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An efficient approach for ship collision design of reinforced concrete pontoon walls

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Abstract. This paper presents an efficient method for collision design of prestressed concrete pontoon walls. High fidelity finite element models of a container ship bow and a prestressed concrete pontoon wall are first established. Integrated numerical simulations are conducted to study the structural deformation of the pontoon wall during the collision. Parametric studies are also carried out to investigate the effect of the pontoon wall thickness. Based on the failure mode of the pontoon wall, a punching shear check procedure is proposed. This method yields a good accuracy while significantly reduces computational efforts. Hence, the proposed approach can be used for collision analysis in the preliminary design phase of floating pontoons.

1. Introduction

The Norwegian Public Roads Administration is planning to build a highway along the west coast of Norway. New installations must be constructed to cross the wide and deep fjords along the route. Convectional structures with fixed foundations cannot be constructed and novel floating bridges should be designed and constructed alternatively [1-4]. For floating bridges, one of the main concerns is the pontoon safety against accidental ship collisions. Ship collisions may result in structural damage in the pontoon wall and subsequent flooding in the pontoon compartments [5, 6]. Further, progressive collapse of the bridge may also occur due to the excessive flooding in the pontoon.

Floating support mudules, i.e. pontoons, pylons, platforms, are commonly constructed with reinforced concrete or steel material. Compared with steel floating foundations, reinforced concrete floaters are easier to construct and the cost is also generally lower. Therefore, reinforced concrete structures are widely used to construct large scale floating structures. However, normal strength concrete floating structures are vulnerable to accidental ship bow collisions. High strength ship bows may induce excessive punching shear damage in the concrete structures [6]. Consequently, progressive collapse may occur to the whole floating structure if the floating unit is flooded. Therefore, it is important to design the floating concrete units against accidental ship collisions.

Three approaches are generally used for ship collision analysis and design of concrete structures. Experimental tests are the most direct approach for obtaining the collision force and structural damage during a collision [7]. However, this method is seldom conducted due to site limitations and cost.

Another approach which is widely used for ship collision is numerical analysis. Reliable results can be obtained with validated numerical models [8-10]. Numerical analysis, however, requires significant modelling and simulation efforts. Hence, it is not suitable for practical use in the preliminary design phase. Validated analytical method can provide efficient and accurate results and thus can be used efficiently in practical engineering practice [11, 12].

This paper aims to investigate the ship collision response of RC pontoon walls and propose simple but reliable design check procedures for both structures. In this work, high fidelity finite element models of an RC pontoon wall and a container ship bow are first established. The impact demand and failure mode are identified for RC pontoon walls, respectively. Based on the failure mode of the pontoon walls, a simple design check procedure, which can be used in the preliminary design phase, is proposed for RC pontoon walls.

2. Finite element models

In this study, finite element models of a reinforced concrete pontoon wall and a container ship bow are established based on the structural drawings for numerical collision analyses.

2.1. Pontoon wall model

The pontoon model is established for a cable-stayed continuous floating bridge as shown in Figure 1 [13]. The cable-stayed navigation span in the middle is supported by two towers resting on two main pontoons. These two pontoons are particularly exposed to the passing ships. Hence, the two main pontoons have a higher possibility of subjecting to accidental ship collisions compared to other side pontoons. In addition, they are essential supporting structures regarding the overall stability of the whole bridge. Hence, the focus is placed on the collision analysis of the main pontoons in this study.

Figure 1. Rendering of the floating bridge concept.

The main pontoons are divided into sub-compartments so that the damage of one or two compartments shall not lead to overall flooding of the pontoon. A finite element model of the pontoon was developed based on this prototype. It should be noted that only the front wall of the first middle compartment was modelled in detail as shown in Figure 2. This is because developing the whole pontoon model requires extensive modelling efforts and the computational time would be excessive. It is not necessary to model the whole pontoon for a local ship collision analysis as most of the structure is far away from the impact region and is thus not expected to have any influence on the local collision response of the front wall [6]. The pontoon-supported bridge load was not included in the analysis as the collision duration is very short compared to the natural frequency of the bridge. Therefore, a ship collision accident can be considered as a transient process and thus the loads can be ignored for local collision analysis. The load effects from the construction and fabrication stage were also neglected.

To accurately model the RC pontoon wall, a detailed modelling was applied to the concrete, reinforcements and prestressing tendons in the pontoon as shown in Figure 2. The concrete part in the pontoon wall was modelled with 8-node solid elements while the reinforcements and tendons were all modelled by circular beam elements. The reinforcements are embedded inside the concrete cover of the pontoon wall. The prestress in the concrete was introduced by tendons made by strands of high strength steel wires. The height, width and thickness of the pontoon wall are 20 m, 13.3 m and 0.9 m, respectively. The diameter of the rebar and the stirrup is 15 mm and 8 mm respectively, while the vertical and transverse tendons have a diameter of 90 mm and 70 mm respectively. A detailed description of the structural modelling including prestressing modelling can be found in Sha and Amdahl [6].

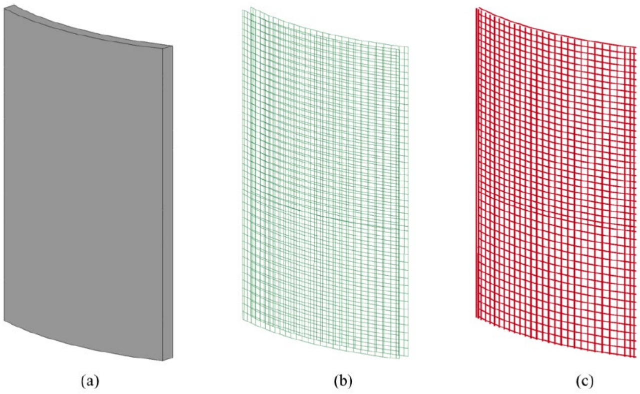

Figure 2. Finite element model of the pontoon wall portion, (a) concrete, (b) rebar and stirrups, and (c) prestressed tendons [6].

2.2. Ship bow model

According to the statistical and risk analysis of passing ships, the design ship is selected as a 20,000-ton container ship. The ship bow model as shown in Figure 3 is developed based on the actual structural drawing. This ship has an overall length of 166.62 m and a moulded breadth of 27.4 m. The depth and the scantling draught of the ship are 13.2 m and 9.6 m, respectively. In this work, the first 20 meters of the ship bow structures are modelled. The various decks, stringers and transverse frames are modelled in addition to the outer shell panels. The vertical stiffeners have a spacing of 0.6 m. The thickness of the steel components in the ship bow varies from 7.5 mm to 20.5 mm.

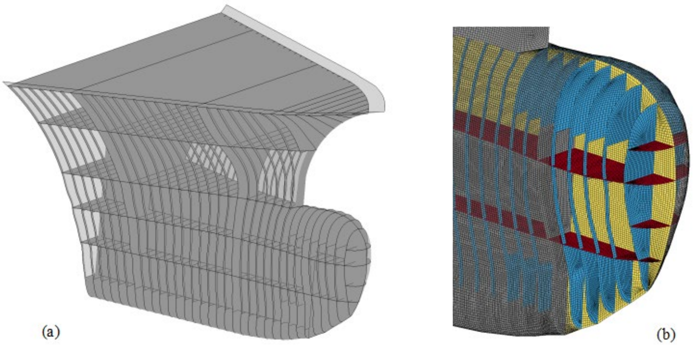

Figure 3. (a) FE model of the ship bow and (b) structural mesh.

2.3. Material modelling

The extended Karagozian & Case Rel3 (MAT_72Rel3) material model was used for the concrete in the pontoon [5]. This material model has been widely employed to model the dynamic behaviour of concrete including plasticity and damage softening after failure. This material model can automatically generate stress and strain parameter by only specifying the compressive stress. Therefore, no stress-strain curve is required for the concrete material. The model has been proven yielding reliable numerical simulations of concrete material damage to shock and impact loads. For the concrete in the pontoon wall, compressive strength of 60 MPa is used. Concrete failure is considered by utilizing the erosion algorithm MAT_ADD_EROSION with a failure strain of 0.1 [14].

The material model MAT_PIECEWISE_LINEAR_PLASTICITY was employed for the steel reinforcements and tendons. The reinforcements are made of normal mild steel while the tendons are made by high strength steel strands. A user-defined power-law hardening material model was for the steel in the ship bow which has a characteristic strength of 275 MPa. The stress-strain curve of the steel used for the ship bow is shown in Figure 4. Detailed parameters for all materials are listed in Table 1.

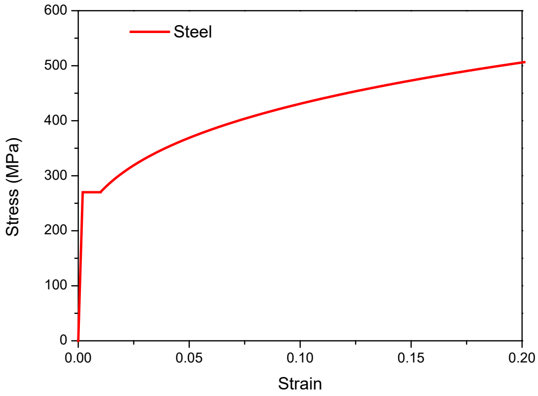

Figure 4. Stress-strain curve of the steel in the ship bow

Table 1: Parameters of concrete and steel materials.

Materials	Items	Values
Concrete	Density	2400 kg/m^3
	Poisson’s ratio	0.2
	Compressive strength	60 MPa
	Failure strain	0.1
Steel (Reinforcements)	Density	7850 kg/m^3
	Poisson’s ratio	0.3
	Young’s modulus	2.1E11
	Yield stress	275 MPa
	Failure strain	0.35
Steel (Tendons)	Density	7850 kg/m^3
	Poisson’s ratio	0.3
	Young’s modulus	2.1E11
	Yield stress	1860 MPa
	Failure strain	0.35
Steel (Ship bow)	Density	7890 kg/m^3
	Young’s modulus	210 GPa
	Poisson’s ratio	0.3
	Yield stress	275 MPa
	Strength index	740 MPa
	Strain index	0.24

3. Numerical results

3.1. Impact force and structural damage

In the simulation, the ship bow collided with the pontoon walls at a constant speed of 10 m/s. All nodes at the four edges of the pontoon wall were fixed in all degrees of freedom.

As shown in Figure 5, the impact force increases from zero until 35 MN at 0.7 m ship displacement due to the crushing of the ship bow. Later, the general force level is between 30 MN and 40 MN due to the gradual engage and damage of internal bow frames and decks. The RC wall with a thickness of 0.9 m can resist the bulb impact with very limited spalling damages on the surface. Major damage occurs in the ship bulb, which dominates the energy dissipation as shown in Figure 6.

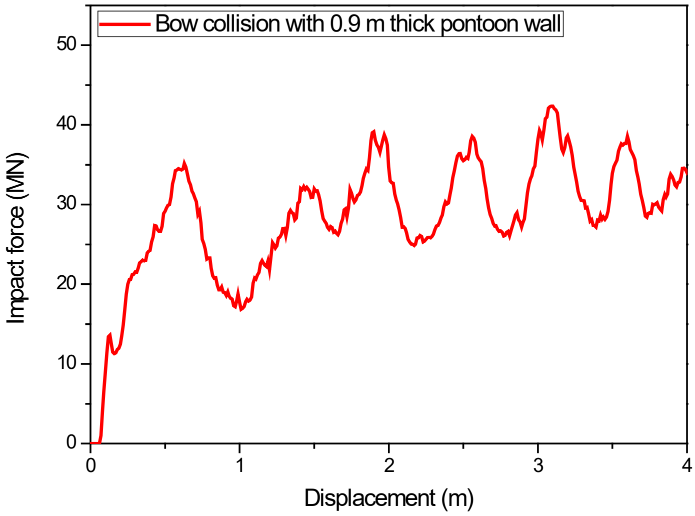

Figure 5. Force-displacement curves for ship bow collision with the 0.9 m thick pontoon wall.

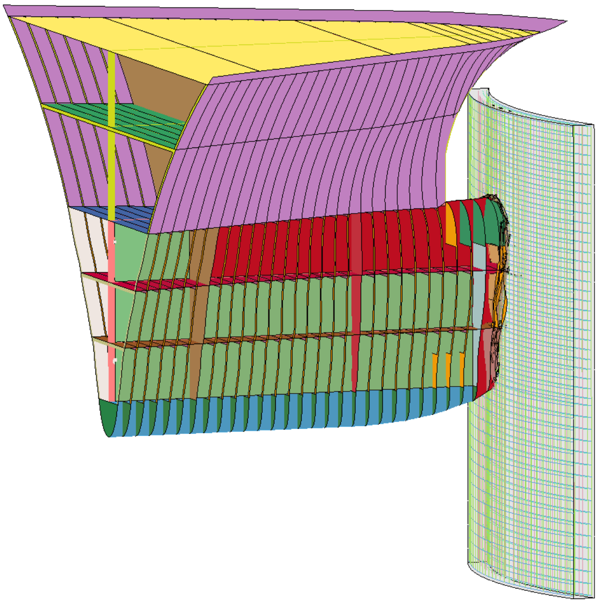

Figure 6. Structural damage for ship bow collision with the 0.9 m thick pontoon wall.

3.2. Effect of pontoon wall thickness

Further, it is interesting to analyze how the pontoon wall thickness affects the collision response of the pontoon wall and the ship bow. Numerical simulations are conducted for pontoon walls with smaller thicknesses of 0.7 m and 0.8 m.

Figure 7 shows that both the 0.7 m and 0.8 m thick pontoon walls are unable to resist the impact of the ship bow. The punching damage of the pontoon wall is associated with a sudden drop in the resistance. A thinner wall fails earlier and results in a lower energy absorption ability. The energy dissipated for 0.8 m thick wall is about 60 MJ while only 18 MJ collision energy is dissipated for the 0.7 m thick wall as shown in Figure 7 (b). This shows that the structural damage is very sensitive to the relative strength of the ship bulb and the pontoon wall. The major deformation switches from the ship to the pontoon when the wall thickness is reduced from 0.9 m to 0.8 m or less.

Figure 8 shows the side views of the 0.7 m thick pontoon at various ship displacements. It is obvious that the bulb collision-induced damage is concentrated at the impacted area. A localized punching shear failure can be observed around the impacted region. Similar damage mode is also observed for the 0.8 m thick pontoon wall.

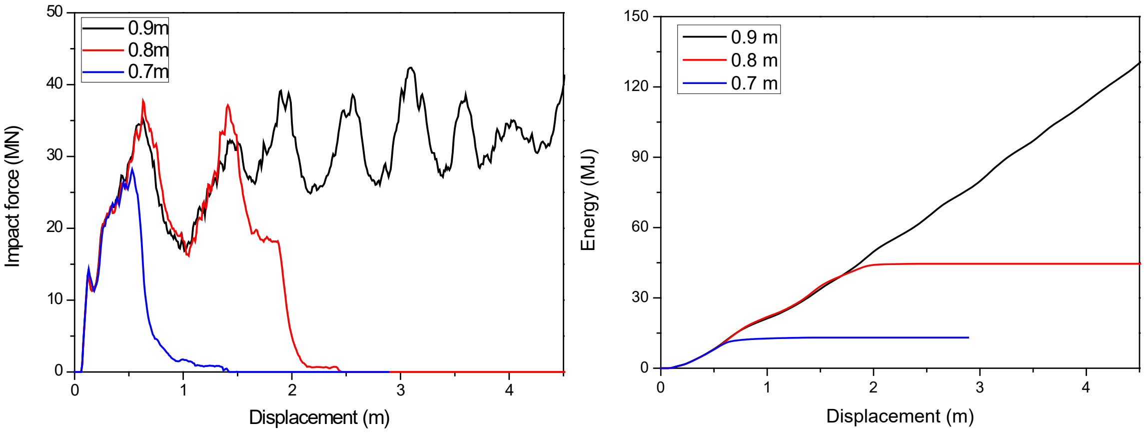

Figure 7. (a) Force-displacement curves and (b) energy dissipation curves for RC walls with different thickness.

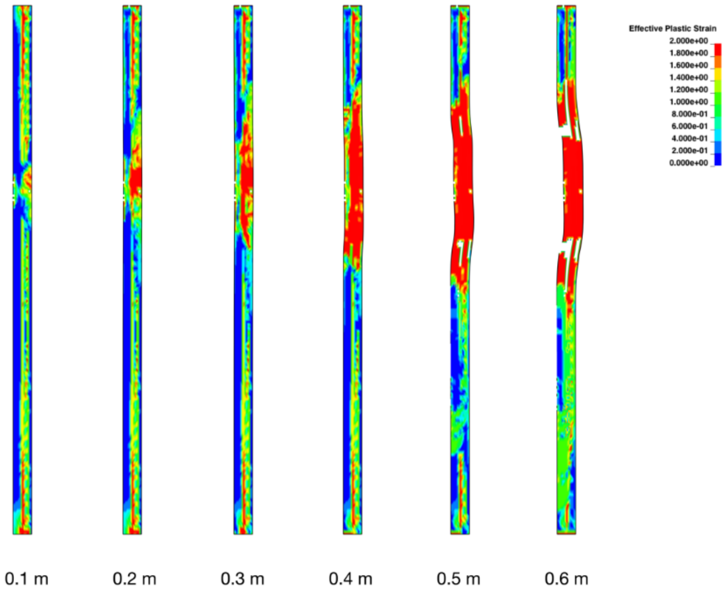

Figure 8. Side view of the strain profiles for the 0.7 m RC wall at various ship displacement.

4. Simplified method

In the preliminary bridge design phase, it is often difficult to conduct detailed numerical analyses with high-resolution FE models. It is more desirable that simplified design approaches can be used in the early design phase. In this paper, a design procedure, which can be used for punching shear failure prediction of concrete pontoon walls subjected to ship bulb collisions, is proposed.

For punching shear design of concrete slabs, it is reported [15] that the critical shear crack theory (CSCT) proposed by Muttoni [16] which includes the size effect, yields better results than the design codes ACI 318-14 [17] and Eurocode 2 [18]. Consequently, the CSCT method is used to predict the punching shear capacity of pontoon walls against ship bulb collisions in this study.

In the CSCT method, the punching shear capacity is determined as the intersection between the failure criterion and the load-rotation curve. The failure criterion is defined by a relationship between the punching shear capacity (V_C) of a slab and the rotation (ψ) of the slab. The shear demand is expressed by the impact load (V_d) - slab rotation curve. A semi-empirical failure criterion which relates the punching shear capacity to the rotation of the structure was proposed by Muttoni [9] as

$$V_C = \frac{3/4}{1+15\dfrac{\psi d}{d_{g0}+d_g}} \cdot u_0 d\sqrt{f_c} \tag{1}$$

where u_0 is the perimeter of the critical section for punching shear and d is the effective depth of the wall. f_c is the average cylinder compressive strength of concrete. $\frac{d}{d_{g0}+d_g}$ is a size coefficient that accounts for the wall thickness and aggregate size. d_g is the maximum aggregate size and d_{g0} is a reference size equal to 16 mm. For a pontoon wall structure, it is recommended to take the maximum aggregate size d_g no larger than one-third of the effective depth d [19].

The load-rotation relationship can be simplified by assuming a parabola with a 3/2 exponent for the rotation as a function of the load-flexural strength ratio $\frac{V_d}{V_{flex}}$. The flexural strength V_{flex} is equal to $8m_d$, where m_d is the yield moment of the slab. The load-rotation relationship can be obtained by

$$\psi = 0.33\frac{L}{d}\frac{f_s}{E_s}\left(\frac{V_d}{8m_{Rd}}\right)^{3/2} \tag{2}$$

where L is the main span of the slab. f_s and E_s are the yield strength and modulus of elasticity of the reinforcements.

The failure criteria of the RC walls with 0.7 m, 0.8 m, and 0.9 m calculated with Eq. (1) while the load-rotation relationships are obtained from Eq. (2). The punching shear capacity can be readily obtained as the intersections of the failure criteria and the load-rotation curves. Here, we obtain a punching shear capacity at the intersections of 33 MN, 44 MN, and 59 MN for the 0.7 m, 0.8 m, and 0.9 m thick pontoon wall, respectively.

The obtained punching shear capacity of the three RC pontoon walls are compared with the ship bulb strength as shown in Figure 9. It can be observed the punching shear capacities of 0.7 m and 0.8 m thick pontoon walls are smaller than the maximum ship bulb strength. The 0.9 m thick RC pontoon wall, however, has a sufficient capacity compared with the ship bulb strength. The predictions are in line with the numerical observations where punching shear failure occurs in the 0.8 m and 0.7 m thick pontoon walls while the 0.9 m thick pontoon wall remains intact.

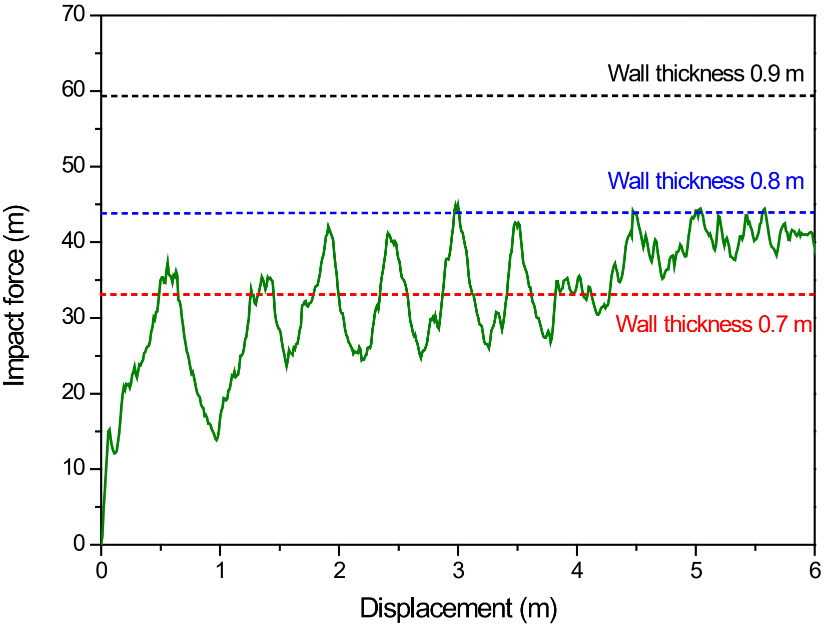

Figure 9. Comparison of impact demand and punching shear capacity for the RC pontoon walls.

5. Conclusions

The findings of the current study are summarized as follows:

1. The 0.9 m thick RC pontoon wall can resist the bow impact of the 20,000-ton container ship. Severe damage occurs in the ship bow which dissipates the majority of the collision energy. The pontoon wall, however, has very limited damage and can maintain its integrity after the collision.
2. Further reducing the pontoon wall thickness to 0.8 m or 0.7 m will result in a punching shear failure in the pontoon wall under the collision from the same container ship bow. The ship bow has a small local deformation upon contact.
3. A design check procedure that can be used for design RC pontoon walls against ship bulb collisions is proposed. The impact force and damage initiation obtained from the design check procedure agree well with the numerical results. This indicates that the proposed analytical punching shear failure model captures the essential physical effects of the collisions.

Acknowledgements

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