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# A new block assembly method for shipbuilding at sea

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**Abstract.** In this paper, we introduce a new method for assembly of shipbuilding blocks at sea and present its feasibility focusing on structural safety. The core concept of this method is to assemble ship building blocks by use of bolting, gluing and welding techniques at sea without dock facilities. Due to its independence of dock facilities, shipyard construction capability could be increased considerably by the proposed method. To show the structural safety of this method, a bulk carrier and an oil tanker were employed, and we investigated the structural behavior of those ships to which the new block assembly method was applied. The ship hull models attached with connective parts are analyzed in detail through finite element analyses, and the cargo capacity of the bulk carrier is briefly discussed as well. The results of these studies show the potential for applying this new block assembly method to practical shipbuilding.

**Keywords:** ship blocks assembly method; shipbuilding, structural design; stress assessment; finite element method

## 1. Introduction

Conventionally, large ships are constructed by assembling small blocks of the final structure (Eyres 2007). Since the assembly process is generally performed in a dry dock by welding, the construction capability is largely dependent on the dock facility. Because there is a continuing trend toward ships of greater size, many shipbuilding companies are faced with tremendous costs to expand their dock facility.

To alleviate this limitation and increase construction capability, a variety of methods have been proposed to advance the shipbuilding process. For example, by applying underwater welding method, large ship blocks could be assembled at sea (Eyres 2007). STX Offshore & Shipbuilding connects large ship blocks in a floating dock (http://www.stx.co.kr/), Samsung Heavy Industry has

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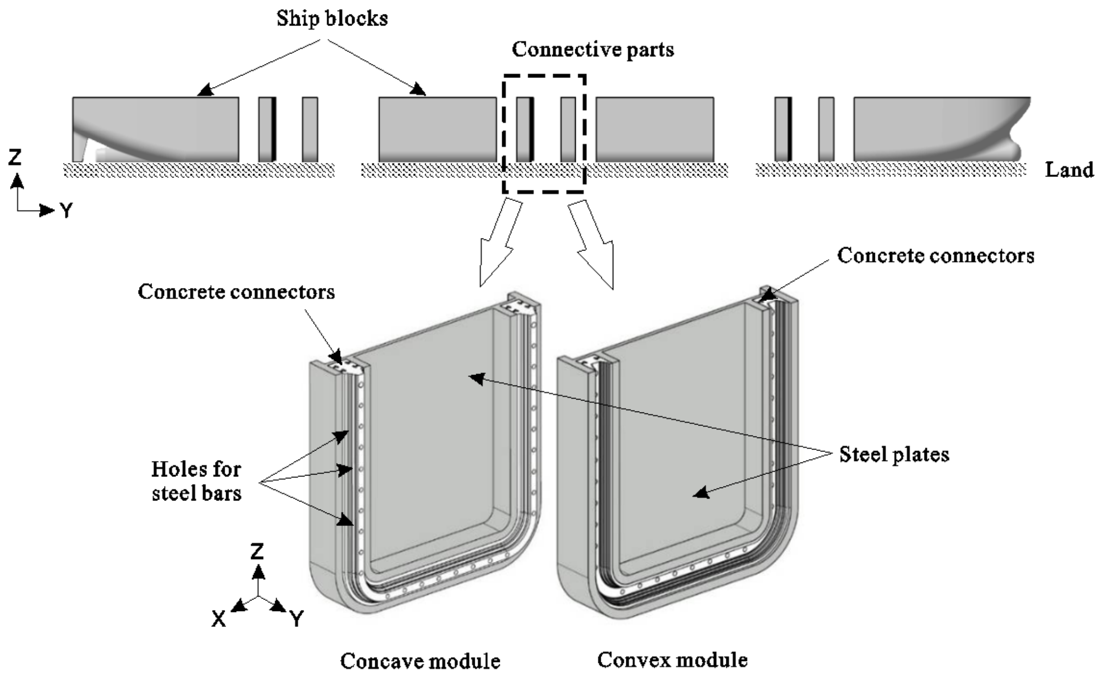



Fig. 1 Step 1 of the new block assembly method

also operated floating docks for the shipbuilding process. Hanjin Heavy Industries developed a working module to create dry space in which laborers could weld ship sections in the water (Lee *et al*. 2003). To increase shipyard construction ability, Hyundai Heavy Industries assembled ship blocks totally on land without using dry dock (http://hhi.co.kr/). Recently, the simulation based methods and optimization techniques have been also employed shipbuilding planning (Inozu *et al*. 2006, Kim *et al*. 2005). However, such methods require advanced operation techniques and addition of shipbuilding facilities.

In contrast to the methods used to assemble block of steel structures, bolting and gluing techniques have been widely used to construct concrete floating structures at sea. This is possible because of the large cross-sections of connective parts, and due to the material properties of concrete. An excellent example of this application is the SR520 Bridge over Lake Washington, USA (WSDT 2013), which is a 2.4 km long assemblage of concrete pontoons (25~50 m). Since each concrete pontoon is waterproofed, assembly procedures, including bolting and gluing, could be easily performed on the water. Our idea presented in this study is motivated by the fact that these techniques are also possible for steel ships, if a proper steel-concrete composite structure is adopted for the parts connecting the ship blocks.

Similar techniques were used in recent proposal we made for assembling ship blocks at sea without dock facility (Lee *et al*. 2011). This is a method that, after fabricating waterproofed ship blocks in the dry dock, assembly procedures using mainly bolting and gluing methods are performed on the sea. This is made possible by using prefabricated ship blocks with steel-concrete composite connective parts. To be more easily assembled at sea, the connective parts of the ship capability could be increased without expanding dock facilities, and maximum ship size, restricted by the dock size, could become flexible.

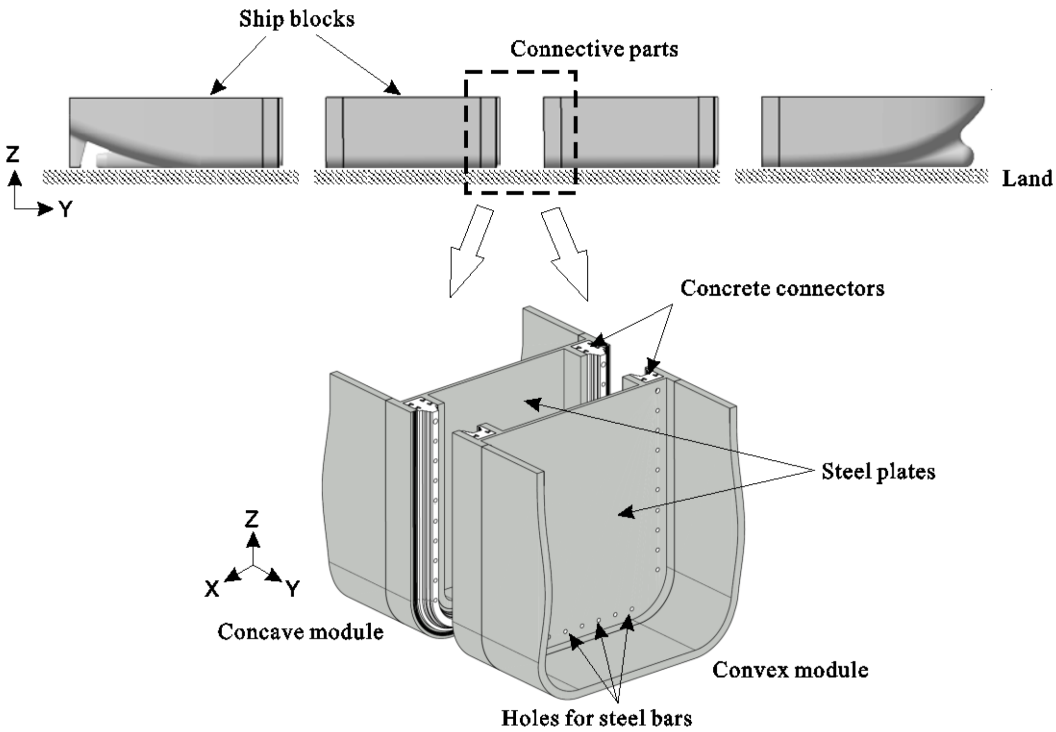



Fig. 2. Step 2 of the new block assembly method

In this paper, we first describe the concept of new block assembly method and its detail. Then, the strength assessment of the ship blocks applying the new assembly method is conducted. Two kinds of target ships are chosen to be analyzed, which are a bulk carrier and an oil tanker. In order to determine the number of steel bars for one section and the size of connective part, preliminary calculation for the connective part is performed. Next, we establish the finite element models of the two target ships that are attached with connective parts to check the maximum effective stress. In addition, changes in torsional stiffness and cargo capacity caused by the attachment of connective parts are investigated.

## 2. New block assembly method

Recently, Lee and his colleagues proposed a new ship block assembly method for use at sea without a dock facility (Lee *et al*. 2011). In this section, we specifically explain the procedure of the new assembly method.

(Step 1) Ship segments are fabricated in the form of several large ship blocks on dry docks. At the same time, the connective parts are fabricated, see Fig. 1. Connective parts are made up of steel and concrete, which consist of concave and convex modules of ship hull to be more easily assembled at sea. To ensure the water-tightness of the ship blocks, temporary steel plates are installed on both concave and convex modules, and blank holes for steel bars are waterproofed using rubber packing.

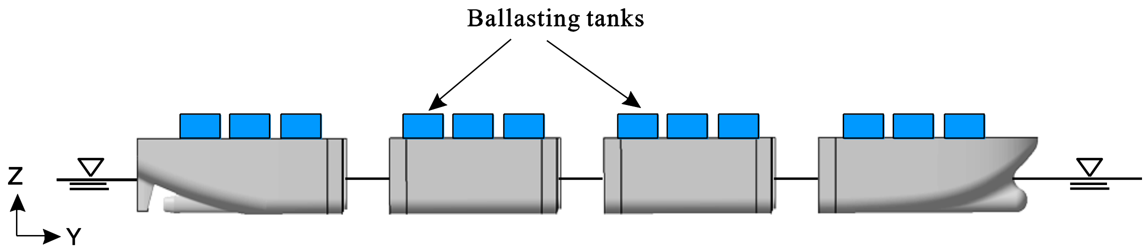



Fig. 3 Step 3 of the new block assembly method

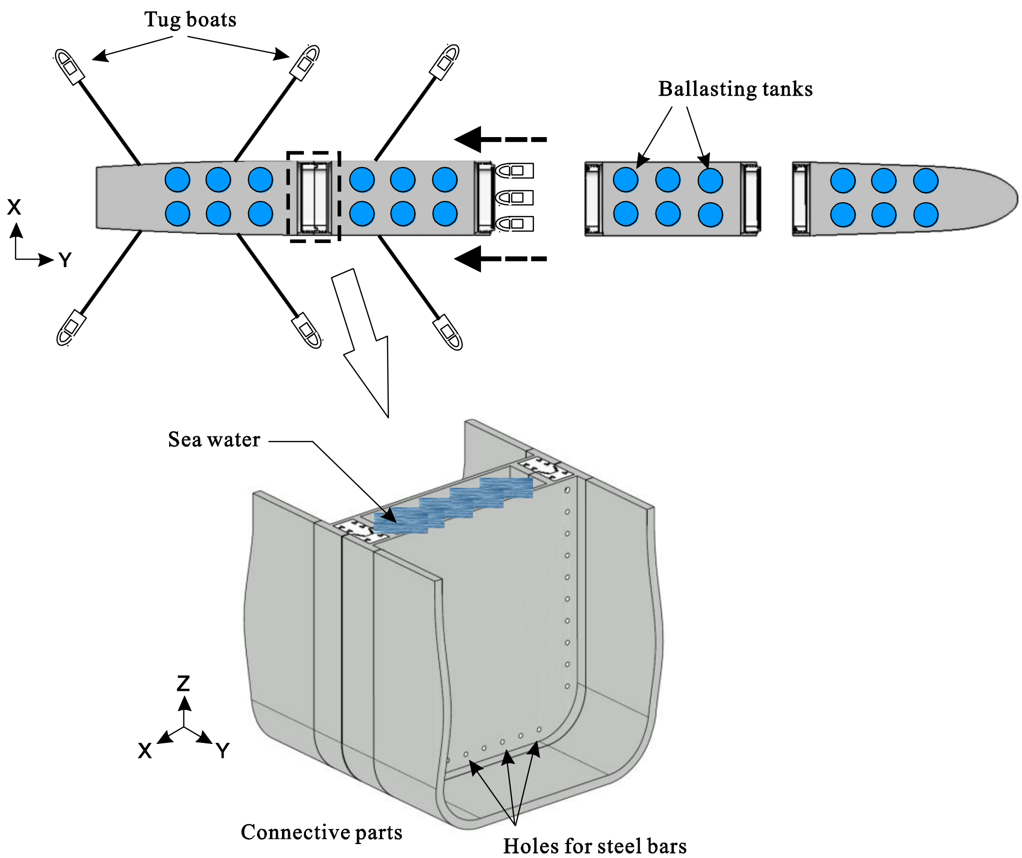



Fig. 4 Step 4 of the new block assembly method

(Step 2) Next, the concave and convex modules are welded to each ship block in the dry dock, see Fig. 2, and the ship blocks are moved for the assembly procedure to sea. Note that the assembly procedure must be performed in still water conditions to prevent overturn by unpredicted wave loads.

(Step 3) In order to assemble the ship blocks, they should be aligned horizontally. In this step, the ballasting tanks of their lighter ship blocks are filled with seawater so that all the blocks become of similar draft, see Fig. 3. If the ballast of each block is insufficient, extra ballasting tanks could be applied to adjust the alignment of the ship blocks.

(Step 4) Tug boats are used to drag the ship blocks close together. When two ship blocks are close

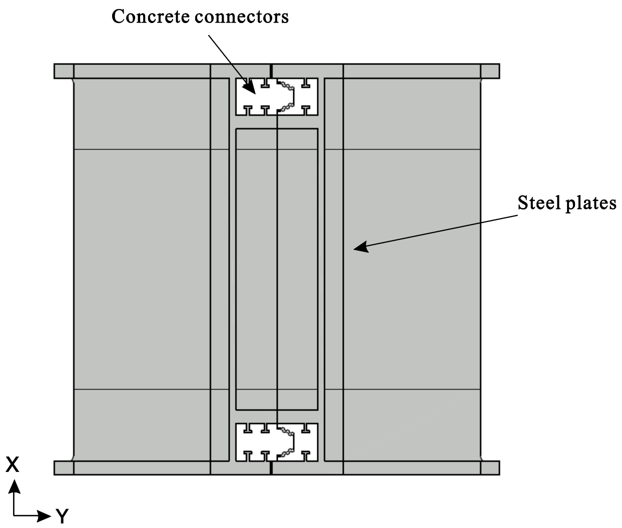



Fig. 5 Connective parts after pumping out the sea water

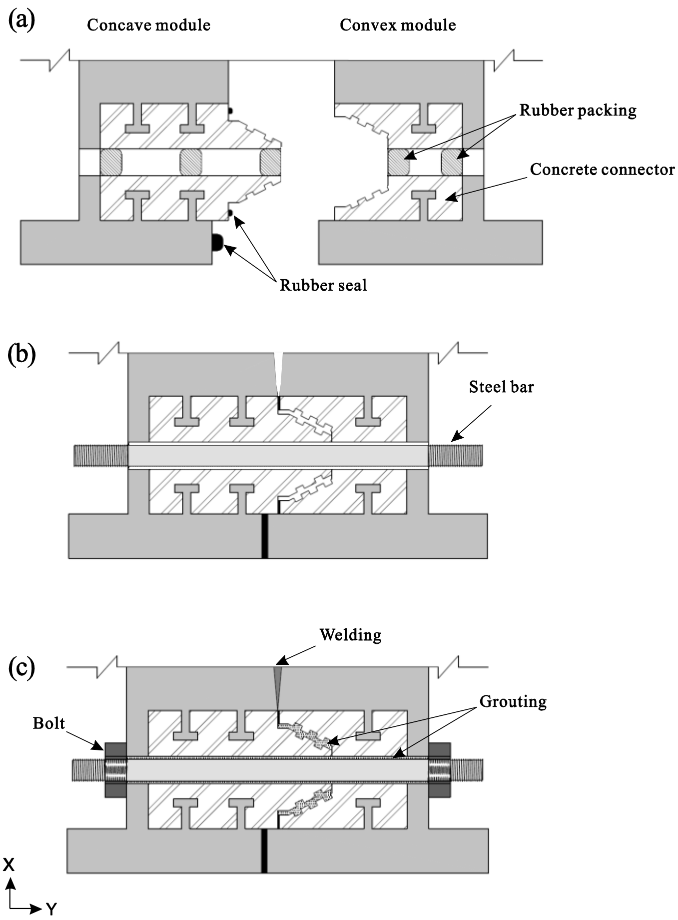



Fig. 6 Step 5 of the new block assembly method

enough, tug boats push the ship blocks so that the convex part of one block is inserted into the concave part of another block, see Fig. 4. The seawater left in the connective part is pumped out and then both blocks are attached by hydrostatic water pressure. Any extra ballasting tanks are also removed. Fig. 5 shows the connective part after pumping out the water.

(Step 5) Fig 6 presents a specific assembly procedure. Until Step 4, the blank holes for insertion of steel bars are waterproofed by rubber packing, see Fig. 6(a). After removing the rubber packing, the steel bars are put into the holes as shown in Fig. 6(b). Note that rubber seals also could be used to adjust for the manufacturing tolerance between concave and convex parts. Then, bolts are connected to both ends of each steel bar, welding is done inside the connective part, and empty places are filled with grouting materials, see Fig. 6(c). These assembly techniques (i.e., bolting, welding and gluing) lead to improvements in the strength of the connective parts. The ship blocks are assembled in this way one after another. After assembling the ship blocks, the steel plates used for waterproofing are also removed.

Using the new assembly method, the dry dock facility is only used to construct the ship blocks up to Step 2, Therefore, once the ship blocks are fabricated and cleared from the dry dock, it can immediately be used to start building the next ship. Moreover, because the assembly of ship blocks occurs offshore, the ultimate size of a ship does not depend on the size of the dry dock. Due to its advantages, the proposed block assembly method could make a major contribution to increased productivity in the shipbuilding enterprise. In the following sections, we report the results of our investigation into the feasibility of the proposed assembly method.

## 3. Preliminary calculations

To design a ship to be constructed using the new assembly method, the dimension of connective part and the number of connecting steel bars need to be decided to meet the section requirements (e.g., section modules and inertial moments). Here, we present the necessary preliminary calculation procedures using Common Structural Rules (CSR) (IACS 2006). We consider two target ships to conduct the strength analysis of the ship structure attached with connective part. One is 80,000 DWT[1] bulk carrier (Amlashi and Moan 2008), the other one is 159,000 DWT oil tanker (Read *et al*. 2000).

In the CSR, the minimum section module $Z_{\min}$ of the hull is given by

$$Z_{\min} = 0.9kC_{wv}L^2B(C_b + 0.7)\times 10^{-6} \tag{1}$$

with

$$C_{wv} = 10.75 - \left[\frac{300-L}{100}\right]^{\frac{2}{3}}, \tag{2}$$

where $k$ and $C_{wv}$ represent the steel factor and wave coefficient, respectively. $L$, $B$, and $C_b$ represent the ship length, breadth, and block coefficient, respectively, and these parameters of the two target ships are given in Table 1.

[1]Deadweight tonnage (DWT)

Table 1 Parameters of target ships

| Items | Bulk carrier | Oil tanker |
|---|---|---|
| $L$ | 223.8 m | 272.7 m |
| $B$ | 32 m | 46.2 m |
| $D$ | 20 m | 25.3 m |
| $C_b$ | 0.896 | 0.830 |
| $C_{wv}$ | 9.916 | 10.329 |
| $k$ | 1 | 1 |
| $I_{\min}$ | 152.7 m$^4$ | 410.0 m$^4$ |
| $Z_{\min}$ | 22.8 m$^3$ | 50.1 m$^3$ |

Table 2 The preliminary calculation results of connective part sections

| Case | $N_{side}$ | $N_{bottom}$ | $2r$ (mm) | $t_c$ (mm) | Bulk carrier | | Oil tanker | |
|---|---|---|---|---|---|---|---|---|
| | | | | | $I$ (m$^4$) | $Z$ ( m$^3$) | $I$ (m$^4$) | $Z$ ( m$^3$) |
| 1 | 8 | 8 | 80 | 160 | 266.4 | 22.8 | 660.7 | 50.1 |
| 2 | 10 | 10 | 70 | 160 | 265.2 | 22.7 | 660.5 | 50 |
| 3 | 10 | 10 | 80 | 150 | 265.6 | 22.7 | 659.5 | 50 |
| 4 | 10 | 10 | 80 | 160 | 267.8 | 22.9 | 663.3 | 50.2 |

The minimum inertia moment $I_{\min}$ is also given by

$$I_{\min} = 2.7 C_{wv} L^3 B (C_b + 0.7) \times 10^{-8} . \tag{3}$$

Based on Eq. (1) and Eq. (3), the minimum section modules and minimum inertia moment of the two target ships were calculated, see Table 1.

Because the preliminary calculations for the two target ships were quite similar, we just show the calculation procedure for the bulk carrier. Furthermore, only the results for the sagging condition are considered here because the values of $I$ and $Z$ for the hogging condition are much higher than for the sagging condition. In this case, the upper and lower sides of the structure are bearing tensile and compressive stresses, respectively. Note that the connective part is a kind of composite structure made up of concrete and steel, and that the concrete part that is bearing tension will not be taken into consideration (Assakkaf 2003). As a result, the concrete below the neutral axis is only considered for bending deflection. To calculate the inertia moment of the connective part, the distance between the neutral axis and the bottom is calculated first, and it is denoted $z$. After calculating it, the inertia moment of the connective part section is calculated by

$$I = \frac{E_s \left( I_{plate} + I_{bar} \right) + E_c I_c}{E_s} , \tag{4}$$

where $E_s$ and $E_c$ are Young's modulus of steel and concrete, respectively, and $I_{plate}$, $I_{bar}$ and $I_c$ represent the inertia moment of steel plate, steel bar and concrete parts, respectively.

Subscript $s$ is steel and subscript $c$ is concrete. Here, $E_s$=200 GPa and $E_c$=20 GPa. Poisson's ratio of both steel and concrete is defined as 0.3 in this work.

The section modulus of the connective part is also calculated by

$$Z = \frac{I}{z_{\max}}, \tag{5}$$

where $z_{\max}$ is the maximum distance from the neutral axis to section members. Note that $I$ and $Z$ are defined considering minimum values calculated in Eqs. (1) and (3) ($I \geq I_{\min}$ and $Z \geq Z_{\min}$).

According to above procedures, the preliminary calculations for the connective parts are finished. Table 2 shows the calculation results of four different cases for each target ship. Next, we consider four variables: number of steel bars in the side and in the bottom hull ($N_{side}$ and $N_{bottom}$), concrete thickness ($t_c$), and the steel bar diameter ($2r$). Table 2 shows that every case of the two target ships meets the requirements of the inertia moments shown in Table 1, but only Case 4 of the two target ships satisfies the minimum section modulus. For this reason, we here consider stress assessment for Case 4 using finite element (FE) analysis.

## 4. Finite element analysis

FE analysis is widely used to evaluate the structural safety of ships and floating structures (Amlashi and Moan 2008, Kim, J.H. *et al*. 2014, Kim, J.G. *et al*. 2014, Kim, K.T. *et al*. 2014, Liu *et al*. 2005, Paik *et al*. 2001, Servis *et al*. 2003). In this paper, we performed the stress assessment using ADINA (Automatic Dynamic Incremental Nonlinear Analysis), which is a commercial finite element analysis program. This analysis was conducted in accordance with the CSR (IACS 2006).

Table 3 Stiffener size and hull thicknesses of the connective part in bulk carrier

| Items | Minimum (mm) | Maximum (mm) |
|---|---|---|
| Deck | 20 | 24 |
| Outer Side plate | 20 | 24 |
| Outer bottom plate | 18 | 24 |
| Inner bottom plate | 18 | 20 |
| Hopper, topside sloping plate | 16 | 18 |
| Longitudinal girder | 19 | 19 |
| Side frame | 20 | 20 |
| Corrugated bulkhead | 16 | 18 |
| Horizontal girder | 18 | 18 |
| Longitudinals | 283×9+100×14 | 380×10+100×21 |

Table 4 Boundary conditions of bulk carrier

| Location | | Translational | | | Rotational | | |
|---|---|---|---|---|---|---|---|
| | | $D_x$ | $D_y$ | $D_z$ | $R_x$ | $R_y$ | $R_z$ |
| Aft end | Independent points | - | Fixed | Fixed | - | - | - |
| | Longitudinal members | RL* | RL | RL | - | - | - |
| Fore end | Independent points | Fixed | Fixed | Fixed | Fixed | - | - |
| | Longitudinal members | RL | RL | RL | - | - | - |

* RL means rigidly linked to the relevant degree of freedom of the independent points.

### *4.1 Analysis of a bulk carrier*

The FE model needs to include three cargo holds and four transverse bulkheads, and need to cover both sides of the ship structure. We defined the connective part size for Case 4 in Table 2. Longitudinals and steel bars were modeled by Timoshenko beam, and steel plate and hull were modeled by MITC4 shell (Dvorkin and Bathe, 1984, Lee *et al*. 2008, Lee *et al*. 2014). The size of longitudinals, and requirements for hull thickness were determined by considering the CSR for the bulk carrier, see Table 3. Concrete material is used in the connective part, and hexahedron solid element is used for its FE modeling. The total number of DOFs of the FE model is about 110,000, see Fig. 7.

In FE analysis, ship structures are generally considered a simply supported beam. Therefore, both ends of the FE model are to be simply supported using independent points, which are the end points at neutral axis on centerline. The simple support conditions are applied to these independent points, and since there are no deformations at the ends of simply supported beam, all the nodes on the longitudinal members at both end sections are to be linked rigidly to these independent points (IACS 2006, Servis *et al*. 2003). The details of the boundary conditions are shown in Table 4.

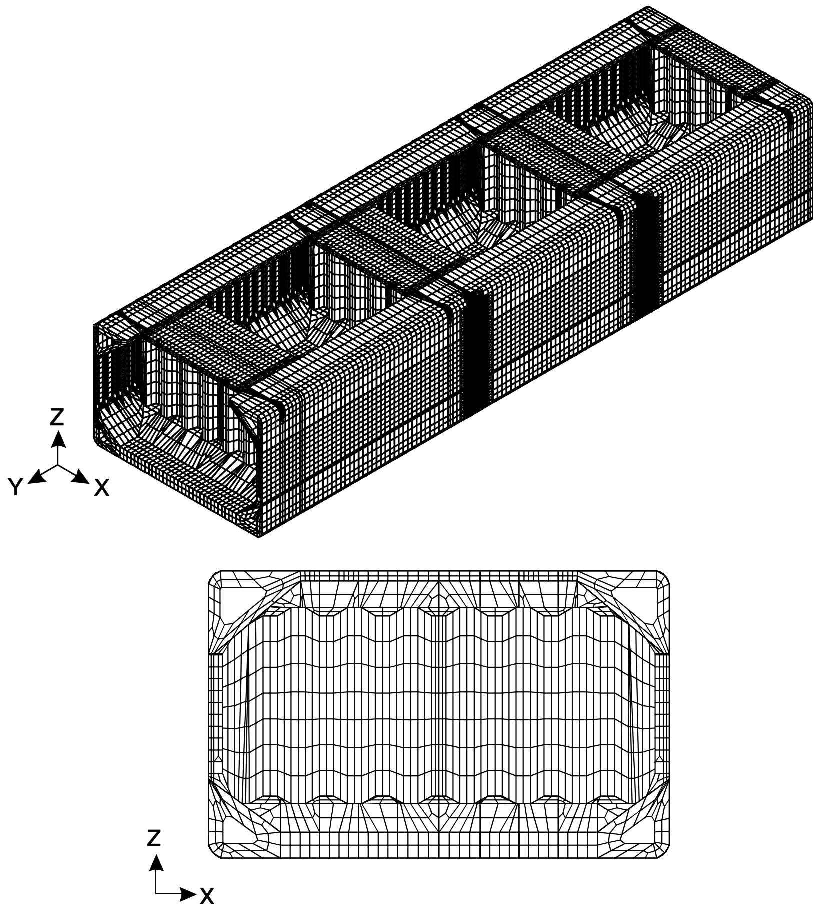



Fig. 7 FE model of bulk carrier

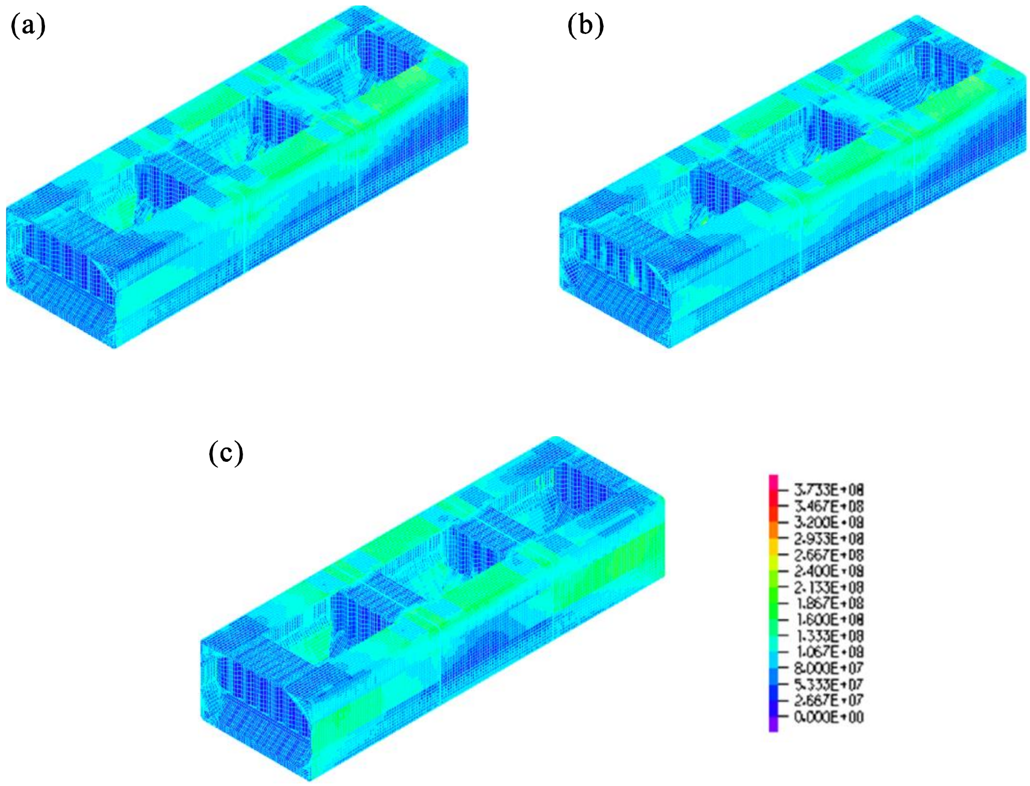



Fig. 8 Effective stresses of bulk carrier (N/m$^2$): (a) Case 1, (b) Case 2, and (c) Case 3

Table 5 Loading cases of bulk carrier

| Case | Draught ($T_s$) | Loading pattern (t/m$^3$) | Aft | Mid | Fore | Design wave |
|---|---|---|---|---|---|---|
| 1 | 8.32 m | 3.0 3.0 3.0 | | | | Beam sea |
| 2 | 8.32 m | 1.0 1.0 1.0 | | | | Beam sea |
| 3 | 8.32 m | 3.0 3.0 | | | | Following sea |

From among the loading cases described in the CSR of the bulk carrier, three loading cases that lead to the most severe tensile stress for the connective part were chosen to be analyzed, see Table 5. Here, $T_s$ is scantling draught that is the maximum draught condition. In design wave, beam sea means that waves come from the vertical direction of the ship, and following sea means that waves come following the direction of the ship movement. The calculated effective stresses for the three

Table 6 Stress assessment of bulk carrier

| Group | Thickness | Effective stresses of loading cases (MPa) | | | Allowable stress (MPa) |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| Concrete | 160 | 22.3 | 21.5 | 28.4 | 40 |
| Inner side steel plate | 30 | 302.9 | 296.1 | 343.0 | 345.6 |
| Back side steel plate | 25 | 118.0 | 116.6 | 137.9 | 235 |
| Outer side steel plate | 30 | 271.4 | 270.4 | 319.1 | 345.6 |
| Deck | 45 | 200.8 | 212.1 | 280.9 | 301.3 |
| Steel bar | - | 324.6 | 321.3 | 311.6 | 345.6 |

Table 7 Stiffener size and hull thicknesses of the connective part in oil tanker

| Items | Minimum (mm) | Maximum (mm) |
|---|---|---|
| Deck | 16 | 18 |
| Outer side plate | 16 | 18 |
| Inner side plate | 14 | 16 |
| Outer bottom plate | 18 | 20 |
| Inner bottom plate | 16 | 18 |
| Tank bottom plate | 16 | 18 |
| Longitudinal girder | 16 | 18 |
| Horizontal stringers | 14 | 20 |
| Transverse bulkhead | 16 | 18 |
| Longitudinal bulkhead | 16 | 18 |
| Horizontal girder | 18 | 18 |
| Longitudinals | 283×9+100x14 | 333×9+100×19 |

loading cases are plotted in Fig. 8, and those details are presented in Table 6.

In the CSR for the bulk carrier, the allowable stress of steel is defined by

$$\sigma_{allow} = \frac{235}{k} \quad \text{with} \quad k = \begin{cases} 1.00 & \text{mild steel,} \\ 0.78 & \text{higher strength steel in grade 32,} \\ 0.68 & \text{higher strength steel in grade 40.} \end{cases} \tag{6}$$

Considering the calculated effective stresses, the backside steel plate and deck could be constructed using mild steel or higher strength steel (Grade 32). However, the higher strength steel should be used for the steel bars and other steel plates in the connective part. For the concrete parts, the low level allowable stress, generally 40 MPa, is enough in these three loading cases.

### *4.2 Analysis of an oil tanker*

Here, we consider an oil tanker. The specific size of its connective part was presented in Table 2. The size of longitudinals and requirements for hull thickness were determined by considering the CSR for oil tankers, see Table 7. The FE model of the oil tanker is modeled by 100,000 DOFs.

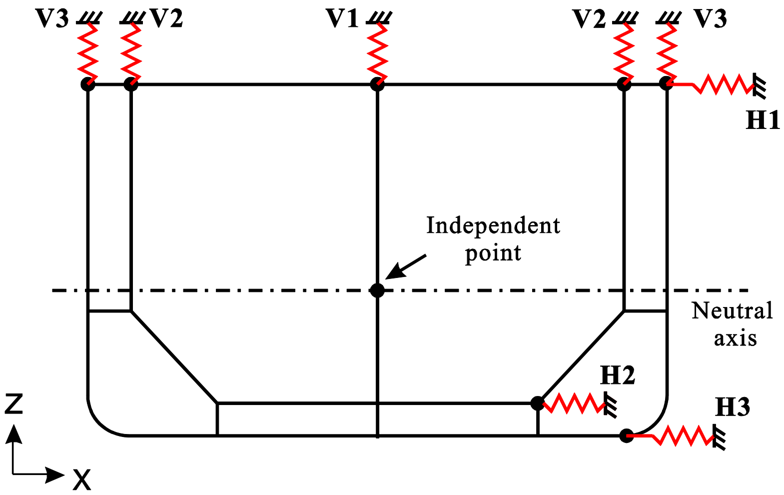



Fig. 9 Arrangement of ground spring elements in oil tanker

Table 8 Gound spring elements in oil tanker

| Spring elements | | $A_{net}$ (mm$^2$) | $k_s$ (MPa) |
|---|---|---|---|
| Vertical direction | V1 | 420.8 | $13.64\times10^3$ |
| | V2 | 464.4 | $15.05\times10^3$ |
| | V3 | 657.5 | $21.31\times10^3$ |
| Horizontal direction | H1 | 413.1 | $13.39\times10^3$ |
| | H2 | 442.8 | $14.35\times10^3$ |
| | H3 | 577.5 | $18.72\times10^3$ |

Table 9 Boundary conditions of oil tanker

| Location | | Translational | | | Rotational | | |
|---|---|---|---|---|---|---|---|
| | | $D_x$ | $D_y$ | $D_z$ | $R_x$ | $R_y$ | $R_z$ |
| Aft end | Longitudinal members | RL | | | | RL | RL |
| | Independent point | Fixed | - | - | - | - | - |
| | Deck | - | Spring+ | - | - | - | - |
| | Inner and outer bottom plates | - | - | Spring | - | - | - |
| Fore end | Longitudinal members | RL | | | | RL | RL |
| | Independent point | - | - | - | - | - | - |
| | Deck | - | Spring | - | - | - | - |
| | Inner and outer bottom plates | - | - | Spring | - | - | - |

+ Spring means the ground spring element.

The boundary conditions of the oil tanker are very similar to those of the bulk carrier, but, in the analysis of the oil tanker, ground spring elements are added to reduce the stress concentration caused by the rigid link between the independent points and the nodes of the end section. The spring constant $k_s$ of the individual ground spring element, to be applied at each end of the cargo tank model, is given by (IACS 2006)

$$k_s = 0.77 \frac{A_{net} E_s}{L_t N_p}, \tag{7}$$

where $A_{net}$ is the shearing area of the individual structural member under consideration, $L_t$ is the length of cargo tank between bulkheads, and $N_p$ is the number of nodal points to which ground spring elements are applied to the structural member. In this study, we here use $L_t$=36 m and $N_p$=132. The arrangement and details of the ground spring elements are presented in Fig. 9 and Table 8, respectively. The boundary conditions of the oil tanker are shown in Table 9. These were conducted in accordance with Appendix B.2.6 of the CSR for oil tankers (IACS 2006).

We selected three representative loading cases from the CSR for oil tankers, see Table 10. The calculated effective stresses in the three loading cases are presented in Fig. 10 and Table 11. Head sea means that the wave comes from the head direction of the ship.

In the CSR for oil tankers, the maximum yield stress of steel is defined as

$$\sigma_{\max} = \gamma \sigma_{yd} \quad \text{with} \quad \gamma \leq 0.9, \tag{8}$$

where $\sigma_{yd}$ and $\gamma$ are the yield stress and safety factor, respectively, and it should be no greater than 315 MPa. As a result, the maximum yield stress of steel in the connective part is 283.5 MPa, and this value satisfies the effective stresses calculated for the oil tanker. The effective stress on the concrete part is also acceptable, see Table 11.

### *4.3 Torsional stiffness*

For a ship hull with large deck openings such as bulk carriers, it is necessary to investigate the hull girder response to torsion. In this section, we compare the torsion response of ships built using conventional shipbuilding, and using the proposed new assembly method.

For FE modeling of the bulk carrier using the new block assembly method, the same FE model used in Section 4.1 is used again. However, the boundary condition is slightly different. It has the same rigid links, but all DOFs at the nodes of the unloaded end of the model are fixed, and other DOFs at the other end of the model are set to be free (Paik *et al*. 2001). The FE model of the bulk carrier using the conventional shipbuilding method can be similarly constructed except for the connective parts.

For torsional stiffness analysis, a single wave torsional moment $M_{WT}$ is considered. In the CSR for bulk carriers, $M_{WT}$ is defined as

$$M_{WT} = \left|M_{WT_1}\right| + \left|M_{WT_2}\right|, \tag{9}$$

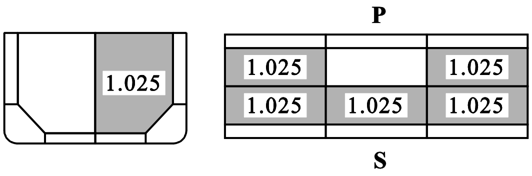
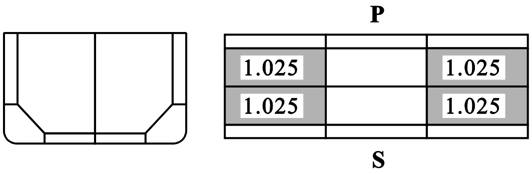
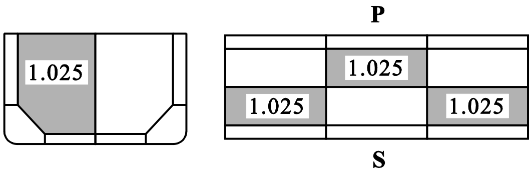
with

$$M_{WT_1} = 0.4C\sqrt{\frac{L}{T_s}}B^2 DC_b \sin\left(\frac{2\pi y}{L}\right), \tag{10a}$$

$$M_{WT_2} = 0.22CLB^2 C_b \sin\left(\frac{\pi y}{L}\right), \tag{10b}$$

where $y$ is the location of the longitudinal axis. Note that the FE model here is not the whole bulk carrier model, but only three cargo holds ($0.2L \leq y \leq 0.8L$). To calculate the maximum value, the torsional bending moment is applied to one end of the bulk carrier ($y$=0.2$L$). Then, using Eq. (9), a

Table 10 Loading cases of oil tanker

| Case | Draught ($0.9T_s$) | Loading pattern (t/m$^3$) | Design wave |
|---|---|---|---|
| 1 | 15.75 $m$ |   | Head sea |
| 2 | 15.75 $m$ |   | Head sea |
| 3 | 15.75 $m$ |   | Head sea |

Port (P), Starboard (S)

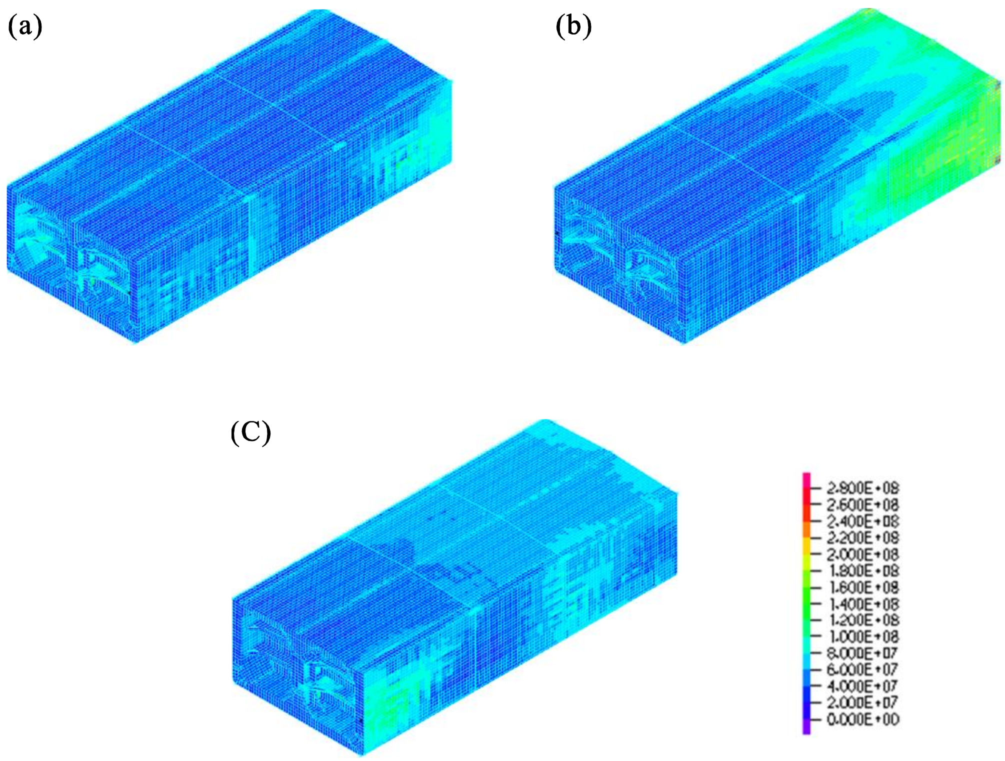



Fig. 10 Effective stresses of oil tanker (N/m$^2$): (a) Case 1, (b) Case 2, and (c) Case 3

Table 11 Stress assessment of oil tanker

| Group | Thickness | Effective stresses of loading cases (MPa) | | | Yield stress (MPa) |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | |
| Concrete | 160 | 19.4 | 23.0 | 17.9 | 40 |
| Inner side steel plate | 20 | 108.4 | 109.5 | 126.5 | 283.5 |
| Back side steel plate | 30 | 166.7 | 189.7 | 126.6 | 283.5 |
| Outer side steel plate | 25 | 111.2 | 137.8 | 108.7 | 283.5 |
| Deck | 25 | 86.5 | 268.5 | 106.8 | 283.5 |
| Steel bar | - | 197.7 | 232.5 | 147.7 | 283.5 |

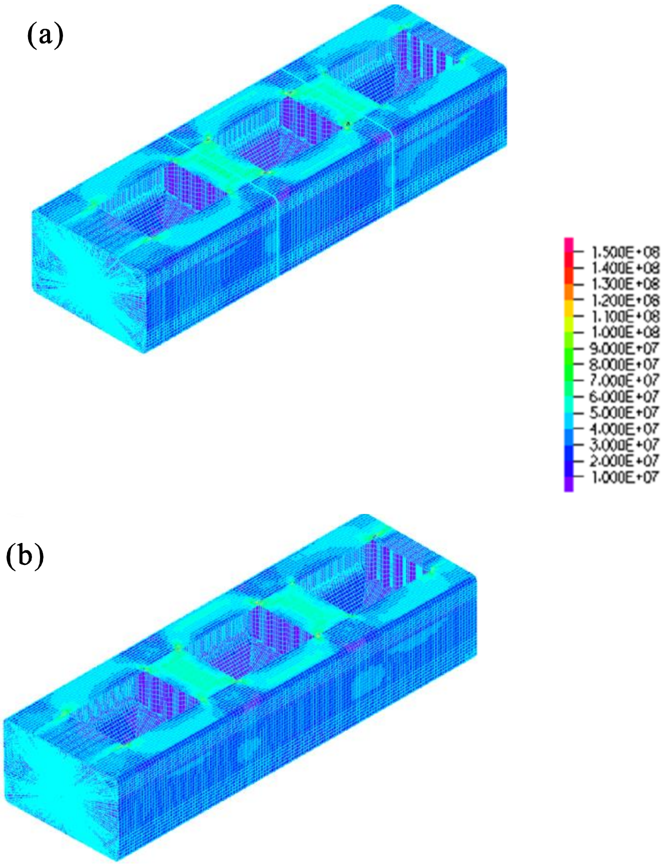



Fig. 11 Effective stresses of torsion in bulk carrier (N/m$^2$): (a) The new block assembly method, (b) The conventional shipbuilding method

single wave torsional moment $M_{WT}$ of the bulk carrier is calculated as $5.21\times10^5$ KNm.

Fig. 11 shows the effective stresses of the bulk carrier FE models using conventional shipbuilding and the new block assembly methods, and the maximum effective stress of the ship structure members was compared, see Table 12. It clearly shows that the maximum effective stress, when using the new assembly method, is generally much lower than the stress of the conventional shipbuilding method. As a result, when the new assembly method is used, the

Table 12 The maximum effective stress under torsion

| Section | Conventional shipbuilding method (MPa) | New block assembly method (MPa) |
|---|---|---|
| Transverse bulkhead | 58.37 | 27.04 |
| Stool | 139.53 | 152.21 |
| Inner bottom | 15.08 | 14.58 |
| Topside tank bottom | 215.84 | 124.33 |
| Longitudinal girder | 162.18 | 94.17 |
| Deck knee | 165.73 | 94.12 |
| Side plate | 42.61 | 41.26 |
| Downside tank bottom | 140.74 | 20.62 |
| Deck | 184.05 | 84.65 |
| Outer bottom plating | 40.64 | 37.27 |

Table 13 Weight and volume changes of ship hull

| | | Conventional shipbuilding method | New block assembly method |
|---|---|---|---|
| Bulk carrier (80,000 DWT) | Hull weight (ton) | $28.865\times10^3$ | $28.919\times10^3$ |
| | Volume of a cargo hold ($m^3$) | $14.559\times10^3$ | $14.548\times10^3$ |
| Oil tanker (159,000 DWT) | Hull weight (ton) | $41.990\times10^3$ | $42.072\times10^3$ |
| | Volume of a cargo hold ($m^3$) | $26.459\times10^3$ | $26.459\times10^3$ |

attachment by connective parts could help increase the strength of the whole ship to resist wave torsional moment.

## 5. Weight and volume changes

To evaluate the economic feasibility of the new block assembly method, we investigated cargo capacity considering ship weight and volume changes caused by the addition of the connective parts. The bulk carrier and oil tanker were also considered. The FE model data in ADINA was used to calculate the hull weight and volume of a cargo hold for the two target ships. Especially, the weights in two target ships can be got directly in ADINA. Note that, for the attachment of the connective part, it is only the part of concrete and the small steel plates to embrace the concrete that cause the weight change.

The volume change of a cargo hold is also simply calculated. In the bulk carrier with single hull, only the side of the connective part has influence to the cargo volume. In the target bulk carrier, the connective part length is 0.45 m, width is 0.16 m, and the length between inner bottom and deck is 12.7 m. Then, the volume change caused by a connective part is 1.83 $m^3$, and the total volume change of a cargo hold is 11 $m^3$. Unlike the bulk carrier with single hull, the oil tanker has no influence to the volume change by the new assembly method because it is double hull.

The hull weight and volume of a cargo hold for the two target ships are presented in Table 13. It shows that changes of hull weight and cargo volume with the new assembly method are under 0.2% for both target ships. As a result, it could be seen that the attachment using the proposed connective parts exert almost no influence on the ship weight and cargo volume (new method does not reduce cargo capacity).

## 6. Conclusions

We have proposed a new method to assemble ship blocks at sea without additional dock facility. Using prefabricated ship blocks with the proposed connective parts, assembly at sea become easy. In the proposed method, bolting, gluing, and welding methods are used to tightly assemble the ship blocks. We conducted strength analysis for the hull of ships with sections attached using connective parts (potentially stronger), and the weight and volume changes caused by applying the new assembly method were investigated (trivial loss of cargo space). Those numerical results demonstrate the structural safety and the economic feasibility of the proposed new assembly method.

Applying this method, shipyard construction productivity could be improved (rapid turnover of dry docks) and ultimate ship size would not be related to the size of dry docks. Although the new block assembly method is only considered here as a shipbuilding process, it could also provide a new way to assemble large offshore structures. However, to employ the proposed assembly method in practical construction, study of local effects such as fatigue and buckling need to be conducted, and other CSR requirements must be investigated in the future.

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