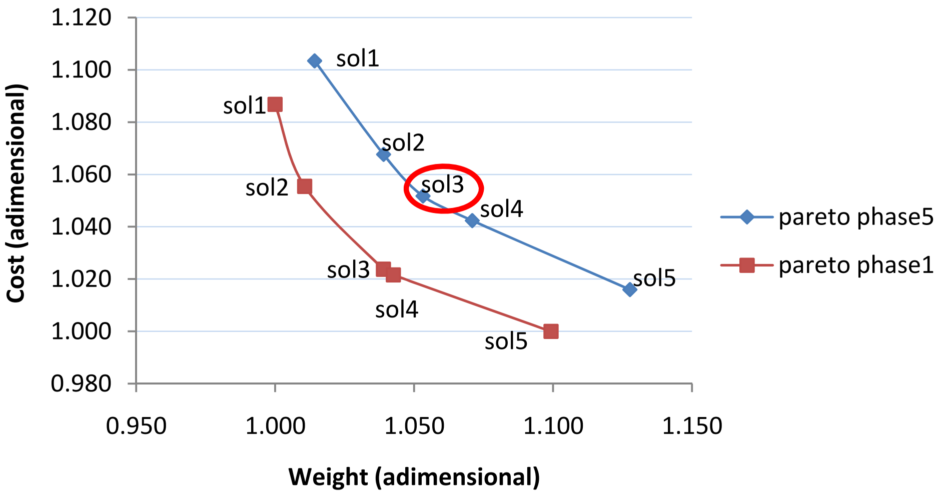
Pareto model i

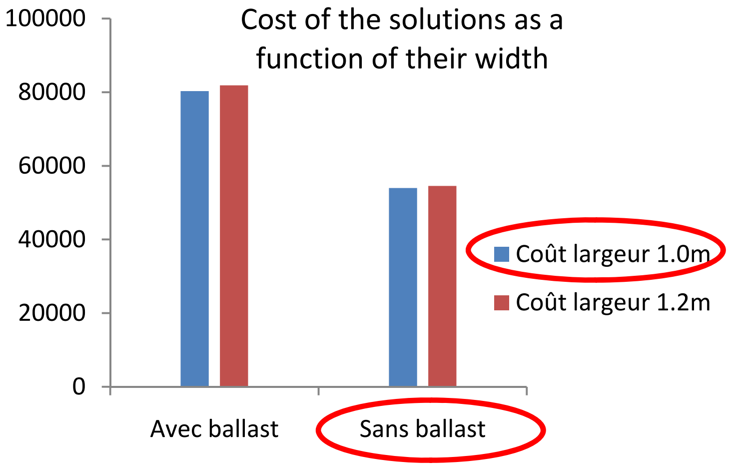
Optimum model i

=> Optimum solution for one model

Pareto curve for model i

- ✓ Considers weight and cost
- ✓ Define a criteria of selection to pick the optimum solution

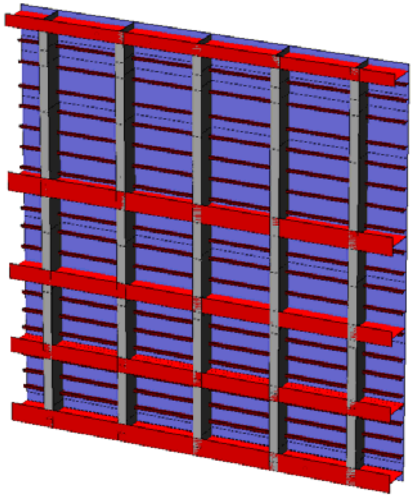




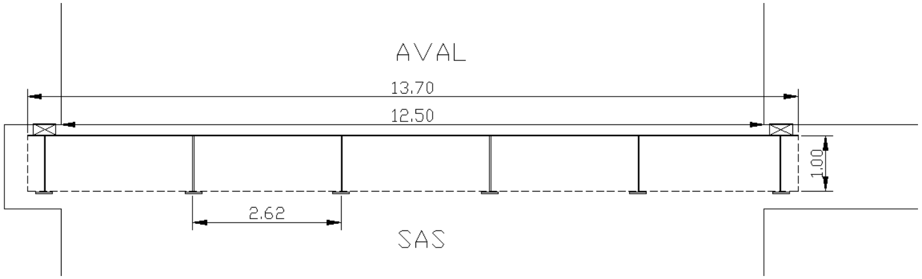
Comparison between the optimum solutions of the 4 models

- ✓ Choice of design: width 1.0 m without waterproof compartment

Final design solution: analysis for all hydrostatic cases

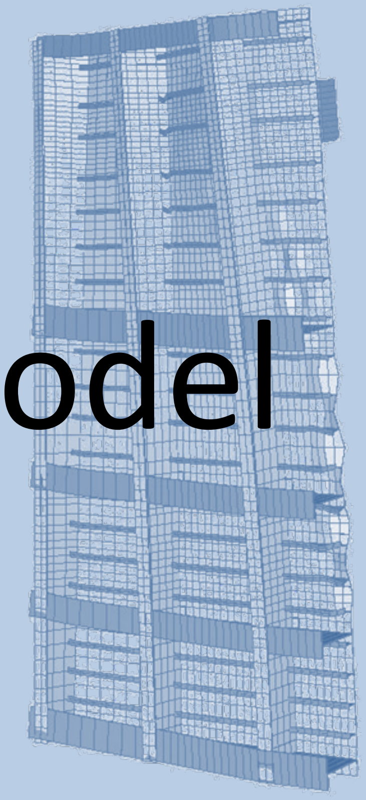


LBR5 Analysis	**In service conditions**		**In flood conditions**		**Downstream side empty**	
Orientation of the gate	**1**	**2**	**1**	**2**	**1**	**2**
Girders	151 MPa		168 MPa		159 MPa	
Stiffeners	156 MPa		168 MPa		171 MPa	
Frames	157 MPa		169 MPa		174 MPa	
Plate (thick./min. th. ratio)	1.16	1.08	1.11	1.04	1.13	1.06
Deflection	1.83 cm		2.04 cm		1.94 cm	

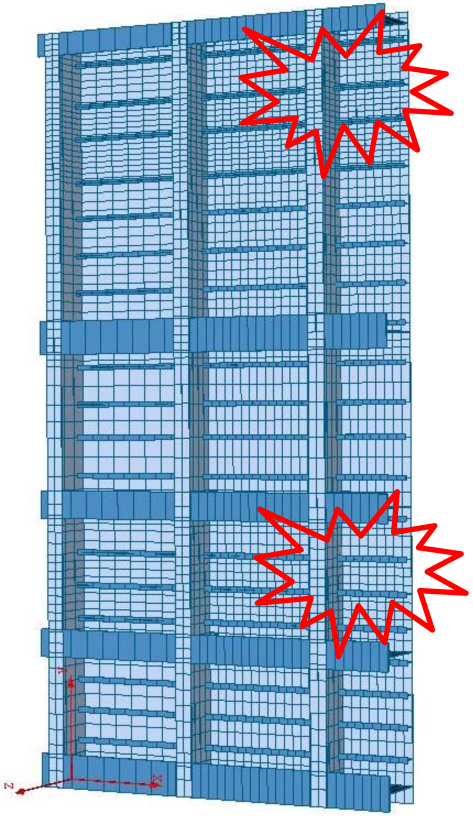


Solution	
Weight	51.4 t
Cost	56 202 €

Finite Elements Model



FEM of the solution



- ✓ Half of the gate
- ✓ FINELG software (V. de Ville, Ulg)
- ✓ Conform to the LBR5 model
- ✓ Simply supported on three sides
- ✓ Refined mesh in the impact zones

Linear elastic analysis for hydrostatic loading

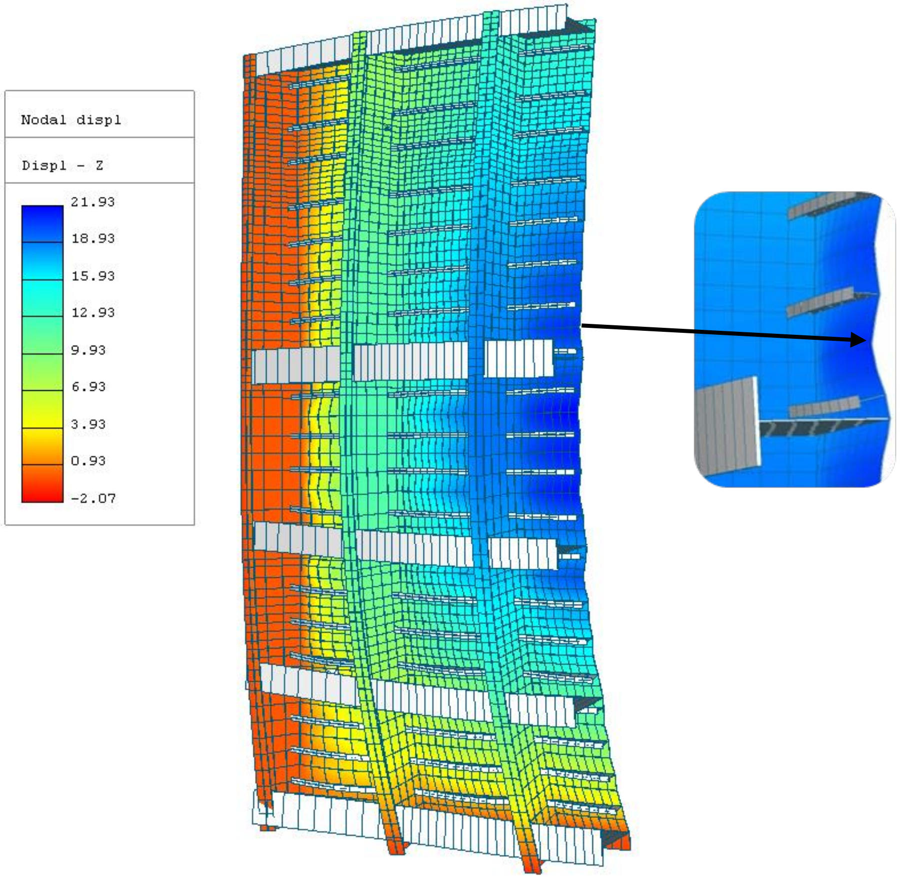
Comparison between LBR5 and FINELG results

- ✓ Good concordance except for the maximal deflection
- ✓ Validate the finite elements model

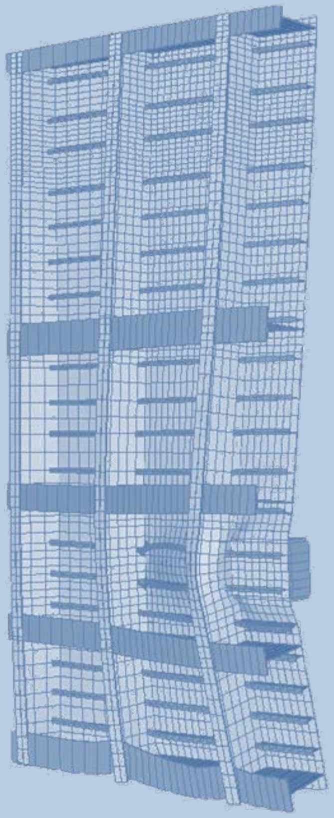
Loading	C1 (service)		C2 (flood)		C3 (downstr. empty)	
Software	**LBR-5**	**FINELG**	**LBR-5**	**FINELG**	**LBR-5**	**FINELG**
Max. stress in frames	157 MPa	149 MPa	169 MPa	157 MPa	174 MPa	171 MPa
Maximal deflection	1.83 cm	2.19 cm	2.04 cm	2.44 cm	1.94 cm	2.31 cm

Differences of maximal deflection?

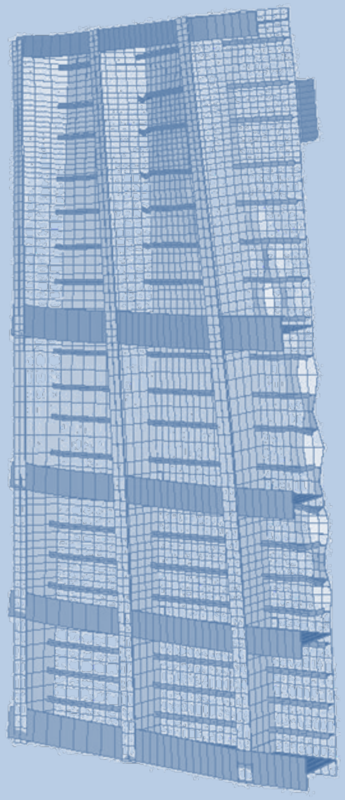
- ✓ Local bending of the plate (not in LBR5)
- ✓ Same plate deflection along the girders with LBR5 and FINELG (no local bending)
- ✓ FINELG gives bigger plate deflection in the middle of unstiffened plate



Deflection shape (mm) for hydrostatic service loading (amplified x80)



Ship impact



Ship impact analysis

1. Vessel impact design criterion?

Class 5a (2000 tons). Speed?
No loss of watertighness and global resistance

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

Compare additional cost of both solutions
→ additional cost to provide the gate a sufficient impact strength?

3. In this analysis: Gate = ship stopping device

Structure must combine sufficient flexibility with sufficient load bearing capacity to successfully absorb the kinetic energy

Gate = ship stopping device

Analysis to perform to design the gate structure?

a) Empirical approach

b) [✓ Analytical-Rational approach]

c) [✓ FEM, quasi-static analysis]

d) FEM, dynamic analysis

FEM, quasi-static analysis

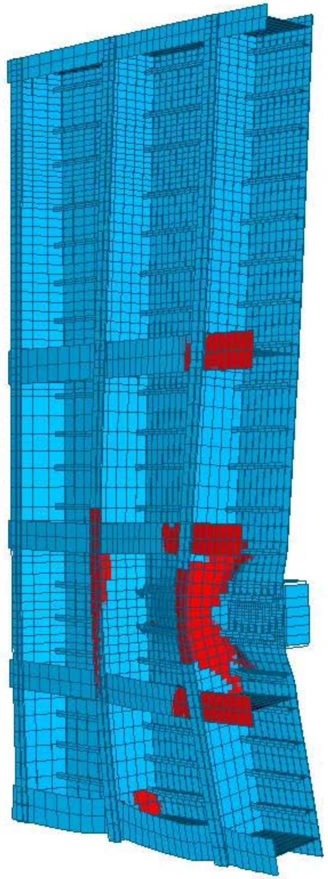
Finite Elements Method

Neglect the dynamic effects → quasi-static analysis

Hypothesis: infinitely stiff barge bow (in fact, the ship dissipates between 5 and 15 % of the initial kinetic energy [Le Sourne et al., 2003])

Simple model of the bow of the ship as a perfectly stiff rectangular element with no evolution of the contact between the bow and the gate

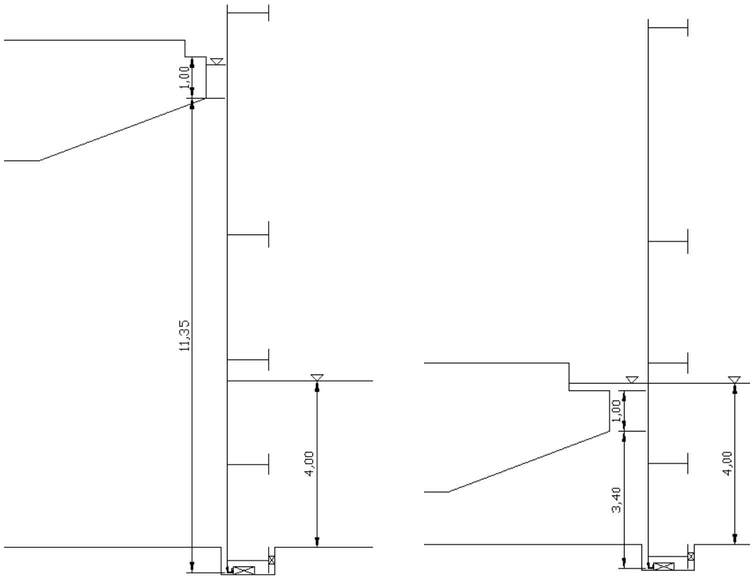
The load F_{impact} on the bow is increased until equalization of the energies



Lock gate simply supported on three sides

Ship impact analysis

- Initial kinetic energy transformed into strain energy of the gate
- Elastic perfectly plastic material law for steel
- Analysis of 3 scenario
    1. Impact at upstream water level (U.W.L.), without hydrostatic load
    2. Impact at upstream water level, with hydrostatic load
    2. Impact at downstream water level (D.W.L.)



1st scenario: impact at U.W.L.

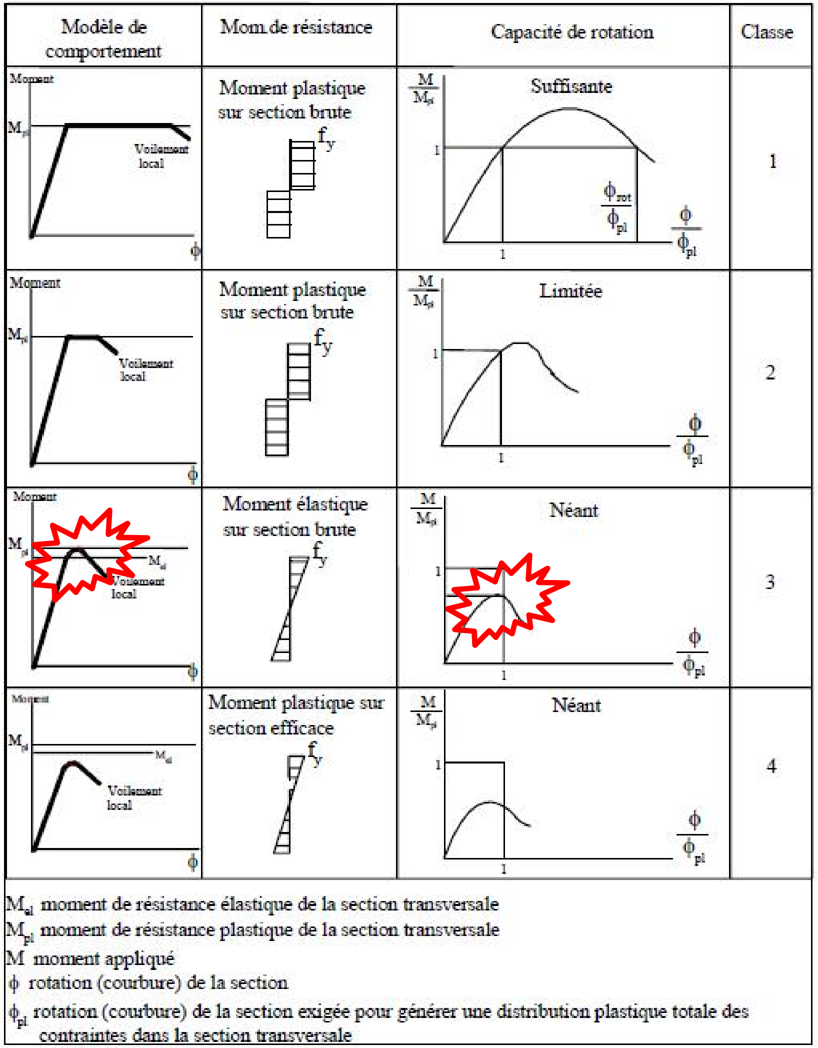
Initially optimized structure

- Elastically designed with LBR5
- Hugues' geometric criteria for T elements (slenderness ratio to avoid instability)
- Hugues' criteria fit with EC3

→ Elastic bending moment OK but buckling before plastic bending moment

→ Low capacity of rotation

→ Inadequate to take advantage of the plastic field

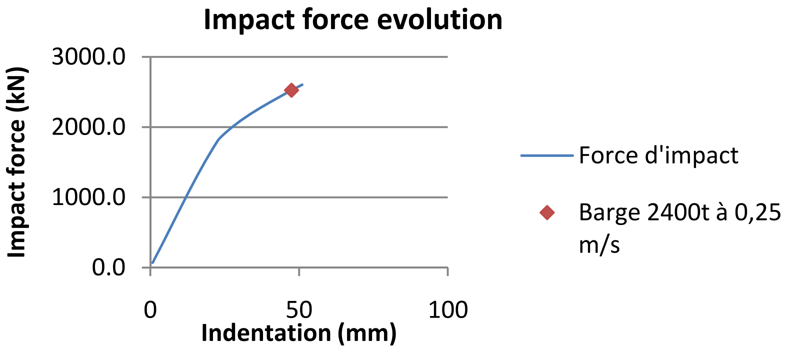


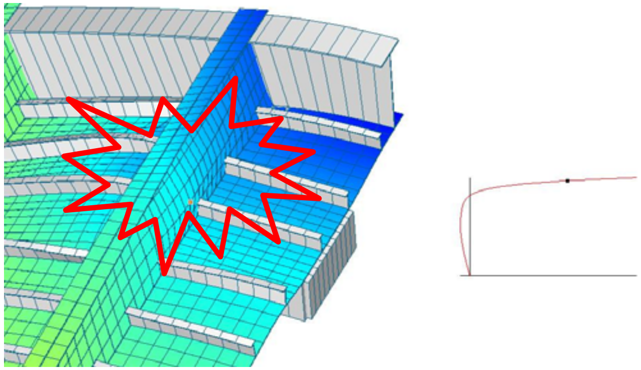
Modèle de comportement	Mom de résistance	Capacité de rotation	Classe
	Moment plastique sur section brute	Suffisante	1
	Moment plastique sur section brute	Limitée	2
	Moment élastique sur section brute	Néant	3
	Moment plastique sur section efficace	Néant	4

M_{el} moment de résistance élastique de la section transversale
M_{pl} moment de résistance plastique de la section transversale
M moment appliqué
ϕ rotation (courbure) de la section
ϕ_{pl} rotation (courbure) de la section exigée pour générer une distribution plastique totale des contraintes dans la section transversale

1st scenario: impact at U.W.L.

- With the initially optimized structure (class 3)





$\Rightarrow$ Instability (frame buckling)
$\Rightarrow$ Fragile global behaviour
$\Rightarrow$ Low capacity for energy dissipation

=> Choice of reinforcing the structure – class 1 cross sections

1st scenario: impact at U.W.L.

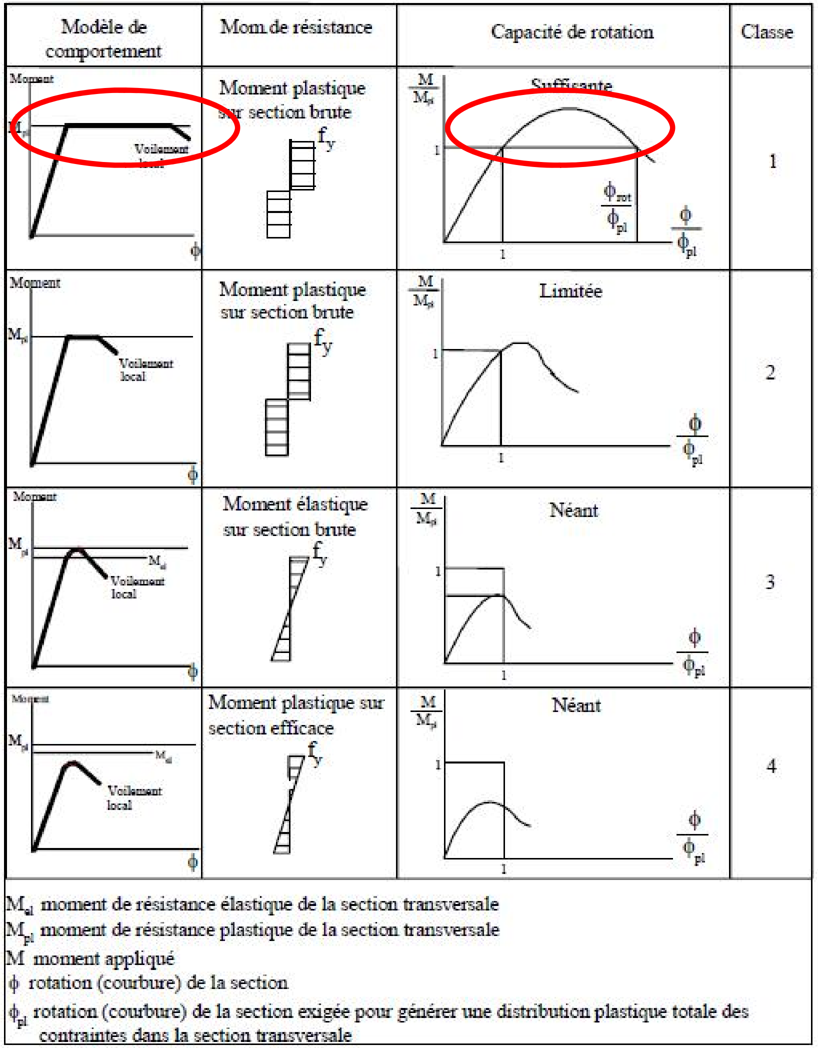
Reinforced structure

- Dimensions of frames and girders increased
- Slenderness ratio: EC Class-1 cross section

  → Fully plastic bending moment

  → Large rotations

  → Take advantage of a yielding behaviour (dissipate large amount of energy)
- Structure total weight: 52 t → 69 t (+34%)
  Total cost +14%

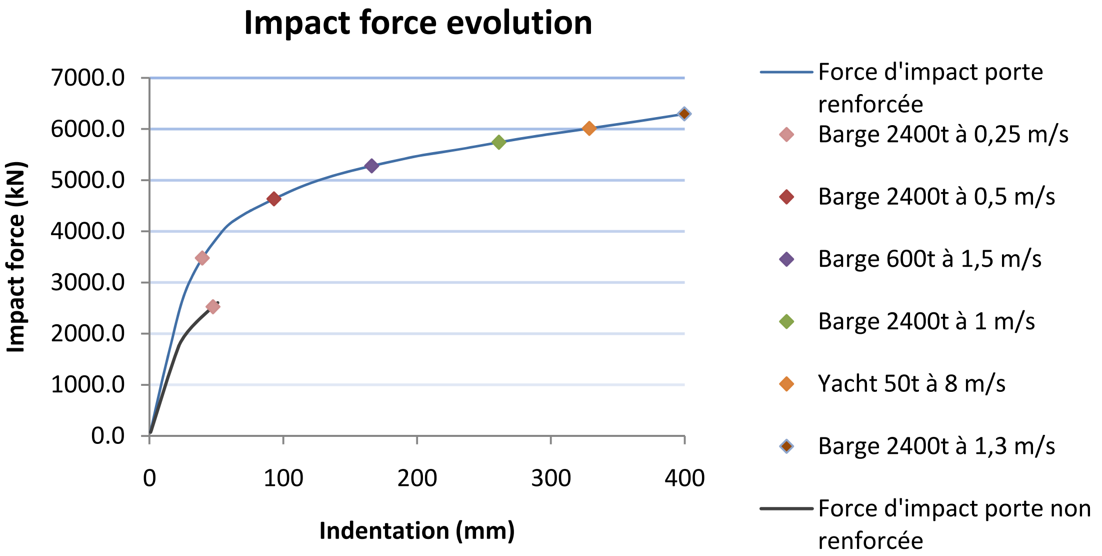


Modèle de comportement	Mom de résistance	Capacité de rotation	Classe
Moment M_{pl} Voilement local ϕ	Moment plastique sur section brute f_y	Suffisante $\frac{M}{M_{pl}}$ 1 $\frac{\phi_{rot}}{\phi_{pl}}$ $\frac{\phi}{\phi_{pl}}$	1
Moment M_{pl} Voilement local ϕ	Moment plastique sur section brute f_y	Limitée $\frac{M}{M_{pl}}$ 1 $\frac{\phi}{\phi_{pl}}$	2
Moment M_{pl} M_{el} Voilement local ϕ	Moment élastique sur section brute f_y	Néant $\frac{M}{M_{pl}}$ 1 $\frac{\phi}{\phi_{pl}}$	3
Moment M_{pl} M_{el} Voilement local ϕ	Moment plastique sur section efficace f_y	Néant $\frac{M}{M_{pl}}$ 1 $\frac{\phi}{\phi_{pl}}$	4

M_{el} moment de résistance élastique de la section transversale
M_{pl} moment de résistance plastique de la section transversale
M moment appliqué
ϕ rotation (courbure) de la section
ϕ_{pl} rotation (courbure) de la section exigée pour générer une distribution plastique totale des contraintes dans la section transversale

1st scenario: impact at U.W.L.

- With the reinforced structure (class 1)



⇒ Global plastic failure mechanism
⇒ Ductile global behavior
⇒ High capacity for energy dissipation

=> Reinforcing the structure with class 1 cross sections was a good choice

Reinforced structure to avoid instability phenomenon – increase ductility

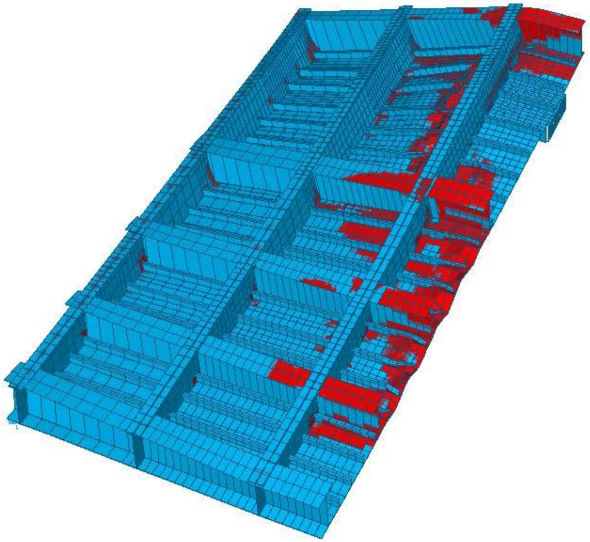
Ductile behaviour – very significant capacity for energy dissipation

Initially optimized structure: 0,08 MJ

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

Yielding at the collapse stage

Initially designed structure

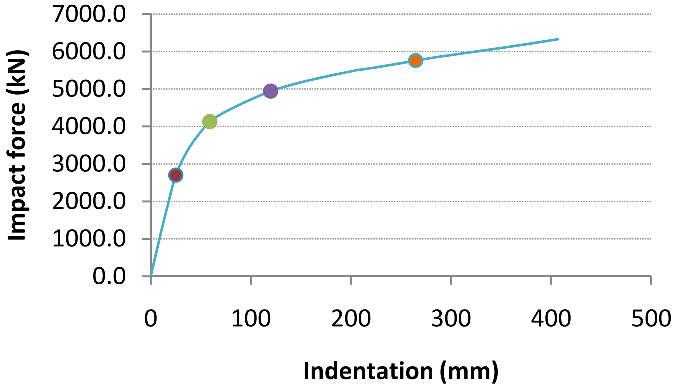


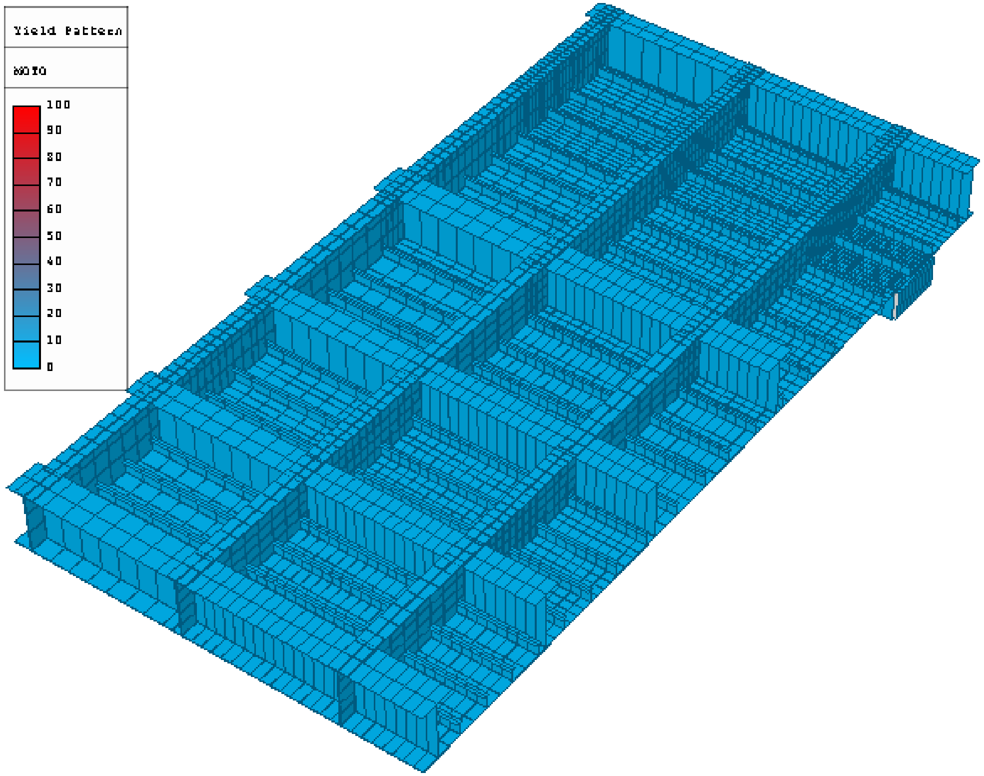
Reinforced structure

Global plastic failure mechanism

- Highlighted by the strain state (yielding)

- Apparition of successive plastic hinges in the girders

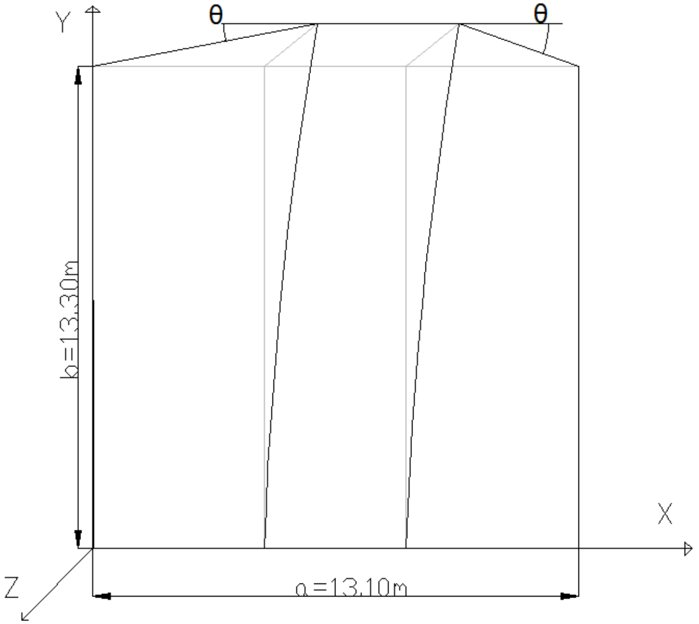




→ The capacity for energy dissipation of the lock gate is strongly related to the ductility of its frames and girders

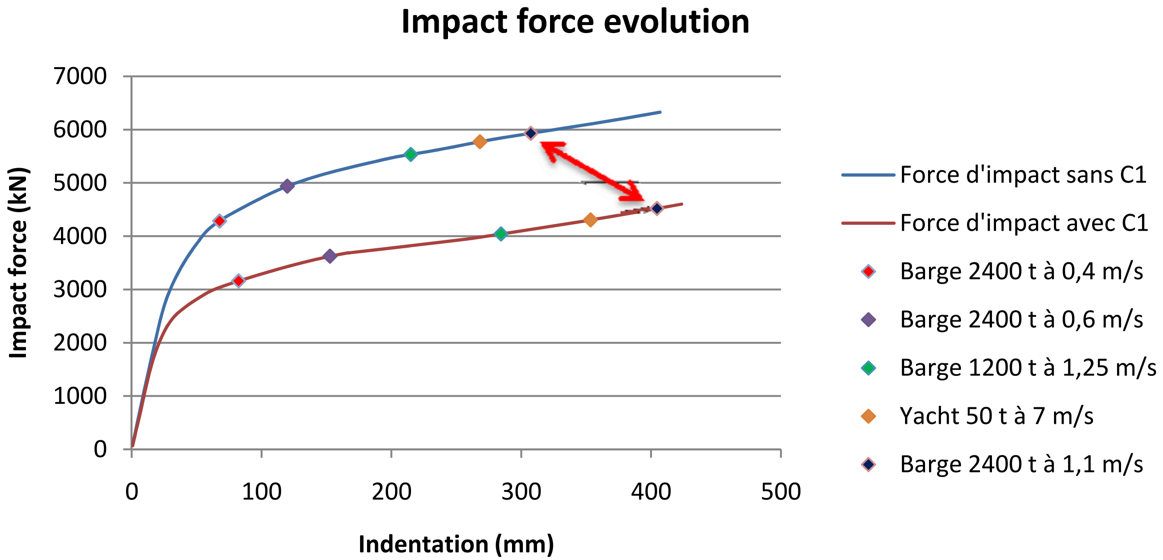
Global plastic failure mechanism

- 2 plastic hinges lines along the gate height
- This will allow us to calculate analytically an estimation of the gate strength



Simplified analytical representation of the global plastic failure mechanism

2nd scenario: impact at U.W.L. + hydrostatic load



The global behaviour of the gate is <u>identical</u> but the structure is previously submitted to a stress field

=> For a same impact (initial kinetic energy):

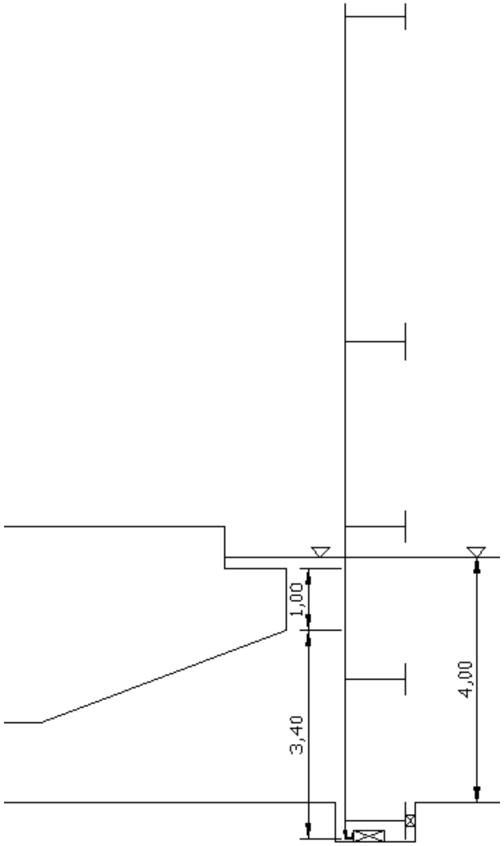
- Indentation ↗
- Impact force ↘
- Yielding in the structure ↗

3rd scenario: impact at D.W.L.

No additional hydrostatic load

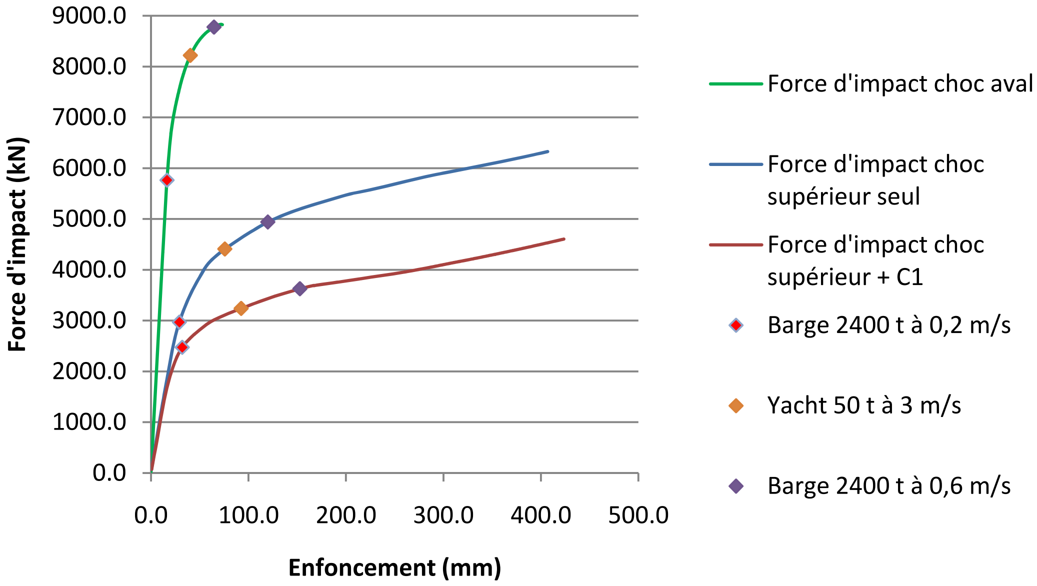
Allows analyzing the influence of the impact zone

Highly stiffened impact zone



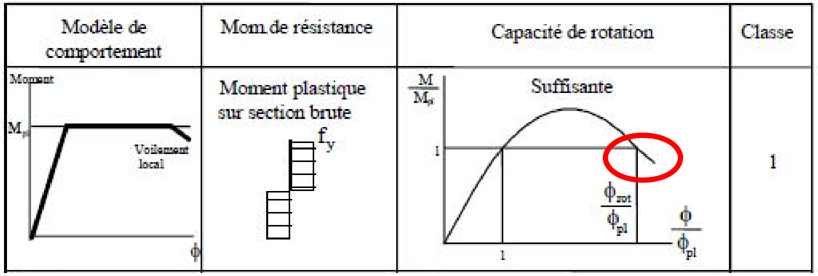
3rd scenario: impact at D.W.L.

- ✓ Fragile global behaviour
- ✓ For a same kinetic energy brought:
  - Impact force much higher
  - Deflection much lower
  - → stiffer behaviour
- ✓ Lower capacity for energy dissipation



3rd scenario: impact at D.W.L.

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



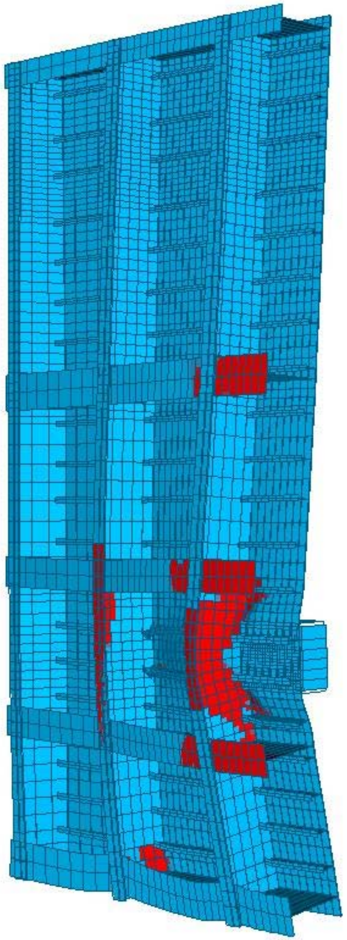
Modèle de comportement	Mom. de résistance	Capacité de rotation	Classe
	Moment plastique sur section brute	Suffisante	1

Transverse stiffness << Longitudinal stiffness

⇒ No propagation of yielding

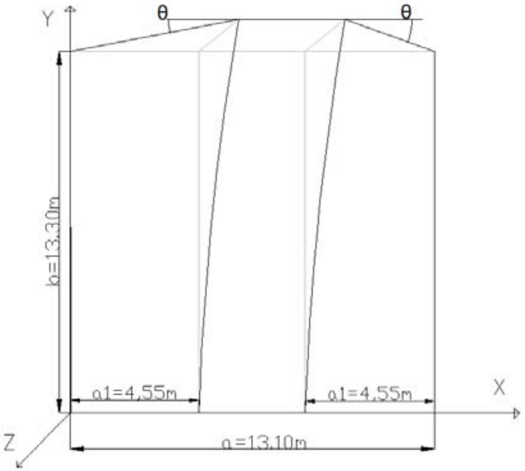
⇒ No global plastic failure mechanism

⇒ Collapse for a small indentation and low energy dissipation (0.5 MJ)



Analytical assessment of the impact strength (1st scenario)

- ✓ Global plastic failure mechanism highlighted by the FEM analysis
- ✓ Analytical method developed by Le Sourne et al. gives an estimation of the impact strength
- ✓ Bending energy rate along the two plastic hinge lines:



$$\dot{E}_b = 2\int_0^l \hat{M}_0 \times \dot{\theta}\, dl$$

$$\dot{E}_b = \frac{2}{a_1}\int_0^l \hat{M}_0 \times \dot{w}\, dl$$

- ✓ 2 unknows:
  - The fully plastic bending moment per unit length of the gate
  - The displacement field

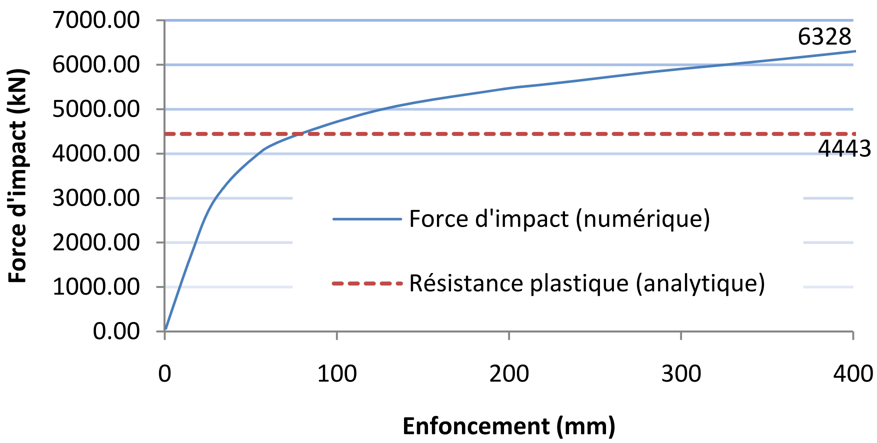
Analytical assessment of the impact strength (1st scenario)

Assumptions:

- Neglect the variation of the fully plastic moment per unit length along the plastic hinges
- Assume a linear displacement field

It holds:

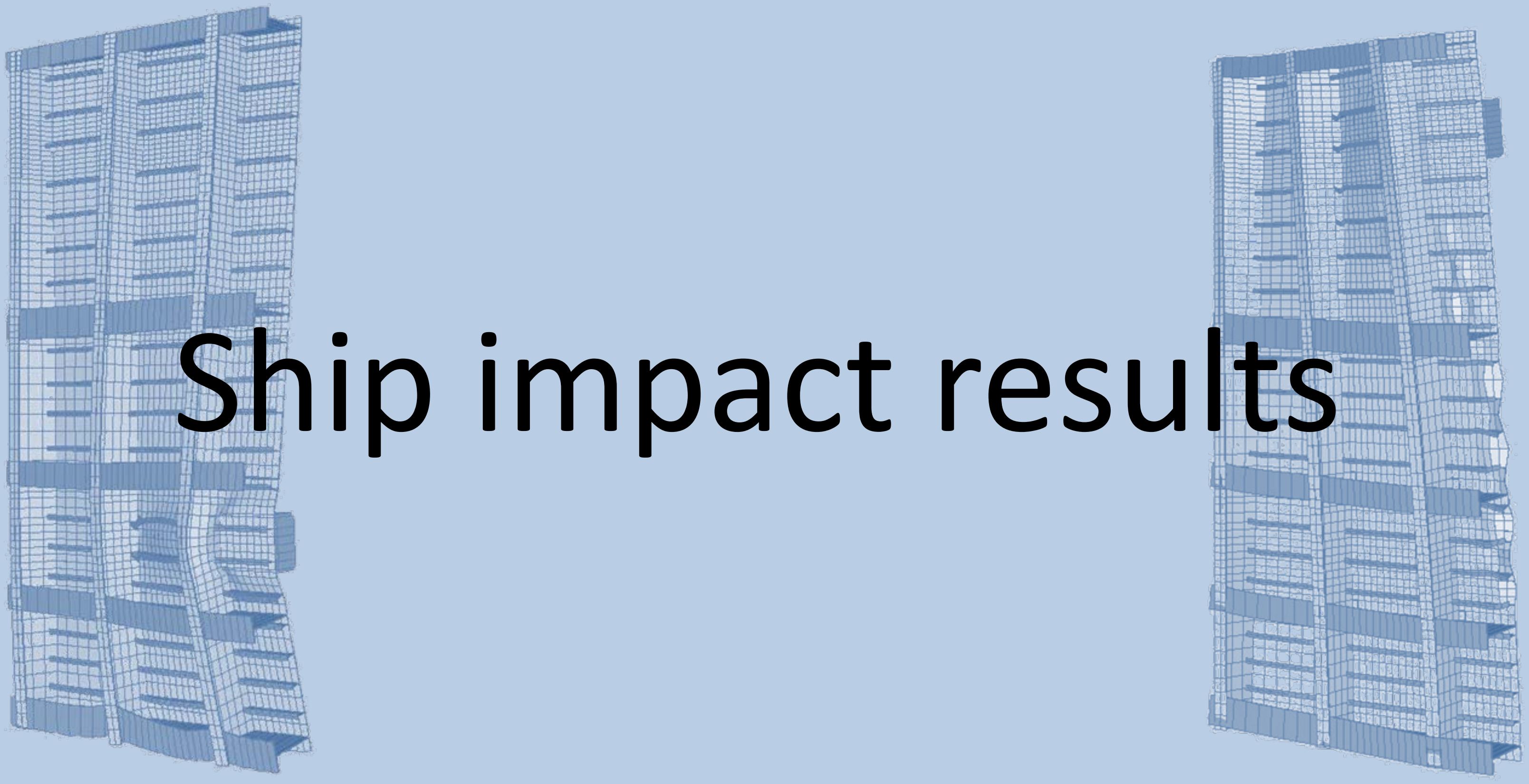
$$P_{gb} = \frac{M_p}{a_1}\frac{b}{h_{impact}} = 4\;443\;kN$$



Numerical analysis strength overtakes by 42 % analytical strength

New mode of strength (membrane)?
Effect of the assumptions and simplifications?

Ship impact results



Presentation of the results

1. Effect of a determined impact on the gate for the different studied cases

Impact of a 1,200 t barge at 0,8 m/s (384 kJ)	U.W.L. without hydrostatic load	U.W.L. with hydrostatic load	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

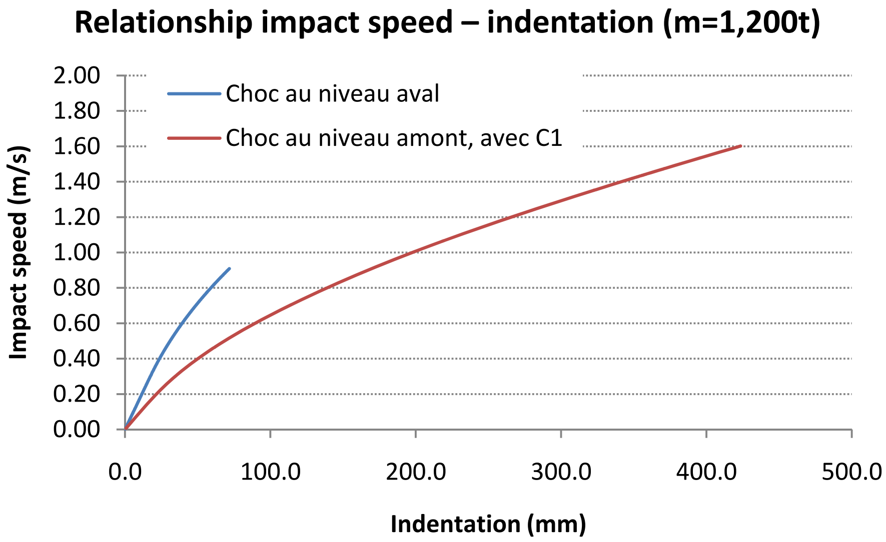
Presentation of the results

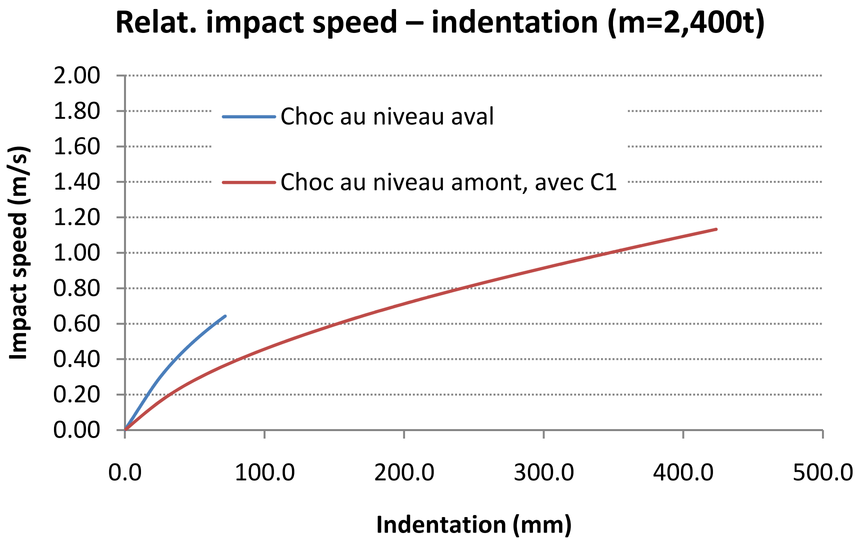
2. Maximum impact speed of a ship of determined weight for the different studied cases

Impact speed (m/s)		U.W.L. without hydr. load (2074 kJ)	U.W.L. with hydr. load (1538 kJ)	D.W.L. (495 kJ)
Yacht 50 t		9.11	7.84	4.45
Barge 600 t		2.63	2.26	1.28
Barge 1,200 t		1.86	1.60	0.91
Barge 2,400 t		1.31	1.13	0.64

Presentation of the results

3. Relationship between the impact speed and the indentation of a ship of determined weight for the different studied cases





Impact of a 1,200 t barge at 0,8 m/s (384 kJ)		U.W.L. without hydrostatic load	U.W.L. with hydrostatic load	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

Impact speed (m/s)		U.W.L. without hydr. load (2074 kJ)	U.W.L. with hydr. load (1538 kJ)	D.W.L. (495 kJ)
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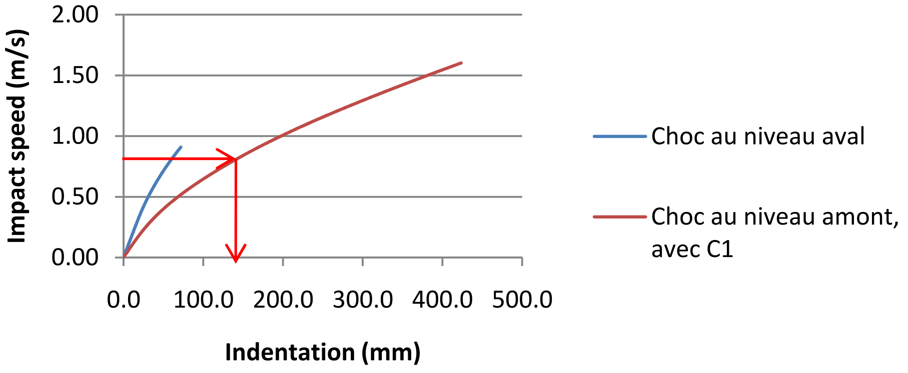
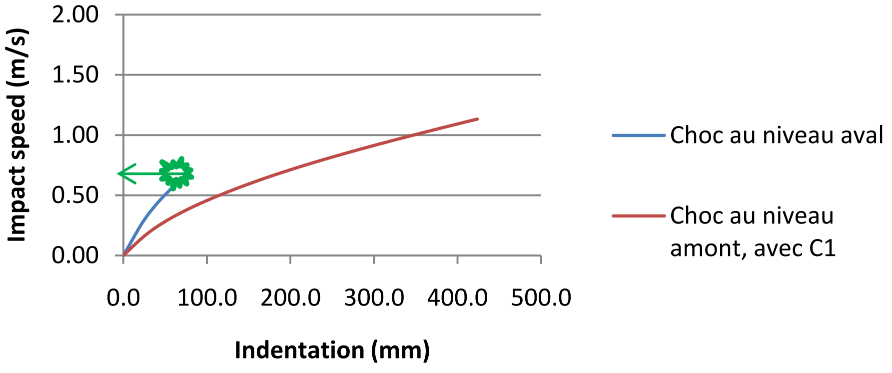
Relationship impact speed - indentation (m=1,200t)



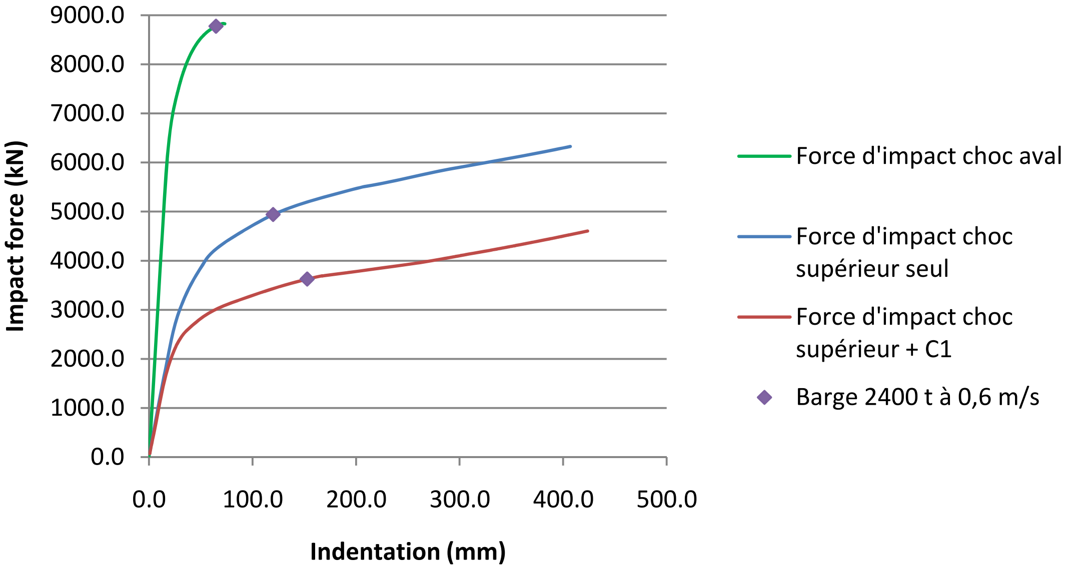
Relat. Impact speed - indentation (m=2,400t)

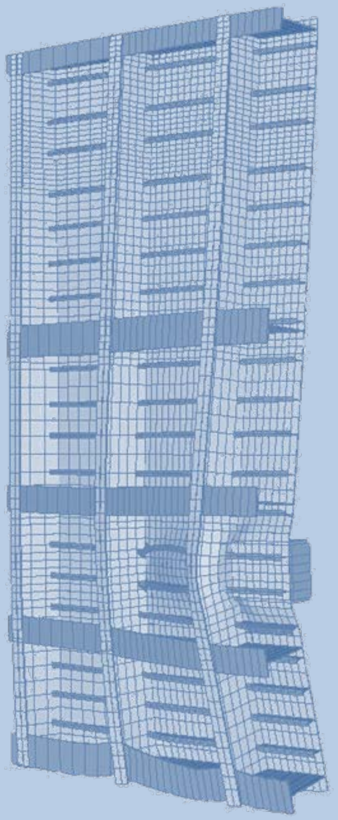


What did we learn from the analysis of the ship impact?

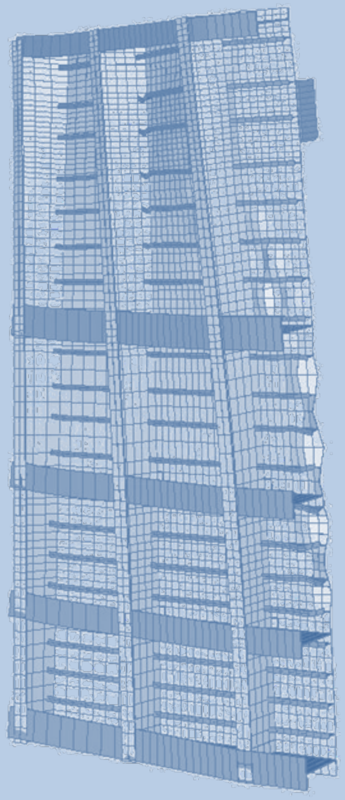
✓ To dissipate energy, it needs ductility => interest of the global plastic failure mechanism

- Ductility of the elements can be achieved by using class-1 cross sections
- 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

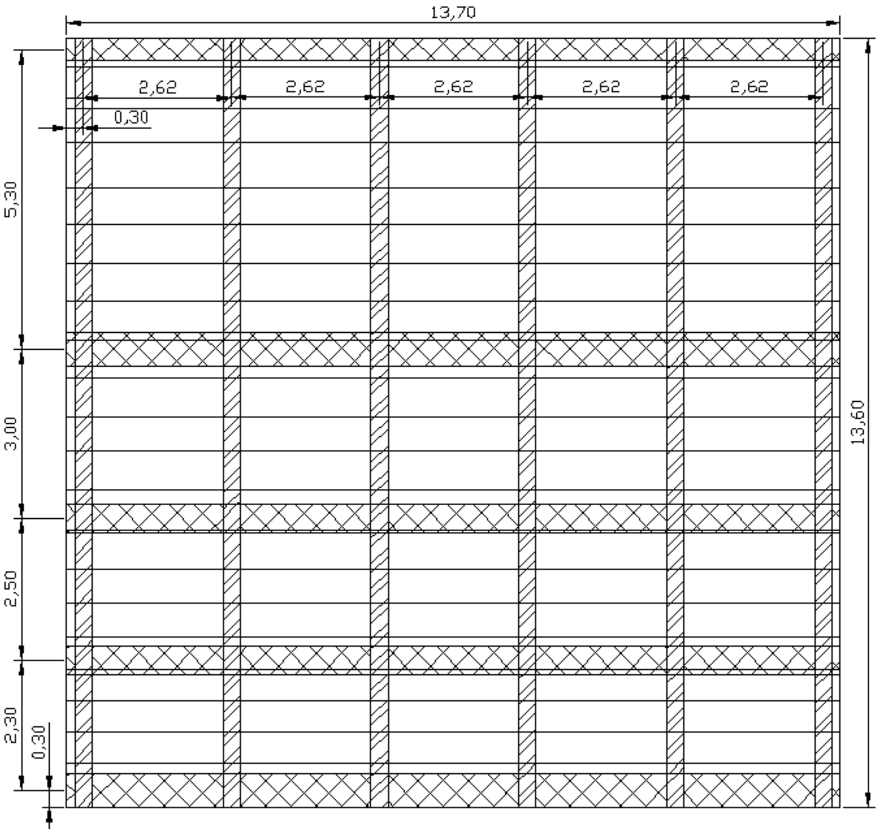


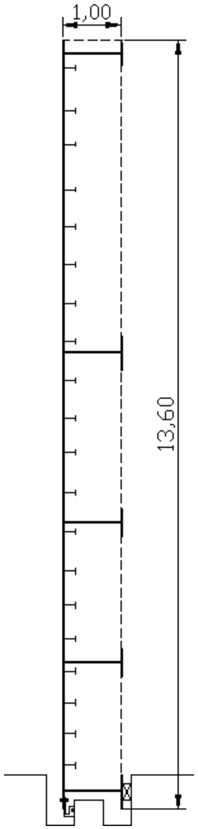


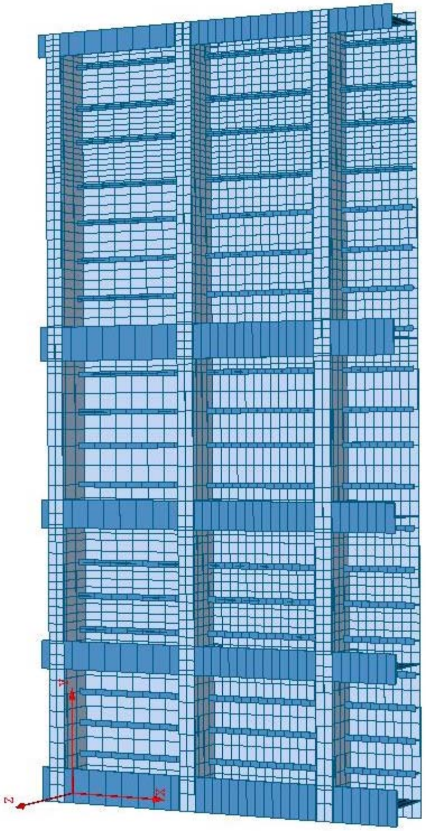
Conclusion



Design and Optimization







1° objective : design and optimization of the downstream lock gate

⇒ Elastic design considering hydrostatic load case

2° objective : ship impact analysis (gate = ship stopping device)

⇒ Analysis of 3 scenario highlighted the following:

- Interest of class-1 cross sections
- Influence of the impact zone (stiffness)
- Influence of the hydrostatic load (previous stress state)

⇒ Increase dimensions of frames and girders (weight +34%, cost +14%)

⇒ 2 kinds of global behavior: Fragile VS Ductile

Analysis of the final (reinforced) structure for hydrostatic loads

Loading	Service	Flood	Downstr. empty
Girders (MPa)	122	137	129
Stiffeners (MPa)	156	168	171
Frames (MPa)	107 – **112**	114 – **118**	120 – **126**
Plate (ép./ép. min)	1,07	1,02	1,05
Maximum deflection	1,50 cm – **1,79 cm**	1,69 cm – **2,00 cm**	1,58 cm – **1,90 cm**

LBR5 analysis of the reinforced structure **(bold = FINELG)**

- ✓ Stiffeners and plate still optimum (σ ≈ 175 MPa)
- ✓ Frames and girders are not optimized because reinforced (class-1) for impact

⇒ Iterative process: ship impact analysis – optimization

⇒ Or introduce new constraints in the optimization software to obtain optimized solutions considering impact strength

Ship impact: new constraints for optimization process?

Aim : dissipate energy => ductility

U.W.L. impact on the initially designed structure (classe 3)

FRAGILE

U.W.L. impact on reinforced structure (classe 1)

Ductile

U.W.L. impact on reinforced structure (classe 1), with hydrostatic load

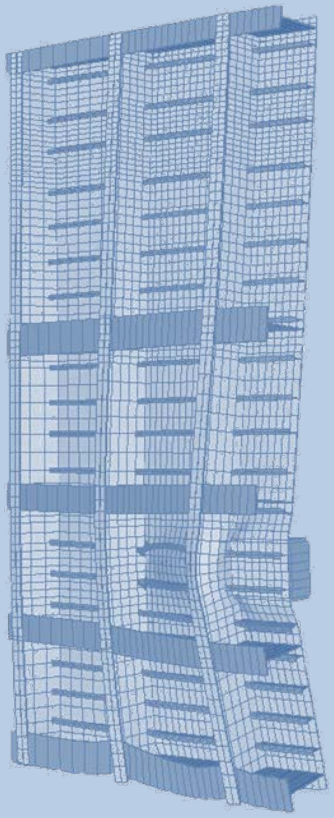
Ductile

D.W.L. impact on the reinforced structure (classe 1)

FRAGILE

⇒ Use class-1 cross sections
⇒ Good design of the stiffness ratios in the impact zones
⇒ … ? Maybe other criteria?

⇒ Finally, develop an optimization software integrating ship impact to be able to compare directly the optimized reinforced solution VS the optimized elastic solution coupled with protective measures against ship impact



Thank you