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Research on the bending efficiency of superstructure to hull girder strength of inland passenger ship

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ABSTRACT

The superstructure of passenger ship becomes more and more plump to satisfy the requirement of different functional area and comfortable space. Therefore, the research on the bending efficiency of superstructure to hull girder strength of the passenger ship is paid more attention. In the present paper, an inland passenger ship is taken into account. The interaction of main hull and superstructure is analyzed based on the two-beam theory. The bending efficiency of superstructure is investigated and discussed which can provide technical supporting to the structural design of the superstructure of passenger ship.

1. Background

Compared to the early passenger ship considered only as a means of transportation, nowadays the modern passenger ship is more likely to serve as a resort on the sea to provide accommodation, leisure, entertainment and other services for passengers. In order to enrich and satisfy the diversified needs of passengers, the passenger ship is developing towards the large-scale and multi-functionalization.

With the great economic benefit of the plump superstructure, it also puts forward higher requirements for the ship's navigational performance and structural strength design. The lightweight design of superstructure is performed under the premise of structural safety and reliability. Therefore, the weight of ship structure can be reduced and the center of gravity will be lower as well. The superstructure bending efficiency which reflects the degree of the superstructure participating in the longitudinal bending is different with various tiers due to the stiffness difference between the main hull and the superstructure of passenger ship. By investigating the bending efficiency of superstructure and corresponding influence factors, the structural design of superstructure can be conducted more rationally and effectively which is important for the design of passenger ship.

For the time being, the bending efficiency of superstructure can be investigated by the direct calculation method and finite element method. The direct calculation method is mainly applied to the hull structural design, including the linear calculation, the empirical formula, the analytical method, and so on. The linear calculation is simple and widely used in the initial stage to estimate the structural stress level. However, the error becomes larger when the stress distribution of the section is not linear any longer. The empirical formula is achieved by fitting amount of collection data so that it shows high precision for the ship types covered in the database. The analytical method is proposed by simplifying the interaction behaviour between the main hull and superstructure. The bending efficiency of superstructure is deduced by the structural stress distribution. The existing analysis method is normally based on different beam theory such as the composite beam theory proposed by Crawford (1950), the column beam theory proposed by Bleich (1952), the two-beam theory proposed by Schade (1965) and the couple beam theory proposed by Naar et al. (2004). For the superstructure of inland passenger ship, its structural type is different from normal transportation ships. There are continuous opening in the side shell and larger size opening in the deck which are not considered in the mentioned methods. So, it is necessary to perform systematic comprehensive research on the superstructure bending efficiency of inland passenger ship.

It is noted there are vertical force and horizontal force in the conjunction of main hull and superstructure. Andric (2007) performed the research on the physics of the main hull and superstructure interaction. Furthermore, methodology in the concept design phase for structural design is proposed. Crawford and Ruby (1955) verified the column beam theory and formula proposed by Bleich (1952) through the

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model test on nine models. Heder and Ulfvarson (1991) proposed a numerical modeling method for side shell openings. The method was verified by the comparison of numerical results and full scale measurements. Fricke and Gerlach (2015) investigated the decrease of shear stiffness due to large window openings and proposed the numerical method to simulate such behaviour. Andri and Ani (2010) researched the hull girder stress distribution along height direction considering the effect of side shell opening. Collapse analysis of a cruise ship (Yao et al., 2006) is carried out considering the effect of side shell opening and recess for lifeboats. The bending efficiency of each deck is calculated by the ratio of FEM results to those obtained by linear theory. Chen (2011) had investigated the participation degree to longitudinal bending of aluminum alloy superstructure. FEM analysis is performed by Zou (2013) to get the stress distribution of typical section of an inland passenger ship. The bending efficiency of each tier of superstructure is calculated and compared with that defined by rules.

In the present paper, the interaction of main hull and superstructure of an inland passenger ship is investigated according to the two-beam theory and finite element method. The participation of superstructure to longitudinal bending is discussed and the influence of the superstructure length and width, the ratio of deck opening and the opening ratio of side shell is discussed. The FEM results are introduced to correct the traditional two-beam theory which can reflect the bending character of superstructure. The research is meaningful for the structural safety and reliability and the lightweight design of superstructure.

2. Superstructural bending efficiency

2.1. Definition

Superstructural bending efficiency reflects the participating degree to the longitudinal bending which is significant to the structural lightweight design on the premise of safety and reliability. The exact definition of the bending efficiency is different in view of different researcher's opinion (Evans, 1983). It is common to define the change of the stress in superstructure as bending efficiency.

$$\nu = \frac{\sigma_1'}{\sigma_1} \tag{1}$$

where σ_1' is the actual normal stress at the position of superstructure neutral axis and σ_1 is the normal stress at the same point assuming that the superstructure is totally effective. Actually, a typical section is usually determined firstly to research the bending efficiency of each tier superstructure.

2.2. Two-beam theory

It is well known there is interaction between the main hull and superstructure. Assuming that the ship hull is in hogging condition in the wave, the upper deck shall be in tension situation due to the longitudinal bending of main hull. The stretch of upper deck is constrained by the lower edge of the superstructure because they are interconnected. At the same time, the lower edge of the superstructure is also be stretched by upper deck. This interaction can be expressed by the horizontal shear force, as shown in Fig. 1.

The deformation of superstructure is opposite to the main hull due to the effect of horizontal shear force. Such phenomenon is obvious for the section which is near the end of superstructure. It is so-called "End effect of superstructure". The superstructure is connected to the main hull so that there is a set of equal value and opposite direction vertical distributed forces to resist the separation, as shown in Fig. 1.

A typical section which is x-distance from the aft end section of superstructure is selected to be analyzed the subjected force and moment, as shown in Fig. 2.

The equilibrium equations of longitudinal force and moment on the neutral axis can be described as,

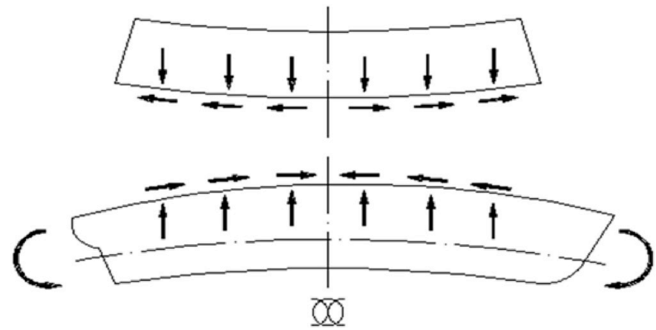

Fig. 1. The interaction of main hull and superstructure.

$$A_1 p_1 + A_f p_f = 0$$

$$M_1 + M_f - A_f e p_f = M \tag{2}$$

where subscript *1* represents the main hull and *f* presents the superstructure. *A* means the section area, *e* is the distance between the neutral axis of superstructure and main hull, *p* represents the mean stress and *M* presents the bending moment.

It is noted that the deflection of main hull and superstructure is related to its bending moment respectively. Considering the influence of shear deformation, the bending moment of main hull M_1 and superstructure M_f can be expressed as follows according to conventional beam theory.

$$M_1 = -E_1 I_1 \left(\frac{d^2 w_1}{dx^2} + \frac{Q_1}{a_1 G_1} \right)$$

$$M_f = -E_f I_f \left(\frac{d^2 w_f}{dx^2} + \frac{Q_f}{a_f G_f} \right) \tag{3}$$

where *E* represents elastic modulus, *I* is moment of inertia, *w* presents deflection, *a* means the shear area including side shell plating and longitudinal bulkhead, and *G* is shear modulus.

By combining the above equations, a four-order differential equation may be obtained for the mean stress in the superstructure, p_f. Then, the bending efficiency of superstructure can be achieved.

3. Traditional assessment method to the bending efficiency of superstructure

The interaction between the main hull and superstructure is so complex that the bending efficiency of superstructure is not so easy to decide. For BV classification, two-beam theory proposed by Schade is adopted. The efficiency ν_i of the tier *i* of superstructure is determined

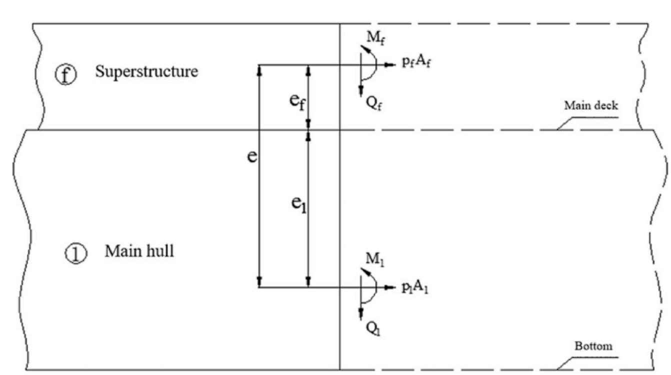

Fig. 2. The forces in typical cross section of main hull and superstructure.

using the formula (Bureau Veritas, 2019) based on statistical data.

$$\nu_i = \nu_{i-1}\left(0.37\chi - 0.034\chi^2\right) \tag{4}$$

where

ν_{i-1}: Bending efficiency of the below superstructure
χ: Dimensionless coefficient defined as $\chi = 100j\lambda \leq 5$
λ: Half length of the target superstructure, in m
j: Parameter of the section, in cm^{-1}, defined as

$$j = \sqrt{\frac{1}{\frac{1}{A_{SH1}} + \frac{1}{A_{SHe}}} \cdot \frac{\Omega}{2.6}}$$

where

A_{SH1}, A_{She}: Vertical shear areas, in cm^2, of main hull and superstructure
Ω: Parameter, in cm^{-4}, defined as

$$\Omega = \frac{(A_1 + A_e)(I_1 + I_e) + A_1A_e(e_1 + e_e)^2}{(A_1 + A_e)I_1I_e + A_1A_e\left(I_1e_e^2 + I_ee_1^2\right)}$$

where

A_1, A_e: Sectional areas, in cm^2, of main hull and superstructure
I_1, I_e: Sectional moments of inertia, in cm^4, of main hull and superstructure on its neutral axes, respectively
e_1, e_e: Vertical distances, in cm, from the upper deck to the neutral axis of the main hull and superstructure, respectively.

The meaning of above symbol is shown in Fig. 3. It is worth mention the geometry parameters of the superstructure should be corrected by the ratio of Young's modulus E_e/E_1 when the main hull and superstructure adopt different material.

The bending efficiency of a typical tier superstructure can be defined as the bending efficiency of central point locating in the neutral axis of mentioned typical tier. It is suitable for the evaluation of the stress distribution of the section not considering the local stress distribution. When calculating the multi-tier superstructure, the main hull and the structures below the *i*-tier superstructure are treated as the equivalent main hull. The actual stress assessed by the rule can be obtained based on the simple beam theory with the correction of bending efficiency.

4. Analytical model

In this section, the finite element model of a typical inland passenger ship is generated. The interaction of the main hull and superstructure is investigated and the bending efficiency of each tier of superstructure is discussed basing on the analysis of the sectional geometry and the sectional normal stress distribution.

4.1. Finite element model

The target ship is one of the largest inland passenger ship which contains six decks and four tiers of superstructure. There are more than 80 passenger cabins and the gymnasium, meeting room, bar and swimming pool in the recreational area.

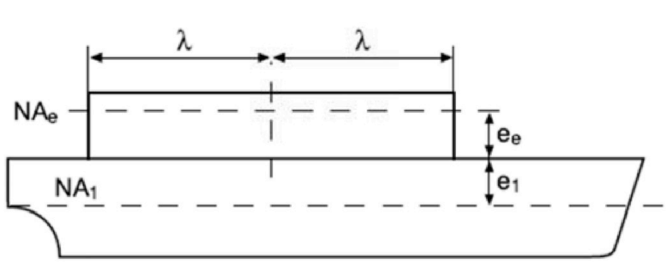

Fig. 3. Parameters definition of the superstructure efficiency.

The target steel ship has a double bottom and single side structural configuration with the decks mainly connected by pillars and transverse bulkheads. The principal dimensions are shown in Table 1 and the height and length of decks are summarized in Table 2.

The superstructure of target ship is distributed along the entire ship so that the whole ship FEM model is necessary to calculate the bending efficiency of each tier. The stiffener is simulated by beam element and the plating is simulated by plate element. The web of girder is simulated by plate element and flange by beam element. The mesh size is basically 250 mm which is half of stiffener space or frame space. There are three divisions for the web. The square plate element is prior to triangular element and the sharp angle element larger than 165° or less than 15° is tried to avoid. There are totally 750,000 elements in the whole ship model. A typical double-span section model is demonstrated in Fig. 4 and whole ship model is shown in Fig. 5.

The ship is usually floating in the water so that it is in equilibrium condition at each time instantaneous. There are no so-called geometry boundary conditions. In order to perform the finite element analysis, the minimum geometry boundary condition is necessary to prevent the rigid body movement. In the present research, the Multi-Point Constraints (abbreviated as MPC) are subjected to the aft end section and all degrees of freedom are fixed to simulate the rigid constraints, as shown in Fig. 6. At the same time, the MPC constraints are set to the fore end section and the vertical rotation angle are forced to simulate the longitudinal bending moment, as shown in Fig. 7.

4.2. Load calculation

The ship is subjected to still water bending moment and wave bending moment. According to the definition of BV Rules NR217, the moments can be calculated as follows.

Still water bending moment in hogging conditions is calculated by

$$M_{HO} = 0.273L^2B^{1.342}D^{0.172}(1.265 - C_B) \quad kN{\cdot}m \tag{5}$$

where

L: length between Perpendiculars (L_{pp}), in m
B: breadth, in m
D: depth, in m
C_B: block coefficient,
$C_B = \frac{\Delta}{L \cdot B \cdot T}$, T is for the draught, in m.

Wave bending moment can be derived by

$$M_W = 0.021nCL^2B(C_B + 0.7) \quad kN{\cdot}m$$

where

n: navigation coefficient, $n = 0.85H_s$
H_s: maximum significant wave height, in m
C: wave parameter,
$C = 10.75 - \left(\frac{300-L}{100}\right)^{1.5}$, $L \geq 90$m.

Table 1
The principal dimensions.

Dimensions	Value	Unit
L_{oa}	112.0	m
L_{pp}	98.0	m
Breadth	16.2	m
Depth	4.4	m
Draft	2.2	m

Table 2
The height and length of decks.

Deck	Height(m)	Length(m)
Sun deck	15.3	86.43
Third deck	12.6	91.44
Second deck	9.9	95.50
First deck	7.2	98.87
Main deck	4.4	99.20
Inner deck	2.7	73.50

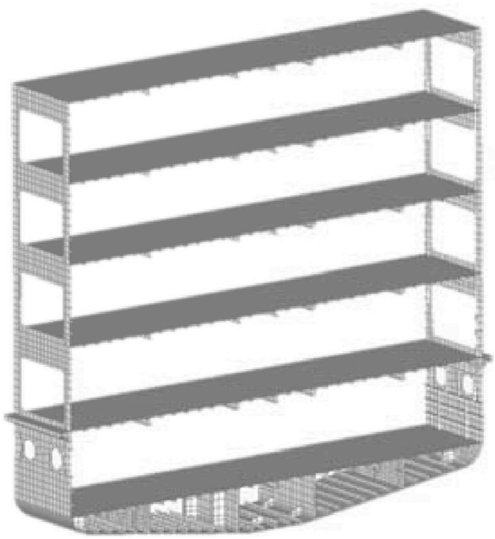

Fig. 4. Typical cross section model.

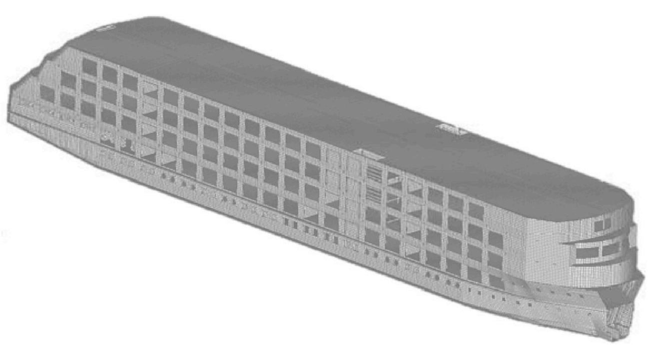

Fig. 5. Whole ship model.

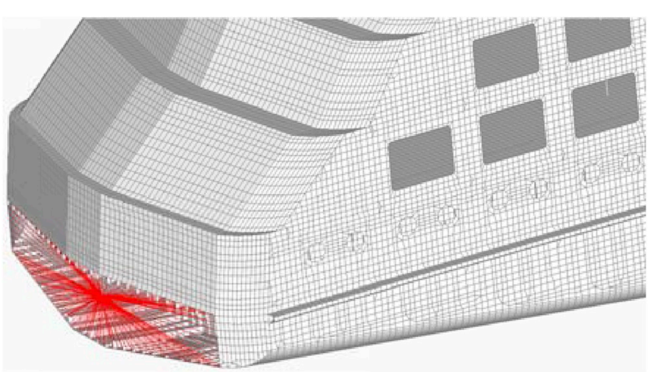

Fig. 6. Rigid constraint at aft end section.

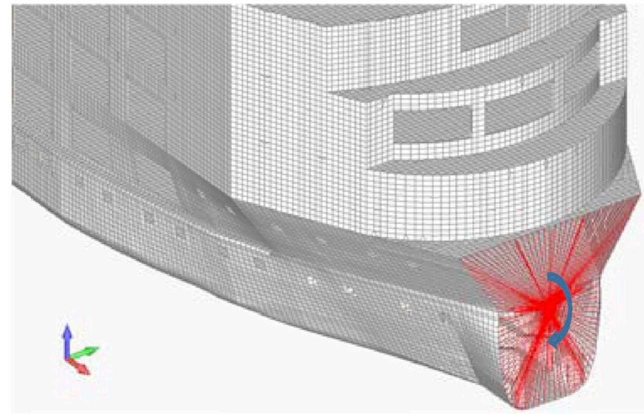

Fig. 7. Bending load applied at fore.

For the target ship, the ratio of length to depth is $L/D = 22.3$. The significant wave height of the navigation route ranges from 0.6m to 2.0m. The significant wave height $Hs = 1.8$m is adopted in the present research. The calculated wave bending moment is *43,*692 kN m and still water bending moment is *126,*317 kN m. The longitudinal bending moment shall include hydrostatic moment and the wave bending moment which is totally 1.700×10^8 *N m*. In the present research, the hogging condition is considered which is generally typical case for passenger vessels. The forced rotation angle is increased in the fore end section until the reaction vertical bending moment reaches the mentioned longitudinal bending moment.

5. Results and analysis

A typical inland passenger ship with four tiers of superstructure is considered in the present research. The structural response under the longitudinal bending is investigated and analyzed. In order to discuss the bending efficiency of superstructure to hull girder strength, the longitudinal nominal stress distribution along depth direction of each element in the typical cross section is compared.

5.1. FEM calculation results

FEM analysis is carried out using the mentioned model, boundary condition and loads condition. Then, the stress distribution of each element can be obtained. The typical cross section at the middle of ship length ($x = 56$m) is chosen for discussion. The longitudinal stress distribution along ship depth in the typical cross section is shown in Fig. 8.

FEM results show that the stress distribution below the main deck is almost linear and that above the first deck is also linear. However, the slope is different that represents the different stiffness in the main hull and superstructure.

5.2. Rules calculation results

On the other hand, the bending efficiency of superstructure according to BV Rules is also performed. The geometric parameters of each tier superstructure are obtained in accordance with the method described in Chapter 3, as shown in Table 3. Then, the bending efficiency of each tier superstructure can be obtained, as shown in Table 4.

For the objective passenger ship, the effective length of each tier superstructure is so long that the dimensionless coefficient χ reaches to 5.0. Therefore, the bending efficiency of each tier superstructure is 100%. The longitudinal stress distribution along ship depth is linear for both main hull and superstructure, as shown by cyan line with diamond mark in Fig. 8.

Comparing with the FEM results, the position of neutral axis obtained by rules shows much higher one. And the stress on the top deck is

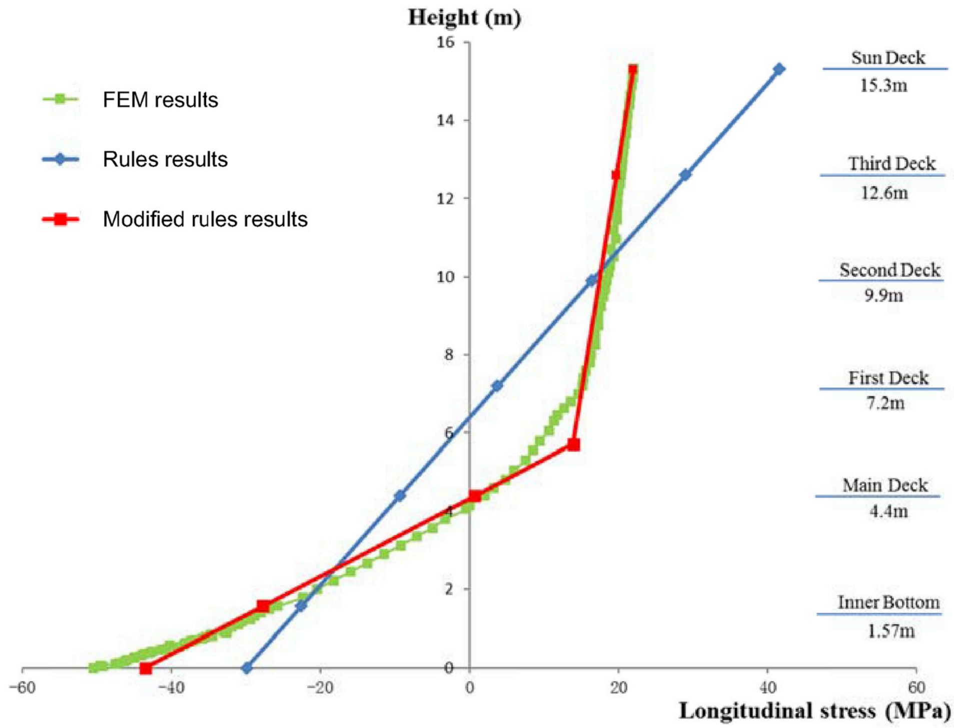

Fig. 8. Longitudinal stress distribution along depth direction.

Table 3
Geometric parameters of each tier superstructure.

	A_{SH1}	A_{SHe}	A_1	A_e	I_1	I_e	e_1	e_f
	cm^2	cm^2	cm^2	cm^2	cm^4	cm^4	cm	cm
First tier	847	420	7387.6	2302.9	1.94E+08	1.03E+07	228.8	243.5
Second tier	1267	405	9690.5	2047.7	5.83E+08	9.17E+06	401.7	231.8
Third tier	1672	351	11738.2	1803.2	1.26E+09	7.70E+06	562.7	232.9
Fourth tier	2023	297	13541.4	1670.5	2.23E+09	6.46E+06	728.2	238.1

Table 4
Bending efficiency of each tier superstructure.

	λ	Ω	j	χ	ν_i
	m	cm^{-4}	cm^{-1}	[-]	[-]
First tier	49.43	2.65E-08	1.69E-03	5.0	100%
Second tier	47.75	2.18E-08	1.60E-03	5.0	100%
Third tier	45.72	2.00E-08	1.49E-03	5.0	100%
Fourth tier	43.21	1.86E-08	1.36E-03	5.0	100%

almost two times and that on the bottom is only half. The contribution of deck constructions to longitudinal strength is not correctly defined in the present rules calculation formula. The influence factors, for example, the ratio of deck opening, the opening ratio of side shell and the ratio of the superstructure width, must be considered in the rules definition in order to reveal the actual characteristics of stress distribution.

5.3. Modified rule calculation results

The bending efficiency defined in the rules is based on beam theory so that the influence of opening cannot be considered. To proper reflect the efficiency of the superstructure, the influence of the superstructure length and width, the ratio of deck opening and the opening ratio of side shell shall be taken into account. So, the efficiency formula ν_i can be corrected as follow (Zhu, 2018):

$$\nu_i = K\nu_{i-1}\left(0.37\chi - 0.034\chi^2\right) \tag{6}$$

where, K is influence factor, $K = f(\Pi(L_S), \Pi(B_S), \Pi(A_{DO}), \Pi(A_{SO}))$. The meaning of other symbols is same as Eq. (4).

5.3.1. Influence factor of superstructure length

The length of superstructure plays an important role in the bending efficiency. It is noted that the longer superstructure participates more for the longitudinal bending. To express the effect factor properly, the ratio of the superstructure length to the ship hull length, $\Pi(L_S)$, is defined as,

$$\Pi(L_S) = \frac{L_S}{L}$$

where L_S is the effective length of superstructure and L is the effective length of main hull.

The calculation model for different $\Pi(L_S)$ is shown in Fig. 9. The correction factor of bending efficiency is expressed in Fig. 10.

It is more effective to transfer the force from the main hull to superstructure with the longer superstructure which leads to higher bending efficiency (see Fig. 10. When the $\Pi(L_S)$ is less than 0.3, the bending efficiency of superstructure is low and increases rapidly as the superstructure length increases. The bending efficiency increases linearly with the superstructure length when the $\Pi(L_S)$ is larger than 0.4.

5.3.2. Influence factor of superstructure width

To investigate the influence of superstructure width on the bending

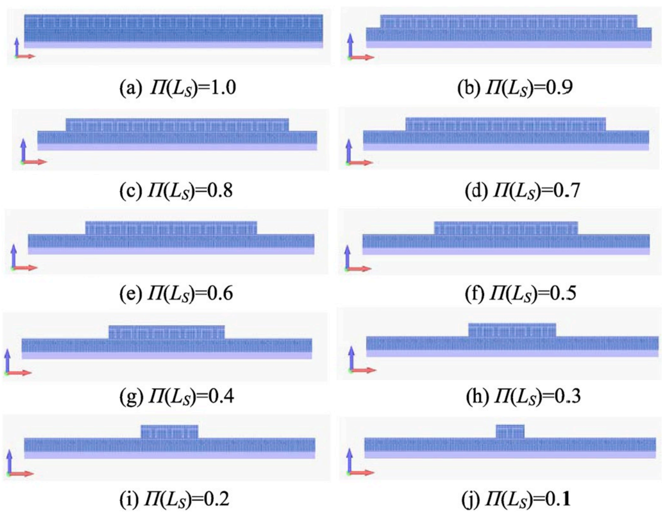

Fig. 9. Length of superstructure.

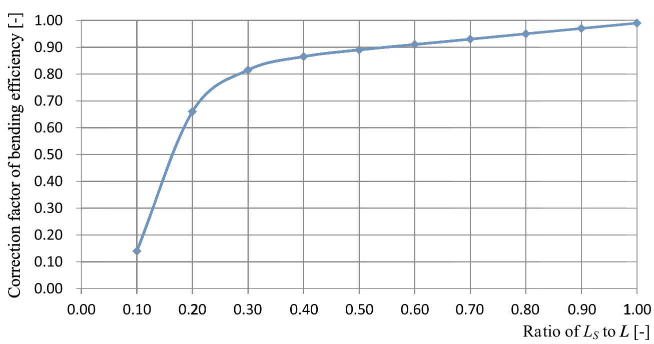

Fig. 10. Correction factor of bending efficiency considering superstructure length.

efficiency, the ratio of the superstructure width to the ship width, $\Pi(B_S)$, is defined as,

$$\Pi(B_S) = \frac{B_S}{B}$$

where B_S is the effective width of superstructure and B is the width of main hull.

In the present research, it is assumed that the width of main hull is unchanged to discuss the effect of different superstructure width. The effect of various $\Pi(B_S)$, 1.0, 0.74, 0.56, 0.37 and 0.19, is discussed. To ensure the force transferring effectively between the main hull and superstructure, the pillars are set at the outer side of superstructure for different superstructure width, as shown in Fig. 11. The correction factor of bending efficiency is demonstrated in Fig. 12.

It can be found the bending efficiency will decrease with the increase of Π(BS). The narrower superstructure width represents the better force transformation which leads to higher bending efficiency. It is worth noting the influence rate of superstructure width is less than 5%.

5.3.3. *Influence factor of deck opening area*

To investigate the effect of deck opening, the ratio of the deck opening area to the deck area, $\Pi(A_{DO})$, is defined as,

$$\Pi(A_{DO}) = \frac{A_{DO}}{A_D}$$

where A_{DO} is the deck opening area and A_D is the deck area.

Seven typical cases, representing the ratio of the deck opening area to the deck area 0%, 4%, 11%, 18%, 25%, 32% and 39%, are considered.

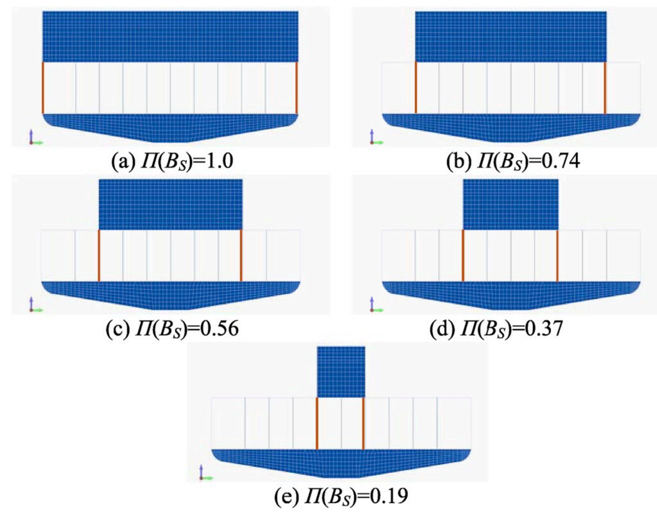

Fig. 11. Width of superstructure.

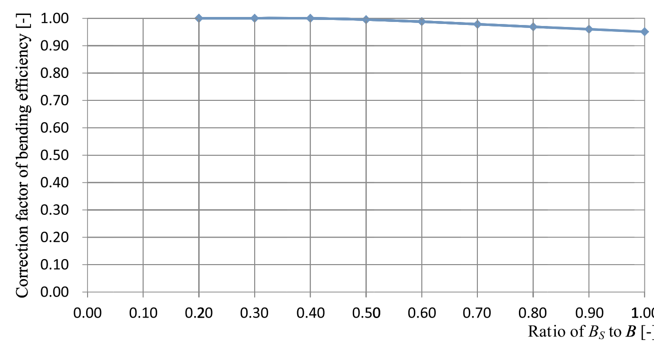

Fig. 12. Correction factor of bending efficiency considering superstructure width.

The meaning of $\Pi(A_{DO})$ is shown in Fig. 13. The midst section is analyzed and the correction factor of bending efficiency is demonstrated in Fig. 14.

With the increase of deck opening area, the structural strength becomes weaker and the effectiveness of superstructure is reduced. The $\Pi(A_{DO})$ is relatively small in most cases so that the influence of deck opening area on the bending efficiency is not crucial in actual situation.

5.3.4. *Influence factor of side shell opening area*

To discuss the effect of side shell opening, the ratio of the side shell

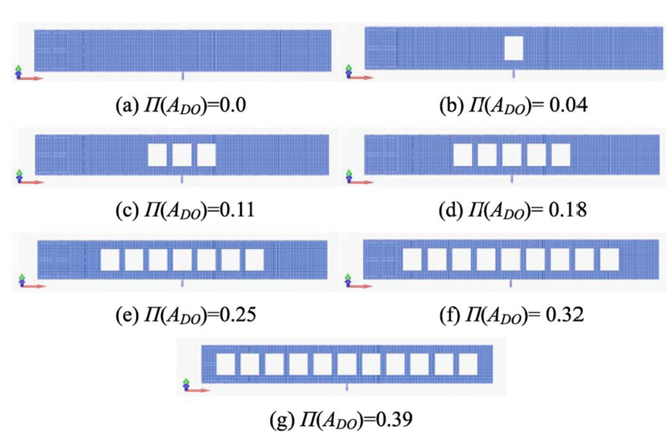

Fig. 13. Deck opening area.

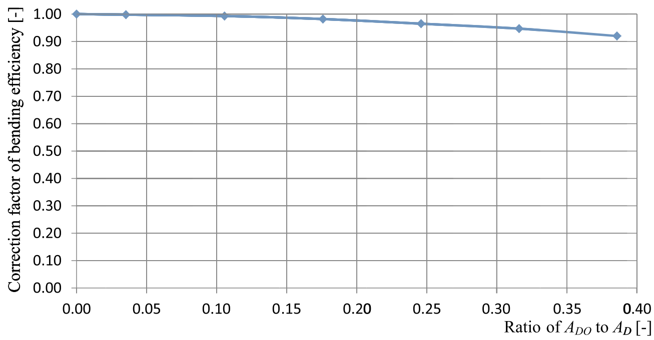

Fig. 14. Correction factor of bending efficiency considering deck opening area.

opening area to the side shell area, $\Pi(A_{SO})$, is defined as,

$$\Pi(A_{SO}) = \frac{A_{SO}}{A_S}$$

where A_{SO} is the side shell opening area and A_S is the side shell area.

In order to better appreciate the scenery along the trip, the passenger ship always sets many openings on the side shell of superstructure. The ratio of side shell opening area to the side shell area can reach 0.3–0.45.

In the present research, the opening size is set 2400 × 1750mm and the distance between openings is 1100 mm. Six typical cases, representing the ratio of the side shell opening area to the side shell area 0%, 10%, 19%, 29%, 38% and 43%, are calculated. The meaning of $\Pi(A_{SO})$ is shown in Fig. 15. The correction factor of bending efficiency is demonstrated in Fig. 16.

Side shell opening makes the force transfer poor. As the side shell opening area increases, the bending efficiency decreases rapidly. When the $\Pi(A_{SO})$ reaches 43%, the efficiency is only 81%.

Considering the effect of superstructure length, width, deck opening area, side shell opening area, the corrected bending efficiency of each tier superstructure can be calculated by Eq. (6). For the objective inland passenger ship, the superstructure length, width and deck opening area are fully effective so that the bending efficiency of each tier superstructure is influenced by side shell opening area, as summarized in Table 5. The stress distribution along depth direction considering the corrected bending efficient is computed and shown in Fig. 8 by red rectangular marked with "Modified rules results".

5.4. Results discussion

The FEM results are obtained by structural direct calculation using whole ship model under longitudinal hogging moment. The rules results are calculated by the present BV rules based on two-beam theory. And the modified rules results are achieved considering the correction factor of superstructure length, width, deck opening area and side shell opening area. They are compared in Fig. 8. According to the FEM results, the stress distribution below the main deck is almost linear and that

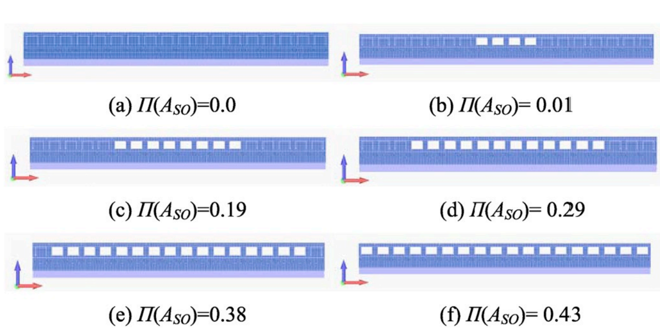

Fig. 15. Side shell opening area.

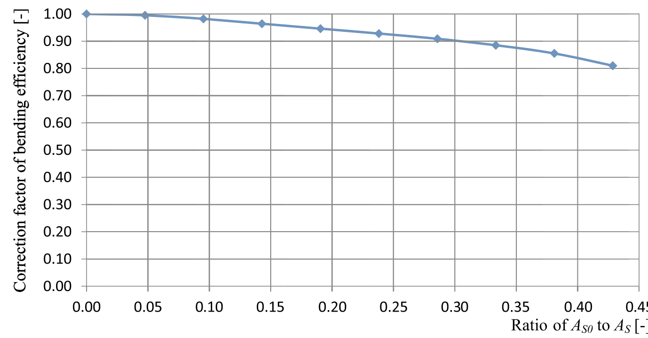

Fig. 16. Correction factor of bending efficiency considering side shell opening area.

Table 5
Bending efficiency of each tier superstructure.

	Bending efficiency
The first tier	100%
The second tier	100%
The third tier	71%
The fourth tier	54%

above the first deck is also linear. There are different slope for that below the main deck and above the first deck. For the passenger ship, the force transformation between main hull and superstructure is not totally effective so that there exists bending efficiency of superstructure.

The present BV rules definition on bending efficiency of superstructure is based on two-beam theory proposed by Schade. It is related to superstructure length, vertical shear areas, sectional area and inertia moment of main hull and superstructure. The influence of deck opening and side shell opening cannot be considered properly in beam theory. For the objective passenger ship, the superstructure length is enough so that the dimensionless coefficient χ is 5.0 and the bending efficiency of each tier superstructure is fully effective. Therefore, the position of neutral axis is relative high which leads to larger longitudinal stress in the uppermost deck and the third deck of superstructure while smaller one in the bottom, as shown in Fig. 8.

It is known from the present research the superstructure length and width, the opening ratio of deck and the opening ratio of side shell have an influence on the bending efficiency of each tier of superstructure. The rules definition can be modified by considering the corresponding correction factors. The modified rules results are expressed with red rectangular mark "Modified rules results" in Fig. 8. The position of neutral axis is reduced a lot and shows good agreement with that of FEM results. The longitudinal stress in the sun deck, the third deck and the bottom is quite different with that of traditional rules results but coincides with that of FEM results. So, the correction factors play important roles on the bending efficiency of superstructure. The modified rules results can basically reflect the characteristics of superstructure bending.

6. Conclusions

It is important for the rational and lightweight structural design of passenger ship to research the superstructure bending efficiency. In the present paper, the whole ship FEM model is generated and the stress distribution along depth direction of a typical section under hogging condition is analyzed. The FEM results are compared with those obtained by BV rules based on two-beam theory. The rules results show higher neutral axis position and quite different stress distribution. The influence factors, such as the superstructure length and width, the ratio of deck opening area and side shell opening area, are investigated and the corresponding correction coefficient is proposed. The results obtained by proposed modification method show good agreement with FEM results in both neutral axis position and stress distribution. The main conclusions can be drawn as follows.

1) Under the longitudinal bending moment including still water bending moment and wave bending moment, the structural behaviour of main hull basically follows beam theory and that of superstructure also follows it. However, the rigidity stiffness of main hull and superstructure are different.
2) The bending efficiency of superstructure to hull girder strength is low if the superstructure length is less than 0.3 times of ship length and it increases with the superstructure length for flump superstructure.
3) The superstructure width has a little effect on bending efficiency. The bending efficiency changes no more than 5% when there are pillars under the side shell of superstructure to ensure the force transformation.
4) With the increase of deck opening area, the structural strength becomes weaker and the effectiveness of superstructure is reduced. The actual deck opening area is so small that its influence on the bending efficiency is not crucial.
5) As the side shell opening area increases, the bending efficiency decreases rapidly. The bending efficiency is only 81% when the ratio of side shell opening area to side shell area reaches 43%.
6) The modified results considering the correction factor of the superstructure length and width, the deck opening area and side shell opening area are good agreement with those of FEM results so that the modified method can basically reflect the characteristics of superstructure bending.

The present research deals with the bending efficiency of superstructure to hull girder strength of inland passenger ship with four decks. The influence factors such as superstructure length and width, the deck opening area and side shell opening area are investigated and discussed. The modified formula is proposed to reflect the bending efficiency of superstructure. The present fundamental research helps to structural design of superstructure for inland passenger ship.

Author contributions section

Pei Zhiyong: Conceptualization, Methodology, Software.
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Zhu Bo: Data Curation.
Wu Weiguo: Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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