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Ultimate strength performance of Northern sea going non-ice class commercial ships

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Abstract. In the early design stage of ships, the two most important structural analyses are performed to identify the structural capacity and safety. The first step is called global strength analysis (longitudinal strength analysis or hull girder strength analysis) and the second step is local buckling analysis (stiffened panel strength analysis). This paper deals with the ultimate strength performance of Arctic Sea Route-going commercial ships considering the effect of low temperature. In this study, two types of structural analyses are performed in Arctic sea conditions. Three types of ship namely oil tanker, bulk carrier and container ship with four different sizes (in total 12 vessels) are tested in four low temperatures (−20, −40, −60 and −80°C), which are based on the Arctic environment and room temperature (20℃). The ultimate strength performance is analysed with ALPS/HULL progressive hull collapse analysis code for ship hulls, then ALPS/ULSAP supersize finite element method for stiffened panels. The obtained results are summarised in terms of temperature, vessel type, vessel size, loading type and other effects. The important insights and outcomes are documented.

Keywords: ultimate strength performance; Arctic; Northern Sea Routes; oil tankers; bulk carriers; container ships

1. Introduction

The global warming has brought about many undesired changes such as the various environmental problems including rising sea level, storms, floods, drought, losing of biodiversity and destruction of ecosystems. Therefore, industry stakeholders have introduced legislation to limit these impacts. A number of efforts are now being made to keep a development-free environment or called green growth (IMO 2008, 2009, 2010).

On the other hand, the decreasing polar ice extent has opened the Northern Sea Routes (NSR) as an advantage of global warming. Shipping on NSR has more cost benefits compared to other

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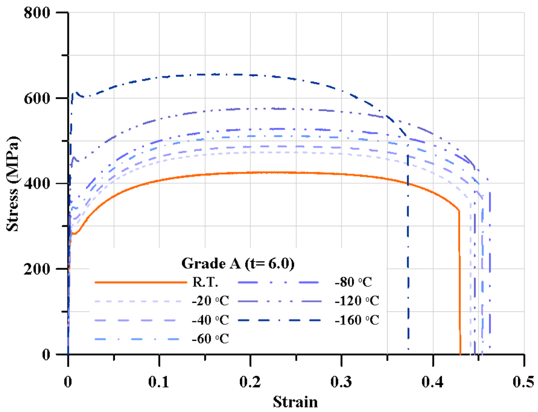
Fig. 1 Configuration of Northern Sea Route and Southern Sea Route (Vidal 2011)

routes. It is reported that the Northern Route may reduce not only the distance (almost 40%) but also shipping period (around 35%). For example, the transportation of cargoes from Busan port (Korea) to Rotterdam port (Netherlands) across the Northern Sea Route takes only 14 days in a distance of 12,700km. But, through the Southern Sea Route, it takes 24 days in a distance of 20,100km, as shown in Fig. 1 (Kwon 2013). Moreover, in 2008 the United States Geological Survey (USGS) estimated that the Arctic might contain 13% of the world's undiscovered oil and 30% of its undiscovered gas. Of these hydrocarbon resources, 84% are believed to be offshore, mostly in waters less than 500m deep (DNV 2012). These two main benefits have led to the increasing interests in the Arctic operating structures.

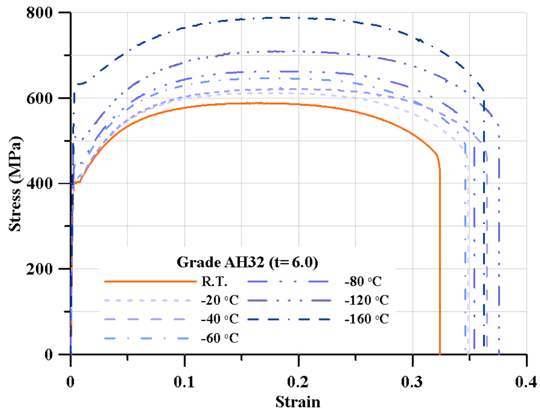
However, ice-free navigation through the NSR is time-limited for about three months per year and requires appropriately strengthened hulls or ice breaker support for safe passage (Wikipedia 2014). Therefore, additional construction cost will be charged for NSR-going vessels due to different environmental conditions including low temperature and ice load.

Therefore, to avoid such cost, one of the good alternative ideas is using normal sea-going vessel in Arctic Sea Route during its opening season. In this study, the ultimate strength performance of normal sea-going commercial ships, which are assumed to be able to operate in Arctic sea route, is investigated. Two main objects are namely ultimate hull girder strength behaviour and ultimate stiffened panel strength behaviour.

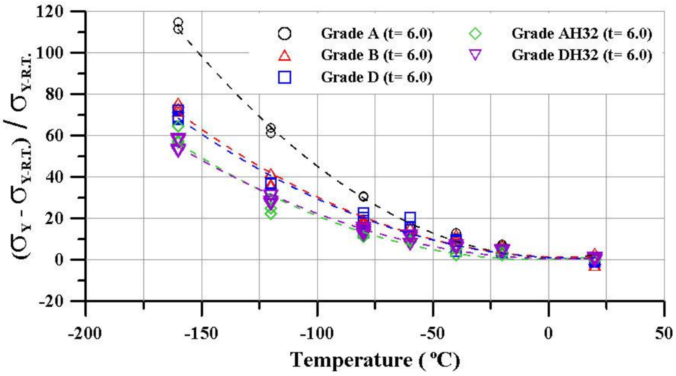
Arctic sea conditions and the effects on material properties are presented in Section 2. In addition, a method for applying the material properties under low temperature to the ship structures is covered in the Section. Based on this assumption, applied examples of twelve representatives of normal sea-going commercial ships are addressed in Section 3. Ultimate strength analysis of both hull girders and stiffened panels are also illustrated in the Section. After that, Arctic sea effects on ultimate strength performance of all structures are analysed and concluded in Sections 3 to 5.



(a) Engineering stress versus engineering strain curves of Grade A mild steel



(b) Engineering stress versus engineering strain curves of Grade AH32 high tensile steel



(c) The ratios of yield strength to temperature on different grades carbon steel

Fig. 2 Material properties at low temperatures

2. Northern sea condition

2.1 Explanation of Arctic environment condition

The NSR provides us a decided advantage in the shipping as shown in Fig. 1. On the other hand, it also demands us a conquest of the harsh environment. The Arctic's climate is characterised by cold winters and cool summers. Average winter temperatures can be as low as −40℃ and the coldest recorded temperature is approximately −68℃.

In the present study, to reflect the Arctic temperature condition, 6 temperature conditions are selected, namely room temperature (R.T., 20℃), 0, −20, −40, −60 and −80℃. In this regards, assumptions in this study are summarised as follows:

- New ice-class ship building is a heavy burden to the economy and time when it is performed only for the NSR voyage purpose.
- Non-ice class ships can sail though the ice-free NSR.
- The 12 normal (non-ice class) commercial ships are adopted for the purpose of the research. It is also assumed that global warming may continue the reduction of Arctic ice extent.

The details of analysis results for twelve vessels are covered in applied example Section.

Table 1 Yield strength on different materials at target temperatures

Material \ Temperature		20℃	0℃	−20℃	−40℃	−60℃	−80℃
MS24	σ_Y (MPa)	235.00	235.00	243.33	258.21	280.23	309.40
	$(\sigma_Y - \sigma_{Y\text{-}R.T.})/\sigma_{Y\text{-}R.T.}$ (%)	0.00	0.00	3.54	9.88	19.25	31.66
HT32	σ_Y (MPa)	315.00	315.00	315.32	323.79	337.81	357.37
	$(\sigma_Y - \sigma_{Y\text{-}R.T.})/\sigma_{Y\text{-}R.T.}$ (%)	0.00	0.00	0.10	2.79	7.24	13.45
HT36	σ_Y (MPa)	355.00	355.00	355.36	364.91	380.70	402.75
	$(\sigma_Y - \sigma_{Y\text{-}R.T.})/\sigma_{Y\text{-}R.T.}$ (%)	0.00	0.00	0.10	2.79	7.24	13.45

2.2 Material properties at low temperature

A series of tensile coupon tests were performed to investigate the material properties at low temperatures on metallic materials for ships (Park *et al*. 2013). In Figs. 2(a) to 2(c), the test results showed increase of strength and irregular fracture strain tendency as the temperature decreased, as shown in. The dramatic increase was observed to on Grade A mild steel than other grades of mild steel and it was relatively dull on high tensile steels. In the present study, the results on Grade A and Grade AH were used to estimate the yield strength of mild steel (MS), 32 Grade high tensile steel (HT32) and 36 Grade high tensile steel (HT36) at targeted low temperatures.

Test results set up two quadratic functions that compute the ratios of yield strength increase to temperature for each material. The estimated yield strengths of different grades of carbon steel at low temperatures with the quadratic functions are shown in Table 1. The estimation is based on the minimum yield strength requirements of materials (ASTM, 2008). Yield strength at 0℃ showed no difference with the R.T. on materials and increased with a same ratio with the test results. Next, the estimated material properties were used in ultimate strength analysis.

2.3 Application of material properties to vessels

Ship structures are subjected to various types of load, which may be grouped according to their characteristics in time: static loads, low-frequency dynamic loads, high-frequency dynamic loads and impact loads. In ship structural analysis and design, the most common loads are the static and low-frequency dynamic loads, the latter usually being treated as static or quasi-static loads.

A ship hull in an intact condition will sustain applied loads smaller than the design loads, and in normal seagoing and approved cargo loading conditions it will not suffer any structural damage such as buckling and collapse. However, the loads acting on the ship hull are uncertain both because of the nature of rough seas and because of possibly unusual loading/unloading of cargo. Therefore, present study did not considered dynamic hardening and DBTT (Ductile-Brittle Transient Temperature) which are important variables for structural analysis under high-frequency dynamic loads and impact loads.

Kim *et al*. (2012) performed low temperature effects on ultimate hull girder strength of commercial ships. But, they applied uniform temperature distribution on whole section of hull girders. In practice, temperature distributions are founded as shown in Fig. 3.

In this regards, following assumptions are applied in this study.

- Five types of Arctic temperatures (R.T. (or 0℃), −20, −40, −60 and −80℃) are applied to the hull girders that are exposed to air.

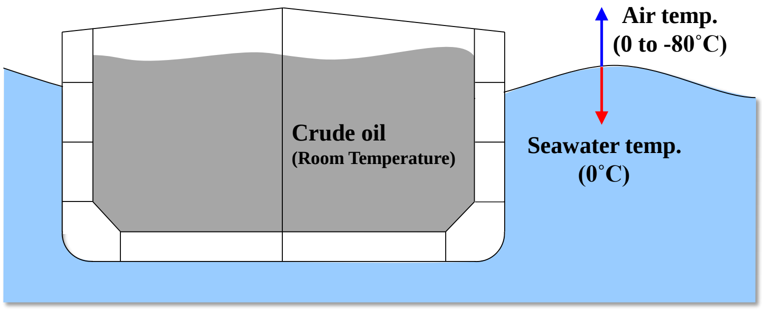
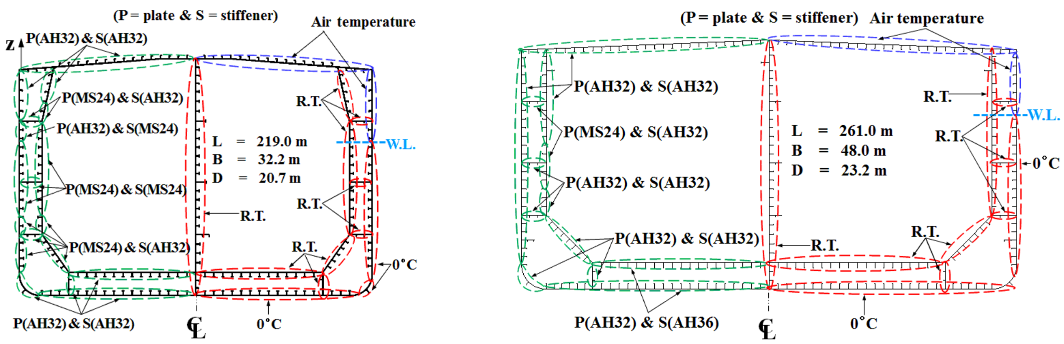


Fig. 3 Explanation of temperature distribution of Arctic sea-going vessel



(a) Panamax (b) Suezmax

Fig. 4 Midship section of oil tankers with applied temperature and material properties

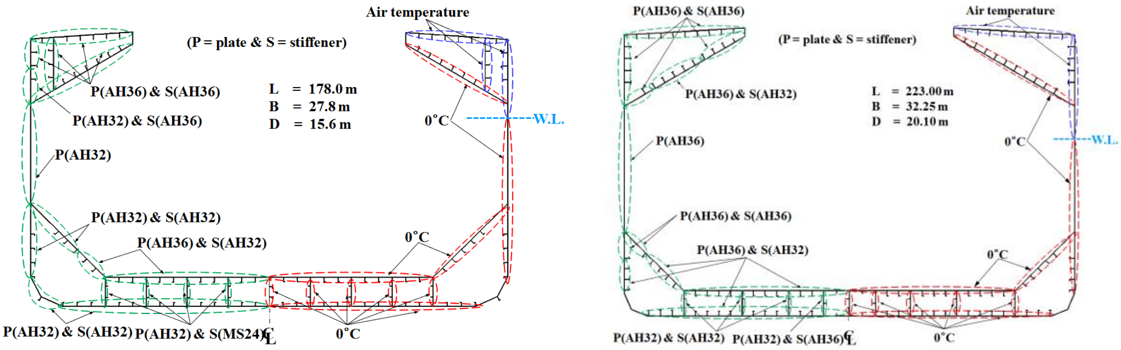
- In the case of Northern Sea Route voyage, unfrozen seawater condition is assumed and its temperatures are applied to 0℃.
- Seawater temperature (0℃) is applied to the hull girder structures below sea level.
- Temperatures of inner side shell are determined by cargo type.

Different temperatures are applied to the each vessel based on the above assumptions.

3. Applied examples

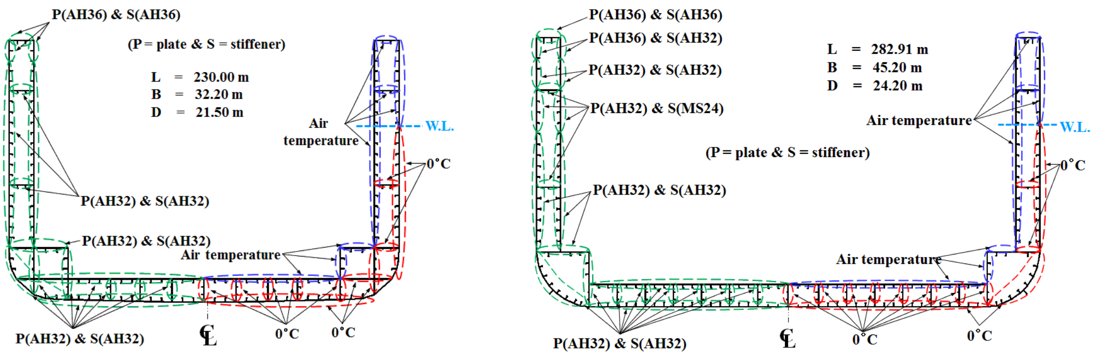
3.1 Target structures and temperature mappings

Three types of ships namely oil tanker, bulk carrier and container ship are selected as the most representative vessels that occupy up to 60 to 70% of whole operating vessels in several recent decades (ISF 2011). Four types of different size vessel per each ship type are selected. Twelve types of target structures namely 4 oil tankers (Panamax, Aframax, Suezmax and VLCC), 4 container ships (3500, 5000, 7500 and 13000 TEU) and 4 bulk carriers (Handysize, Supramax, Kamsarmax and Capesize) are considered in order to investigate the low temperature effects on hull girder structures. Principal dimensions with scantling draught data, which are the most important factor to consider the temperature distribution on outer side member, are presented in Figs. 4 to 6. Two types of different size are presented for each target structures.



(a) 37K Handysize (b) 82K Kamsamax

Fig. 5 Midship section of bulk carriers with applied temperature and material properties



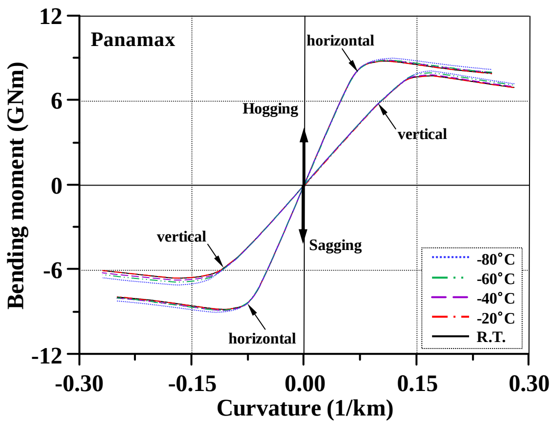
(a) 3,500 TEU (b) 7,500 TEU

Fig. 6 Midship section of container ships with applied temperature and material properties

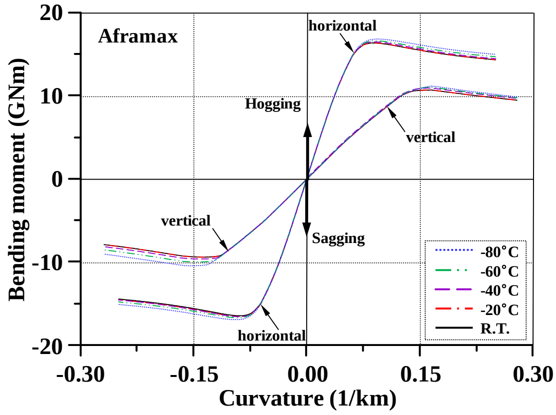
In the case of oil tanker, R.T. is applied to inner side members based on the oil heating, which is generally applied during operation. In the case of bulk carrier, 0℃ is applied to the inner side members based on the assumptions that inner side temperature is not lower than room temperature and the hatch cover. In practice, the same material properties are applied on inner side member for oil tankers and bulk carriers as there is no difference in terms of material properties between R.T. and 0℃ from the test results. In the case of container ships, ambient temperatures are applied to the deck and inner bottom members because this vessel has open type structures.

3.2 Ultimate strength analysis of hull girders

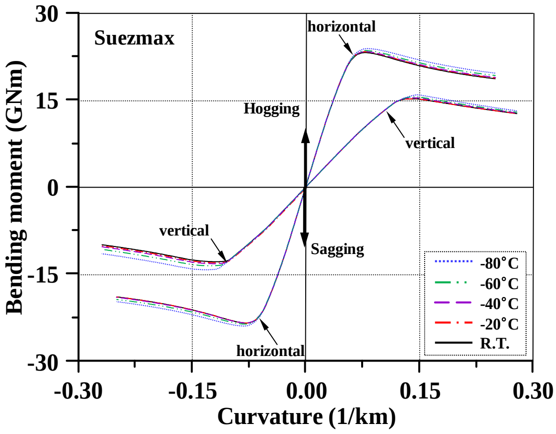
Global strength assessment for longitudinal strength and local strength assessment for buckling strength are carried out at the initiatory ship design stage. In this context, hull girder structure and stiffened panel structure are considered for the ultimate strength examination. There are several numerical methods to evaluate ultimate longitudinal strength performance of ships and ship-shaped offshore structure. With regard to this, numerous comparison studies have been performed to investigate their accuracy and efficiency subjected to corrosion (Kim *et al*. 2012a, b) and grounding (Paik *et al*. 2012, Kim *et al.* 2013).



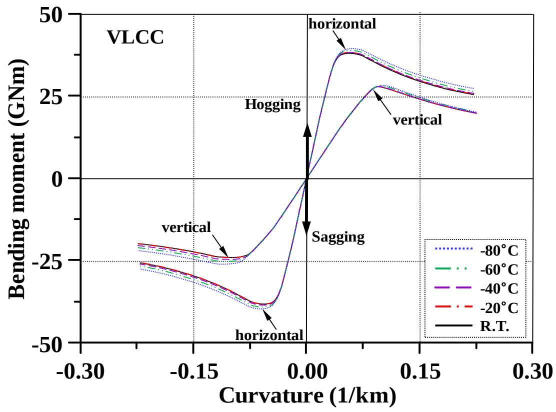
(a) Panamax



(b) Aframax

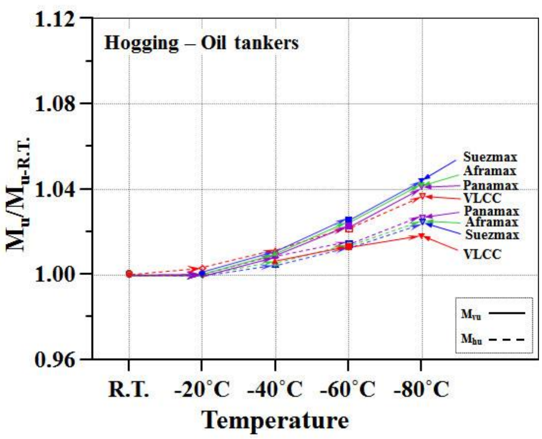


(c) Suezmax

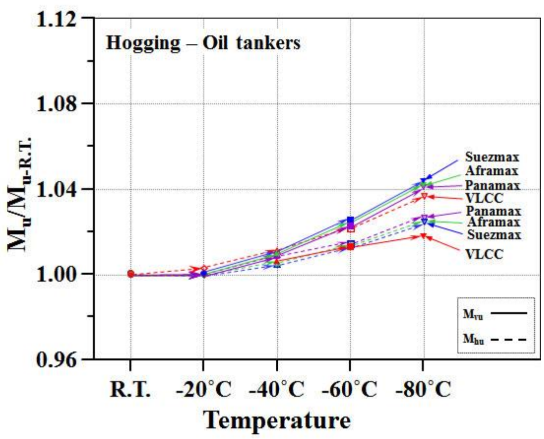


(d) VLCC

Fig. 7 Ultimate hull girder strength analysis for oil tankers



(a) In hogging



(b) In sagging

Fig. 8 Deviation of ultimate hull girder strength of oil tankers with temperature
(M_{vu}= ultimate vertical bending moment, M_{hu}= ultimate horizontal bending moment)

The ALPS/HULL progressive hull collapse analysis program is adopted for the ultimate hull girder strength analysis and ALPS/ULSAP buckling strength analysis for stiffened panel structures is used in this study. The details of ALPS/HULL program may be referred in Paik and Thayamballi (2003).

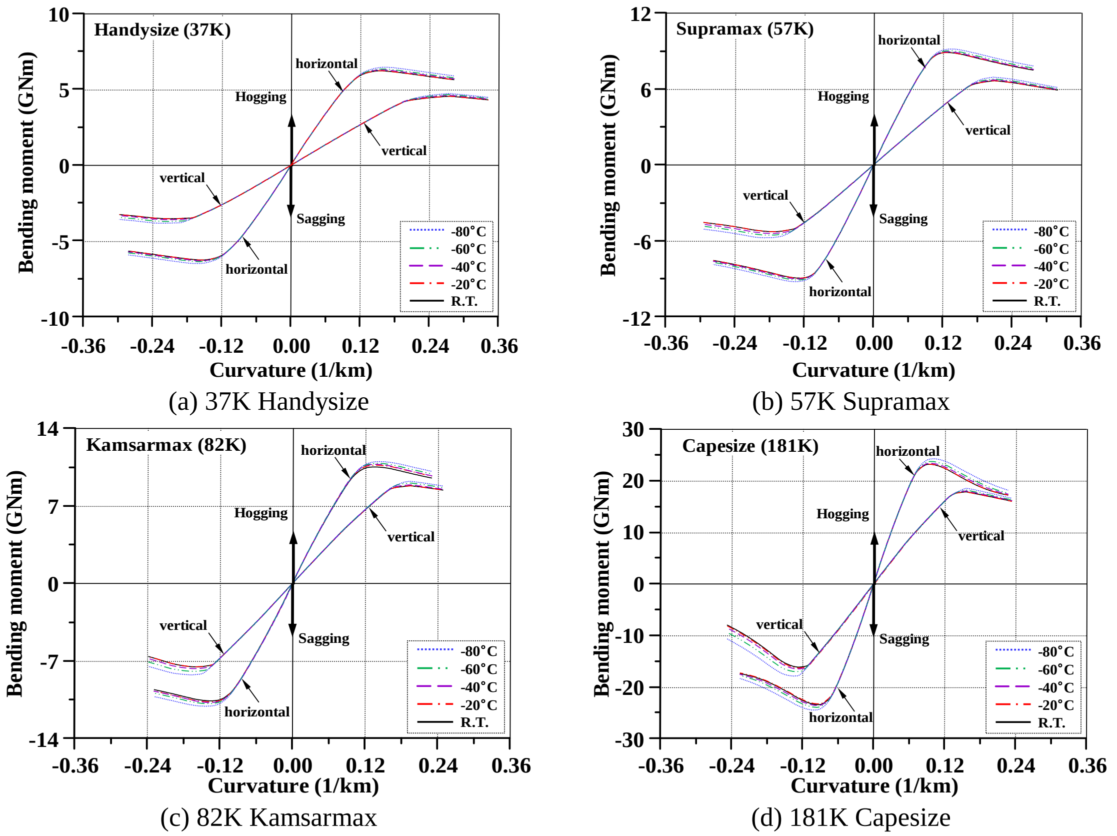
Structural initial imperfection of plate and stiffener members is considered as in Eq. (1).

$$w_{opl} = 0.1\beta^2 t, \qquad w_{oc} = w_{os} = 0.0015a \tag{1}$$

where,

a= the length of the stiffener (between transverse frames),
t= plate thickness,
w_{opl}= the maximum plate initial deflection,
w_{oc}= the column-type initial distortions of the longitudinal stiffeners,
w_{os}= the sideways initial distortion of the longitudinal stiffeners,
β= plate slenderness ratio.

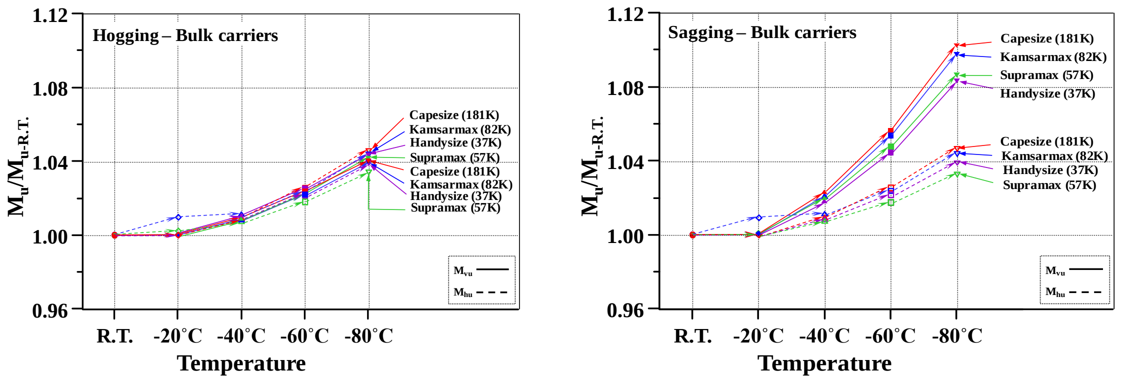
Generally, vertical bending moments (VBM) are mostly applied in ships and ship-shaped offshore structures. In this study, horizontal bending moments (HBM) are also considered for the purpose of the research. Figs. 7, 9 and 11 present analysis results of ultimate hull girder strength under VBM and HBM. Five air temperatures namely room temperature (R.T.), −20, −40, −60 and



(a) 37K Handysize (b) 57K Supramax

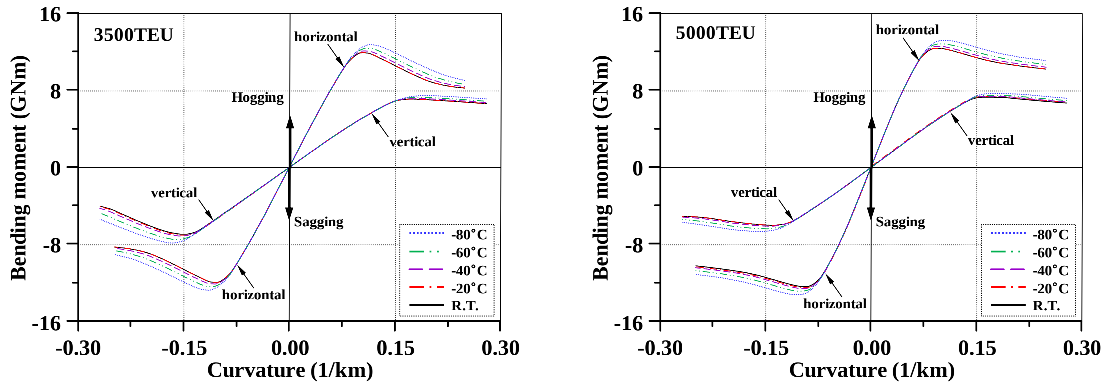
(c) 82K Kamsarmax (d) 181K Capesize

Fig. 9 Ultimate hull girder strength analysis for bulk carriers

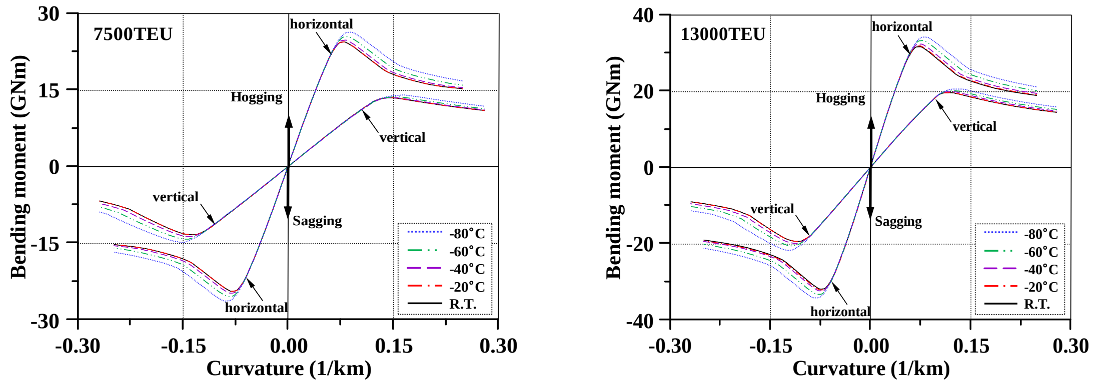


(a) In hogging (b) In sagging

Fig. 10 Deviation of ultimate hull girder strength of bulk carriers with temperature (M_{vu}=ultimate vertical bending moment, M_{hu}=ultimate horizontal bending moment)



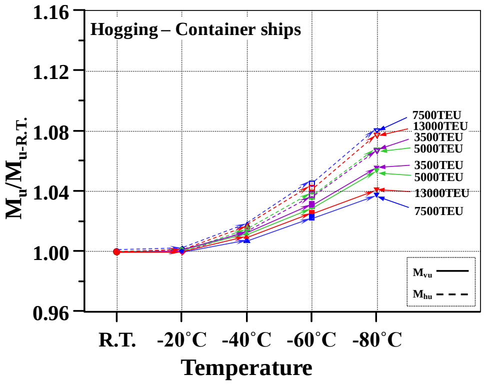
(a) 3,500 TEU (b) 5,000 TEU



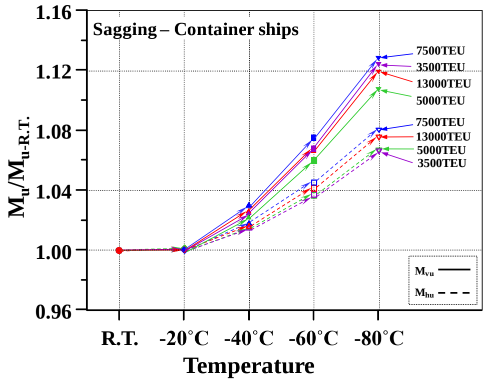
(c) 7,500 TEU (d) 13,000 TEU

Fig. 11 Ultimate hull girder strength analysis for container ships

−80℃ are applied for evaluating the ultimate strength performance of target structures. As mentioned earlier, in the case of 0℃, material tensile coupon test results are samewith R.T. Therefore, only room temperature case is analysed.



(a) In hogging



(b) In sagging

Fig. 12 Deviation of ultimate hull girder strength of container ships with temperature (M_{vu}= ultimate vertical bending moment, M_{hu}= ultimate horizontal bending moment)

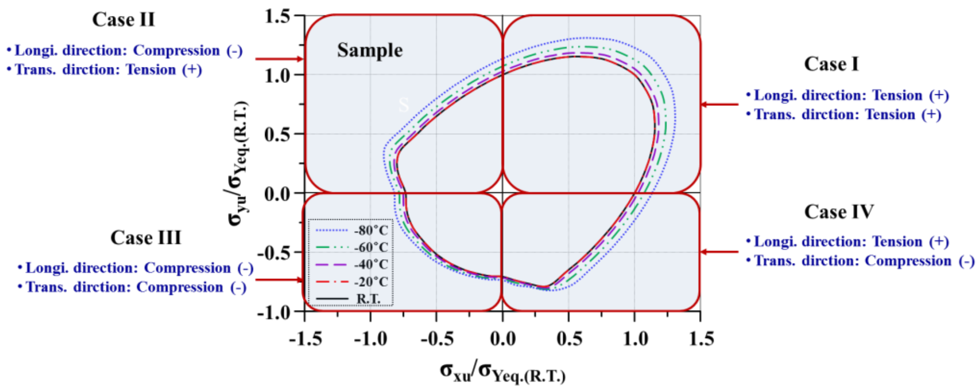


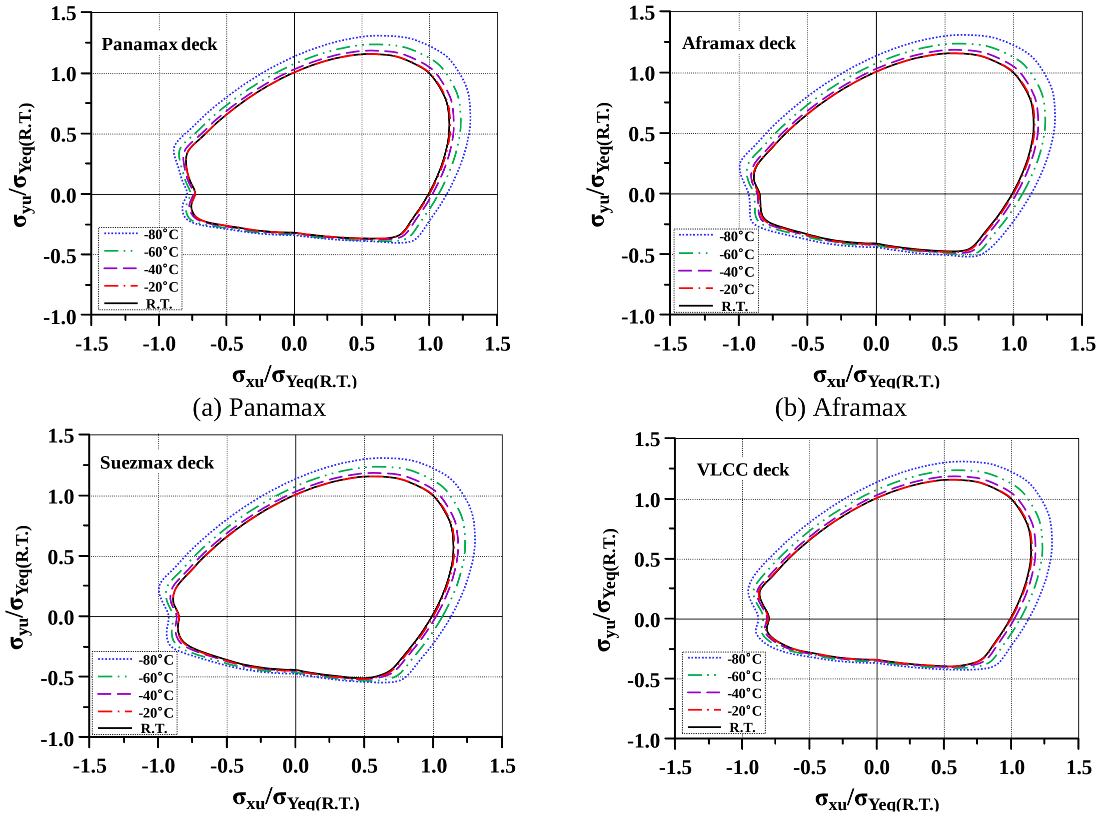
Fig. 13 Definition of analysis case of ultimate stiffened panel

To draw a general tendency, the obtained ultimate strength results are analysed by applying the consistent variables such as vessel size or carrying capacity. For example, ship length (L), deadweight (K) and shipping capacity of container box (twenty-foot equivalent units, TEU) are applied to the target ships as shown in Figs. 8, 10 and 12. Structural members above sea water level are exposed to Arctic ambient temperature, leading to the increase in the strength of materials. The deck part members are applied with compression in sagging. Therefore, the ultimate strength increase in sagging is greater than in hogging. This is observed in all the cases.

The ultimate hull girder strength of oil tankers and container ships increases as temperature decreases. But, it has an irregular tendency with ship capacity, while bulk carrier shows a proportional tendency to temperature decrease and capacity increase in sagging with VBM.

3.3 Ultimate strength analysis of stiffened panels

Generally, stiffened panels of deck and outer bottom parts are targeted for evaluating the local strength assessment at beginning state of ship design. In fact, axial forces such as tension (above the neutral axis of structural members under hogging moment and below the neutral axis of



(a) Panamax (b) Aframax

(c) Suezmax (d) VLCC

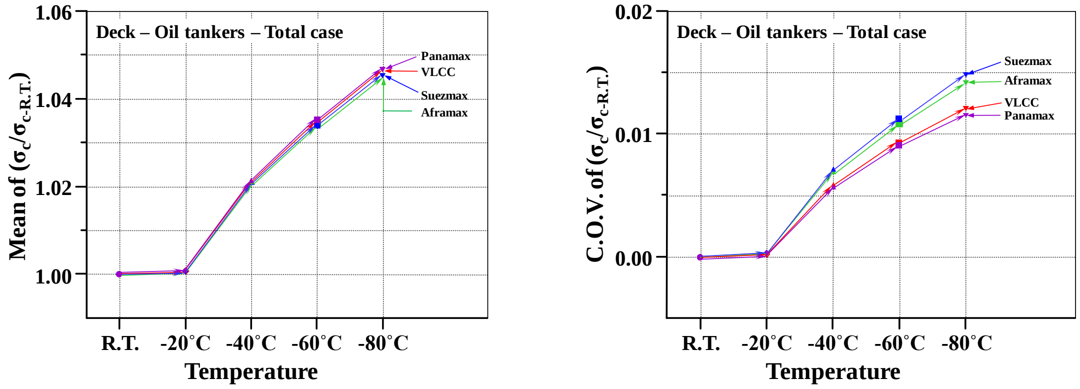
Fig. 14 Ultimate strength analysis of deck stiffened panel for oil tankers

structural members under sagging moment) and compression force (below the neutral axis of structural members under hogging moment and above the neutral axis of structural members under sagging moment) are applied at mid-ship section when the bending moments are applied. The maximum axial forces are applied to the farthest hull girder structural member from neutral axis of structure, i.e., deck and bottom structural members. In the present study, deck stiffened panel, which is exposed to Arctic ambient, is selected to investigate the low temperature effect on the ultimate strength of stiffened panels.

The applied loads shall be defined as four types of loading combinations (case I to case IV) as shown in Fig. 13. Next, Figs. 14, 16 and 18 present the ultimate strength analysis results.

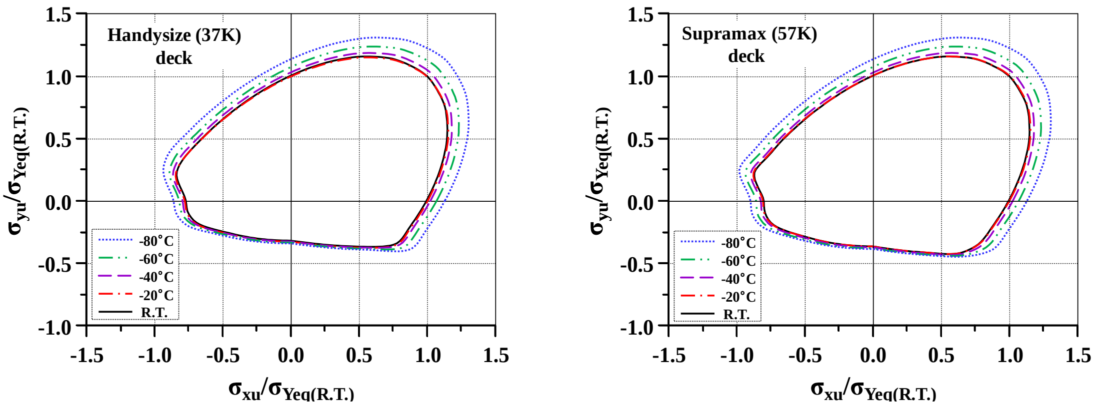
It is observed that the results of ultimate strength on oil tankers and bulk carriers are varied with the temperature decreases are slightly changed when the loading conditions are case III and case IV compared to the container ships. In these cases, scantlings of deck stiffened panels for container ships are significantly thicker than other ships. These thicker member have caused the fluctuation of ultimate stiffened panel strength of container ships.

Figs. 15, 17 and 19 show the summarised results in terms of mean values and coefficient of variation (C.O.V. or CV) depending on temperatures variation and vessel size. Generally, ship size has no effect on ultimate strength at low temperature on oil tankers and bulk carriers, but has effect on ultimate strength at low temperature on container ships. Low temperature has an effect on larger container ships than smaller ships. It is also found that the ultimate strength variation is proportional to the temperature decrease.

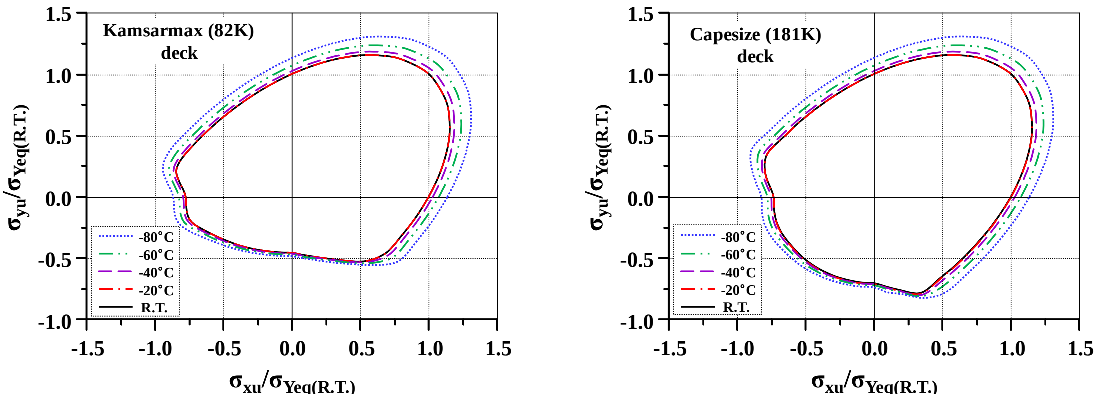


(a) Mean values (b) Coefficient of variations

Fig. 15 Deviation of ultimate stiffened panel strength of oil tankers with temperature

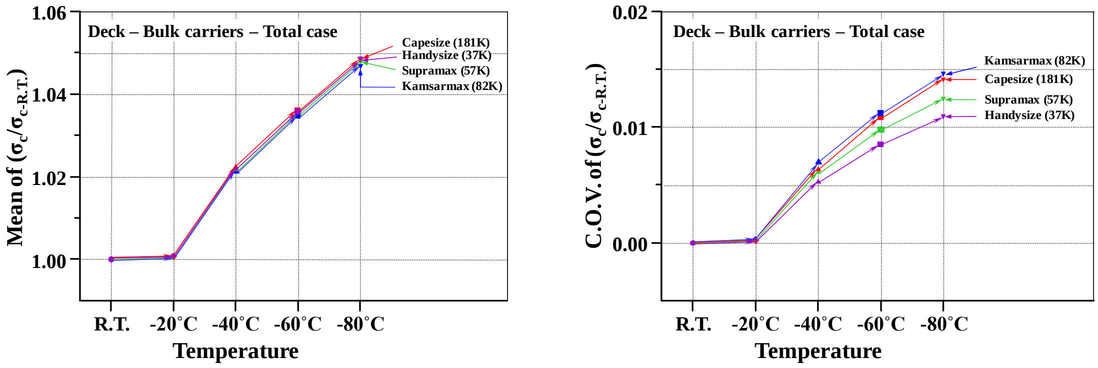


(a) 37K Handysize (b) 57K Supramax



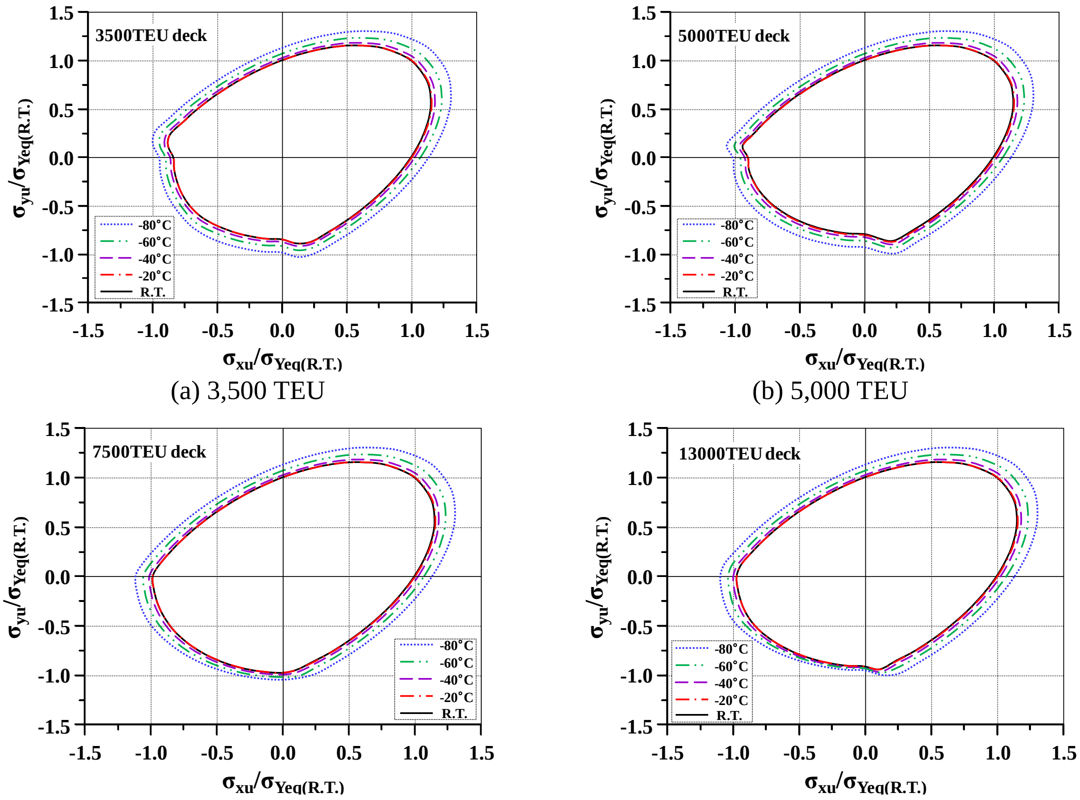
(c) 82K Kamsarmax (d) 181K Capesize

Fig. 16 Ultimate strength analysis of deck stiffened panel for bulk carriers



(a) Mean values (b) Coefficient of variations

Fig. 17 Deviation of ultimate stiffened panel strength of bulk carriers with temperature



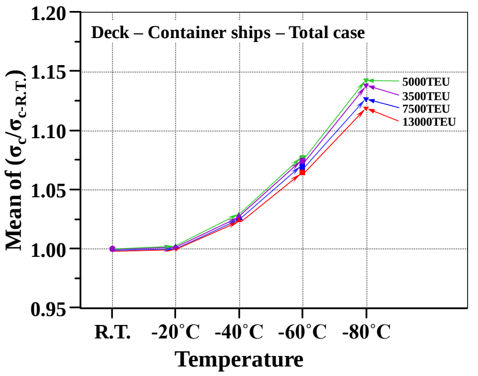
(a) 3,500 TEU (b) 5,000 TEU

(c) 7,500 TEU (d) 13,000 TEU

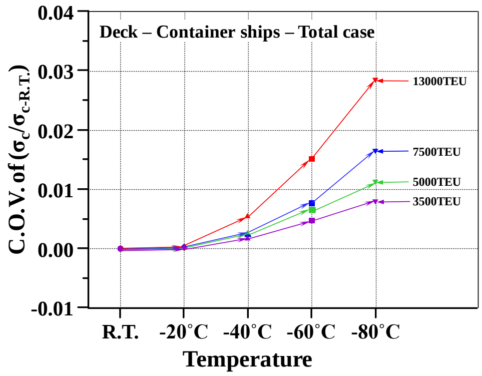
Fig. 18 Ultimate strength analysis of deck stiffened panel for container ships

4. Discussion

The ultimate strength of structures at low temperature increased less than the increase of yield strength. Less increase of the ultimate strengths for hull girder strength and stiffened panel at low



(a) Mean values



(b) Coefficient of variations

Fig. 19 Deviation of ultimate stiffened panel strength of container ships with temperature

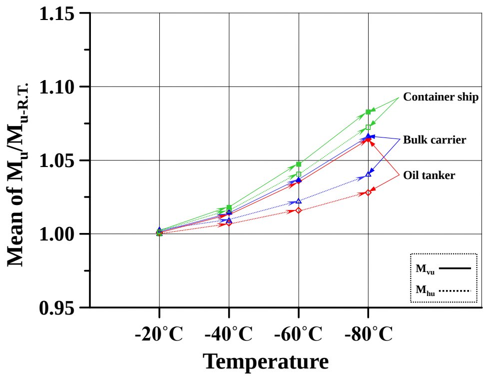


Fig. 20 Comparison of mean value for commercial ships in terms of ultimate longitudinal strength

temperature are also observed in previous studies (Kim *et al.* 2012, Kim *et al*. 2014). It attributes to a temperature mapping method and a progressive buckling. Different temperature mapping on different structure members relevant to a real operating situation affects it, i.e., higher temperature (lower strength) is also applied on structures with a low temperature environment as mentioned in Section 3.1. Moreover, a progressive buckling of structural members under increase load occurs. The most highly compressed member will collapse earlier and the stiffness of the overall hull will decrease gradually. As loads continually increase, buckling and collapse of more structural members will occur progressively until the ultimate limit state (ULS) is reached (Paik and Thayamballi 2003). In other words, the low temperature environment affected on the ultimate strength for hull girder strength and stiffened panel, but it was not the only variable in the ultimate strength estimation.

4.1 Hull girders

Figs. 21 to 23 show the variation of ultimate hull girder strength at different temperatures. Mean and C.O.V. are calculated with temperature variation as well. In case of vertical bending moment, as the temperature decreases, it is observed that the mean values are 0.1 to 6.4% for oil tankers, 0.1 to 6.7% for bulk carriers and 0.0 to 8.2% for container ships. On the other hand, as the temperature decreases under horizontal bending moment, the mean values are 0.1 to 2.8% for oil tankers, 0.3 to 4.1% for bulk carriers and 0.1 to 7.2% for container ships. Mean value increases higher under vertical bending moment than the mean value under horizontal bending moment for ships.

There are differences in hogging and sagging bending moment results under vertical bending moment between oil tankers and bulk carriers, as shown in Fig. 23(a). These differences are shown in Fig. 21(a) for oil tankers and Fig. 22(a) for bulk carriers. These differences could be due to the difference in terms of mid-ship shape and composition of materials of each structural member. On the other hand, hogging and sagging bending moment results under horizontal bending moment are similar for each type of ship.

The C.O.V. increases as the temperature decreases and it is sensitive under vertical bending moment. The increment largely varies in the order from the most sensitive to the least sensitive as follows: container ship, oil tanker and bulk carrier.

The effects of low temperature on each vessel size (i.e., length, shipping capacity and deadweight) are presented in Figs. 24 to 26. There are no significant differences covering the ship size of each type of vessel except for Panamax class oil tanker case in sagging. This difference is caused by ratio of ship breadth (B) to depth (D). The B/D ratios for other three oil tankers are 2.00 to 2.09, but the B/D ratio for Panamax class double hull oil tanker is 1.56.

From Figs. 21 to 26, it could be said that the ultimate hull girder strength is more sensitive to low temperature under vertical bending moment than under horizontal bending moment, except for container ships under hogging moment. Moreover, the low temperature has less effect on ship size, except for Panamax class oil tanker in sagging. The obtained results could be summarised as the following order and as shown in Fig. 20.

Ultimate hull girder strength variation at low temperature:

Oil tankers<Bulk carriers<Container ships under VBM&HBM

4.2 Stiffened panels

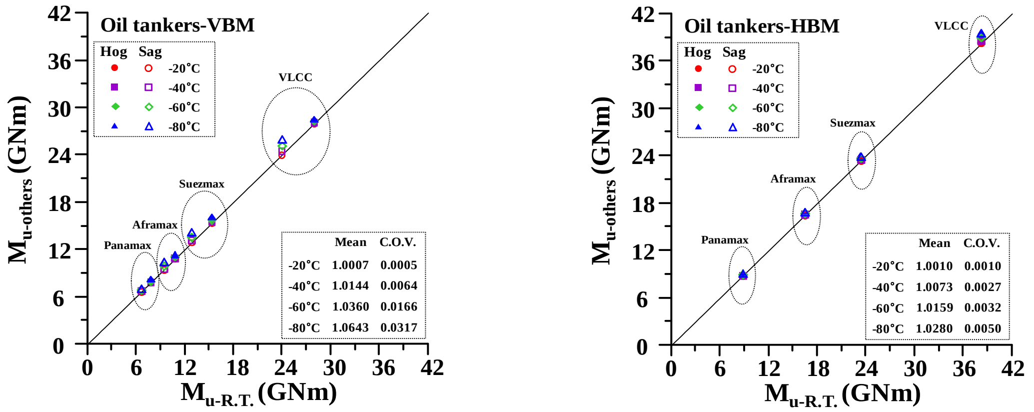
Figs. 27 to 29 show the variation of ultimate deck stiffened panel strength at different temperatures. Mean and C.O.V. values are calculated with temperature variation from the results. The mean values of ultimate deck stiffened panel strength in case I are same for the three types of ship, i.e., 0.1 to 13.5% for oil tankers, bulk carriers and container ships. The increase ratio is similar to that of material yield strength at low temperature for high tensile steel, as shown in Table 1 as the deck stiffened panels are made of high tensile steel, as described in Figs. 4 to 6.

The mean values in case III are at least 0.1 to 7.7% for oil tankers, 0.3 to 8.2% for bulk carriers and 0.1 to 12.2% for container ships. In other words, the low temperature effects are more sensitive for container ships than oil tankers and bulk carriers. Thick deck stiffened panels for container ships affected the ultimate deck stiffened panel strength.

Ultimate deck stiffened panel strength is more sensitive for oil tankers and bulk carriers when combination stress to equivalent stress increase in Figs. 27 and 28. On the other hand, the ultimate deck stiffened panel strength is similar for container ships in all cases, as shown in Fig. 29. The obtained results could be summarised as the following order:

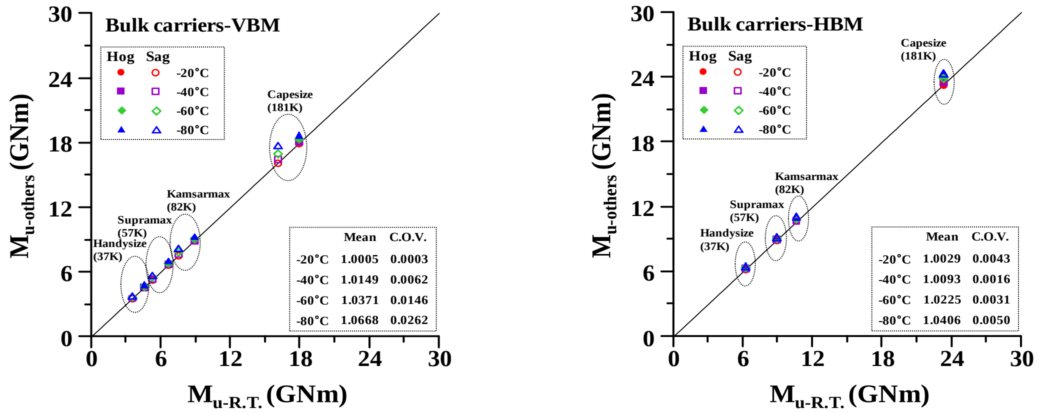
Ultimate deck stiffened panel strength variation at low temperature:

Oil tankers<Bulk carriers<Container ships



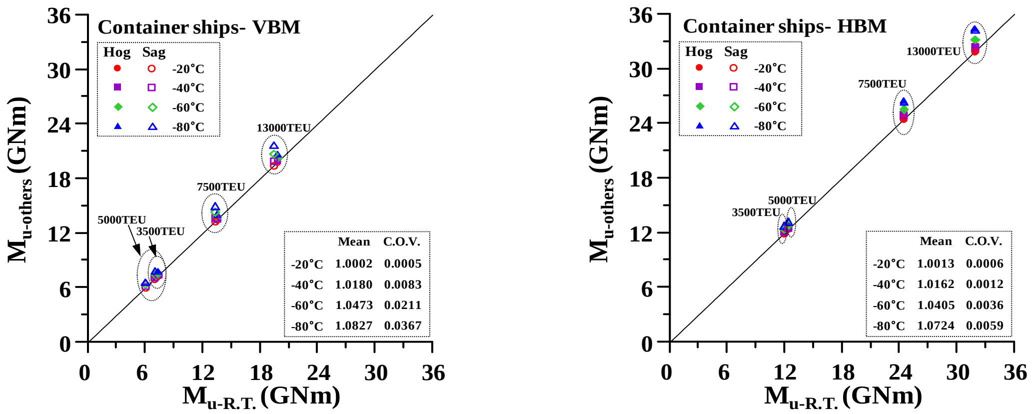
(a) Oil tankers - vertical bending moment (b) Oil tankers - horizontal bending moment

Fig. 21 Effect of temperature variation on ultimate hull girder strength of oil tankers



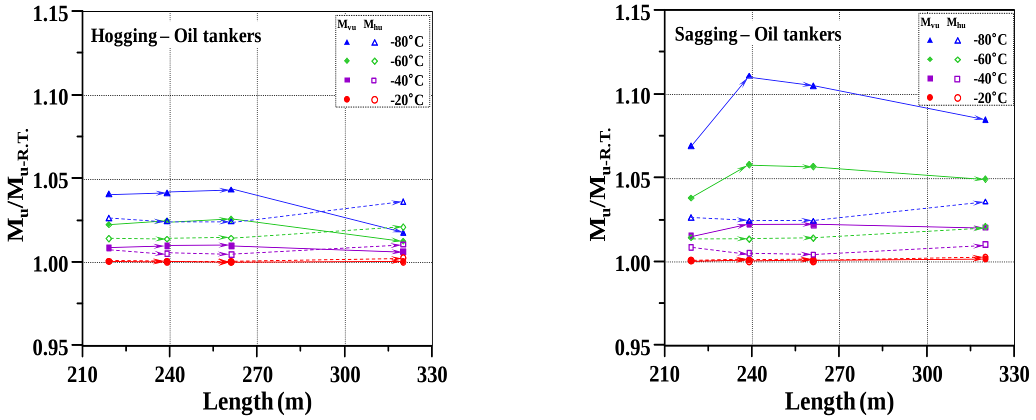
(a) Bulk carriers - vertical bending moment (b) Bulk carriers - horizontal bending moment

Fig. 22 Effect of temperature variation on ultimate hull girder strength of bulk carriers



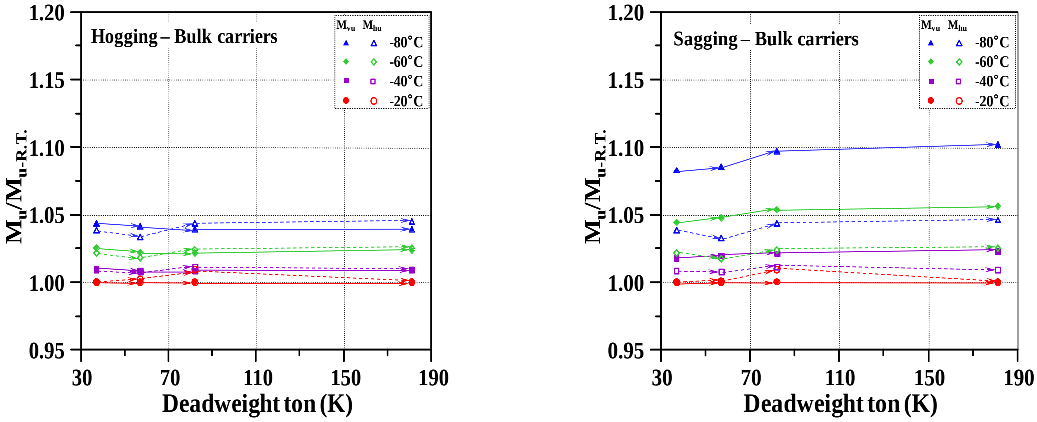
(a) Container ships - vertical bending moment (b) Container ships - horizontal bending moment

Fig. 23 Effect of temperature variation on ultimate hull girder strength of container ships



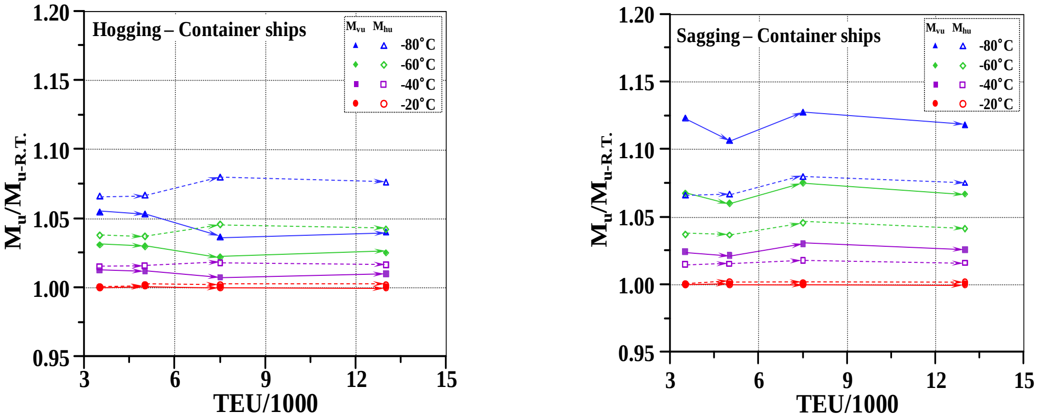
(a) In hogging (b) In sagging

Fig. 24 Trend of ultimate hull girder strength of oil tankers with vessel length



(a) In hogging (b) In sagging

Fig. 25 Trend of ultimate hull girder strength of bulk carriers with deadweight



(a) In hogging (b) In sagging

Fig. 26 Trend of ultimate hull girder strength of container ships with shipping capacity (TEU)

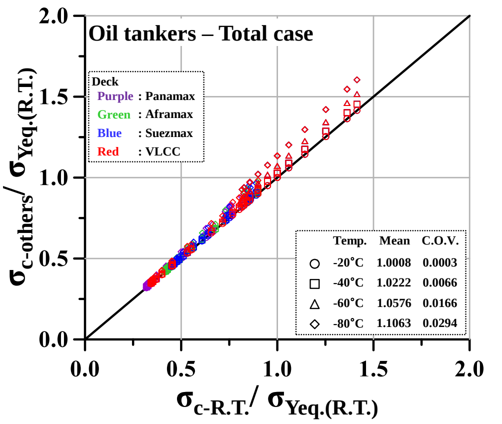


Fig. 27 Effect of temperature variation on ultimate deck stiffened panel strength of oil tankers

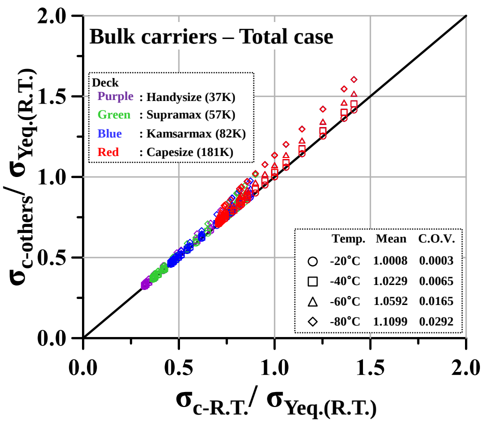


Fig. 28 Effect of temperature variation on ultimate deck stiffened panel strength of bulk carriers

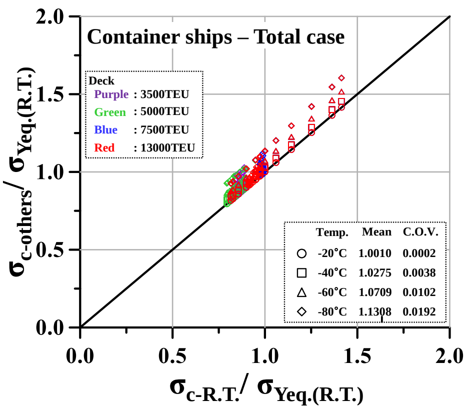


Fig. 29 Effect of temperature variation on ultimate deck stiffened panel strength of container ships

5. Conclusions

In the present study, operability studies of normal (non-ice class) vessels in Northern Sea Route (Arctic sea) are dealt. In total, 12 vessels, i.e., three types of general vessels namely oil tankers, bulk carriers and container ships are targeted. For each vessel type, four representative sizes are considered in order to investigate the general tendency of ultimate strength performance. A series of analyses for target vessels about global (hull girder) and local (stiffened panel) strength are performed with a consideration of low temperature effect.

The temperature distributions are assumed by general common sense as shown in Fig. 3, and those distributions are applied to the vessels as shown in Figs. 4 to 6. The obtained results are compared from the perspective of temperature, vessel size and vessel type.

The obtained results can be summarised as follows:

- Strength of materials increases as temperature decreases for each material. In consideration of Arctic sea navigation, the yield strength increases to 31.7% on Grade A (not allowed for ice class ships but generally used for normal ships) and 13.5% on high tensile steel (Grade AH and DH) at 80℃ than those at room temperature.

- Temperature distribution for operation in Arctic Sea needs a practical service condition. In this study, reliable temperature distributions are applied according to the vessel types.
- The ultimate hull girder strength and the ultimate deck stiffened panel strength of three types of ships namely oil carrier, bulk carrier and container ships increase as the temperature decreases. Generally, the low temperature has greater effects on the ultimate hull girder strength under sagging than hogging and under vertical moment than horizontal bending moment. The ultimate hull girder strength increases at −80°C, 6.4% for oil tankers, 6.7% for bulk carriers, and 8.3% for container ships under VBM and 2.8% for oil tankers, 4.1% for bulk carriers, and 7.2% for container ships under HBM. This tendency to increase from material strength increases in quadratic function mode as like material strength did in material tests.
- In cases of the ultimate deck stiffened panel strength, the low temperature has greater effects than others on loading case I as combination stress increases. Moreover, larger ships tend to be sensitive to low temperature on container ships, while ship size has no definite effect on oil tankers and bulk carriers.
- The ultimate strength variation at low temperature with temperature distribution assumptions in this study is as the following order:

  Oil tankers<Bulk carriers<Container ships

The documented results will be useful to analyse the operability of various normal sea-going (non-ice class) ships for the voyage of Northern Sea Route (Arctic sea) from a point of ultimate strength performance. Further studies on ice class ships and more practical temperature distribution methods with low temperature effect should be considered.

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