Nonlinear numerical analysis of ship impact on lock gates

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SUMMARY

This paper focuses on ship impact analysis on lock gate. First, the lock gate structure is determined by an elastic design and optimization process. Then, a nonlinear numerical analysis by finite elements is conducted to study the response of the lock gate in case of ship impact. It is shown that the elastically optimized structure is not able to resist significant impacts, because of the buckling of its reinforcement elements; the gate is thus reinforced. Finally, several ship impact analyses are conducted on the reinforced gate and they highlight the influence of the stiffener dimensions and the impact zone on the structural behavior of the gate. The results of the numerical analyses underline the importance of the development of a global plastic mechanism with the purpose of dissipating a large amount of energy.

KEY WORDS: lock gate, ship impact, nonlinear analysis, crashworthiness analysis

1. SEINE-ESCAUT EST

The case study is the downstream lock gate of the one of the four new locks planned within the framework of the "Seine-Escaut Est (SEE)" project in the Walloon Region of Belgium. SEE is an ambitious project with the purpose to connect the river basin of the Seine to the European waterway network towards Northern Europe and Central and Eastern Europe (Fig. 1). Within the framework of this project, the Walloon Region plans the upgrading of four locks on the sites of Obourg, Viesville, Marchienne-au-Pont and Gosselies. To take advantage of the standardization, identical downstream gates will be used on these four sites. The dimensions of the gates are 13.70 m length and 13.60 m height and it was decided to build suspended gates moved transversally to the lock.

2. DESIGN AND OPTIMIZATION OF THE GATE

First, an elastic design and optimization of the lock gate was performed using the LBR5 software developed by Rigo [Rigo, 1999]. Different design models of downstream gates were compared, varying by their width or other design choices such as the use of ballast tanks. To lead to the most interesting design, a multicriteria optimization was applied to each model, combining the cost and the weight of the gate structure. The structural calculations were based on elastic analysis considering the hydrostatic load cases. The risks of instability (buckling) of the stiffened elements (stiffeners, frames and girders) were taken into account by the definition of adequate slenderness ratio and the assessment of the ultimate capacity of the beam-column components. The risks of plate buckling were considered using the algorithm of Hugues [Hugues, 1983] that is integrated into the LBR5 software.

Fig. 1 : Seine-Escaut Est (SEE) connection

At the end of the design and optimization study, an optimum solution of the downstream gate was obtained (Fig. 2). The optimum gate is 1.0 m width (minimal value in order to place a footbridge) and has no ballast tanks. The total weight of the gate is 51.4 t and the production cost of the primary structure is estimated to 56,200 €.

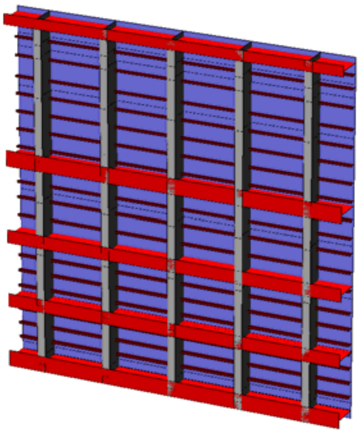

Fig. 2 : Optimum solution

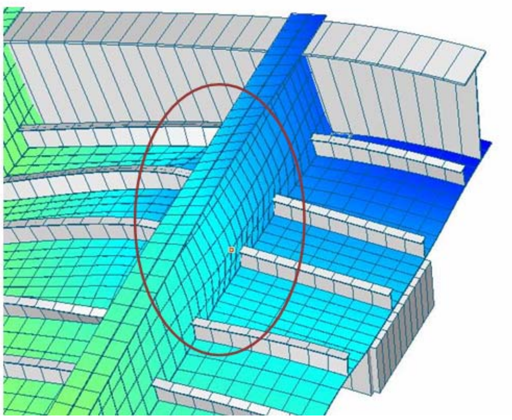

Fig. 3 : Buckling of the central frame

3. NONLINEAR NUMERICAL ANALYSIS OF SHIP IMPACT

The main objective of this paper is to present a ship impact analysis performed on a lock gate. At the beginning of a new project, a series of decision regarding the ship impact load case have to be taken. First of all, ship impact analyses require the definition of critical scenarios (location of the impact, weight and speed of the vessel …). 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 designers have to decide what kind of analysis to perform to design the gate structure.

In the present work, it was considered that the gate would have to resist the ship impact by itself. The aim was to determine the additional cost to reinforce the gate. The considered scenarios of impact are presented below. Finally, the method that has been chosen to perform the ship impact analysis is a quasi-static analysis by finite elements (dynamic effects are not taken into account).

3.1 Finite elements model and assumptions

The numerical analysis was performed using the nonlinear finite elements software FINELG [de Ville, 1994]. The analysis is based on the principle of energy equivalence, thus considering that the kinetic energy brought by the ship is converted into strain energy. An important assumption is that the totality of this strain energy is dissipated by the gate [Le Sourne & al., 2002]. The nonlinear behavior of the steel is assumed as elastic – perfectly plastic. In the numerical simulation, the impact is applied by increasing a uniform force on a perfectly rigid element that represents the ship bow. Three different scenarios of impact were studied: a., the ship impacts the gate at upstream water level (U.W.L.) but the hydrostatic loads are neglected; b., the ship impacts the gate at U.W.L. while the hydrostatic service loads are already applied to the gate; and c., the ship impacts the gate at downstream water level (D.W.L.).

3.2 U.W.L. impact with the initially optimized structure

The first scenario of impact applied on the elastically optimized structure leads to a fragile collapse of the gate for an impact energy of around 75 kJ, i.e. a 2,400 t ship at 0.25 m/s. The collapse arises suddenly by instability of the central frame (Fig. 3). It should be noted that the gate was elastically designed to resist to hydrostatic loads. Consequently, the slenderness ratios of the stiffened panels were adapted for structures working in the elastic field but they were not designed to take advantage of the plastic field. In order to increase the structure capacity for dissipating energy, it was decided to reinforce the primary reinforcement elements.

The Eurocode 3 defines several classes for steel cross sections, as a function of their ability to develop plasticity before that instability phenomenon occurs. In particular, class-1 sections are able to develop their fully plastic bending moment and sufficient rotation to allow for the development of a global plastic mechanism in the structure. For a structure potentially subjected to ship impact, class-1 sections could lead to more adapted behaviors compared to elastically designed sections.

3.3 U.W.L. impact with the reinforced structure

The thickness-height ratios of the sections of the frames and girders were increased to obtain class-1 sections according to the Eurocode classification. The observed behavior of the reinforced gate structure is very ductile compared to the behavior obtained with the initial structure (Fig. 4). Instability phenomenons are avoided and the gate is able to develop a global plastic failure mechanism, dissipating until 2 MJ. However, the total weight is gone up from 51.4 t to 68.7 t (+34%). Different impact levels are marked on the curves of Fig. 4.

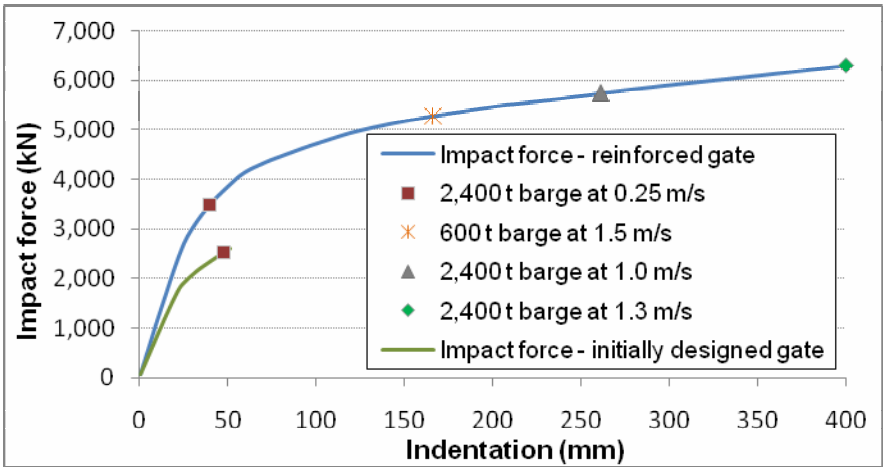

Fig. 4 : Impact force evolution for an upstream water level impact

The analysis of the strain state of the collapsed structure highlights the formation of a global plastic failure mechanism made of several plastic hinges, which strongly contrasts with the fragile failure of the initial structure (Fig. 5). The good ductility of the main girders is a key element to provide the structure with ductility.

When taking into account the hydrostatic load, the global behavior of the gate structure is identical but the structure is more deformable (Fig. 6), because the gate is already submitted to a stress field.

3.4 Impact on the downstream side of the gate

The study of the downstream side impact case allows for the analysis of the impact zone influence. Here, the ship hits the gate in a highly more stiffened zone than in the previous cases. Fig. 6 shows the impact force evolution for the three analyzed scenarios. The gate structure is more fragile for a downstream side impact compared with an upstream side impact. The impact force increases much more quickly and reaches significantly more important values while the indentation remains small. Finally, the collapse arises suddenly for an impact of energy in the order of 450 kJ.

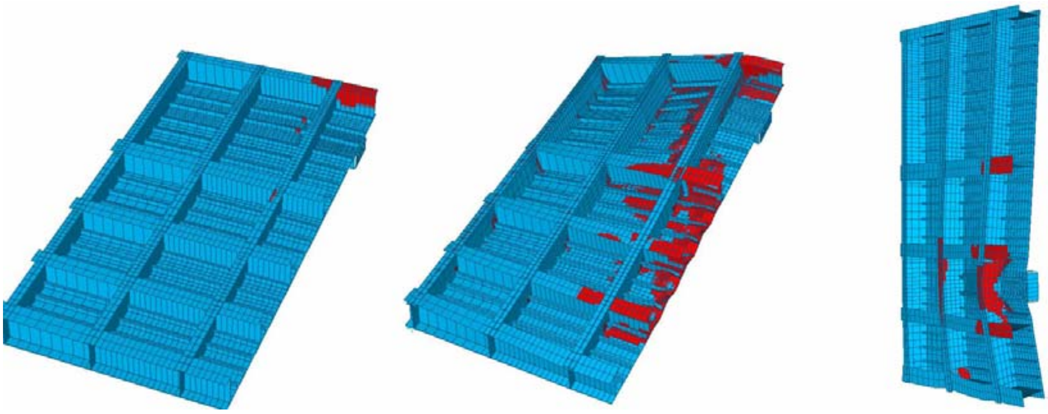

Fig. 5 : Yielding at the collapse stage for U.W.L. impacts on initially designed (left) and reinforced (center) structures and D.W.L. impact on reinforced structure (right)

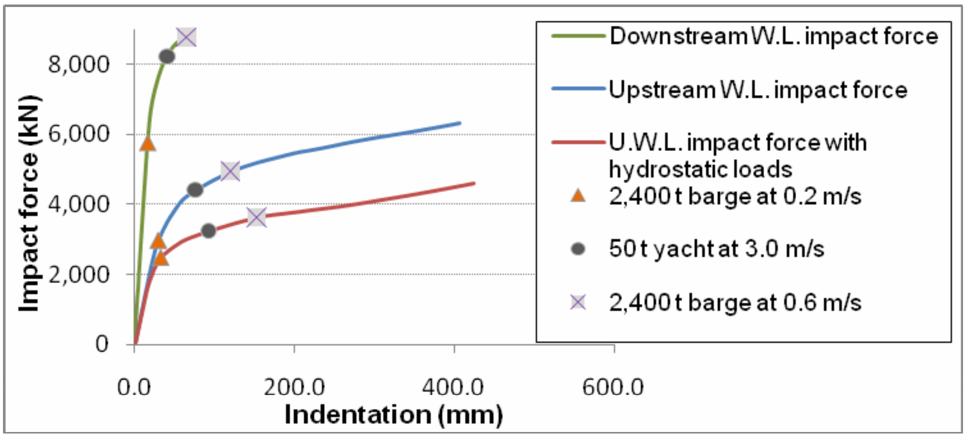

Fig. 6 : Impact force evolution for different impact cases

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 (Fig. 5). 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. Finally, the collapse arises by frame buckling at the level of the plastic hinge, because the rotation of this frame becomes too large.

4. CONCLUSION

The elastic design and optimization of a lock gate considering hydrostatic load cases, as performed in the first part of this work, is a current practice. However, the ship impact analysis has shown that the elastically designed lock gate was not able to resist to significant ship impact by itself. The behavior of the initially optimized gate was very fragile in case of ship impact. Further analyses have shown that the gate impact strength, which is related to the gate capability of absorbing strain energy, can be dramatically increased if a global plastic failure mechanism can develop in the gate that is subjected to ship impact.

The elastic optimization tools are not adapted for the design of a structure that has to take advantage of the plastic field: additional constraints have to be included in these tools in order to provide gate structures with good impact strength. For instance, the present analysis has brought the author to increase the dimensions of the frames and the girders of the optimum solution to obtain class-1 cross sections, which has been proved to provide ductility to the gate elements. It has also been found that the ductility of the structure requires a good propagation of yielding from the potential impact zones to the rest of the gate. In the future, it would be interesting to realize a research focusing on the constraints to fulfill, from the design and optimization stage, in order to provide the gate structure with ductile behavior. It would permit to obtain optimized solutions considering impact strength. Then, this solution should be compared in terms of cost with the elastic optimum solution coupled with protective measures against ship impact.

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REFERENCES

EUROCODE 3 – Design and construction of steel structures – Part 1.1: General rules and rules for buildings, EN 1993-1-1, CEN, Brussels, 2005.

GERNAY T., *"Optimization and analysis of lock gates in the framework of the 'Seine-Escaut Est' waterway upgrading"*, in *PIANC Magazine 'On Course'*, n°141, pp. 11-26, October 2010.

HUGUES O.F., "*Ship structural design: A rationally-based, computer-aided optimization approach*", John Wiley & Sons, Inc., 566p., 1983.

LE SOURNE H., RODET J.-C., CLANET C.: "*Crashworthiness analysis of a lock gate impacted by two river ships*", in *Int. Journal of Crashworthiness*, Vol. 7 (4), pp. 371-396, 2002.

RIGO P., "*Least Cost Optimum Design of Stiffened Hydraulic and Floating Structures*", in *PIANC Magazine "On Course"*, n°101, pp. 33-45, April 1999.

de VILLE de GOYET V., "*FINELg, an advanced analysis and research program*", in 1994 Task Group, *SSRC – Link between research and practice, 50th Anniversary conference, Lehigh University, Bethleem,* Pennsylvania (USA), June 1994.

www.Seine-Nord-Europe.com