Ultimate Hull Girder Strength applying JTP and JBP Methods

1. Introduction

Ultimate hull girder strength is calculated on hull girders of twentyfour existed and existing ships according to the methods specified in JTP and JBP documents. At the same time, a series of progressive collapse analysis is performed to obtain reference solutions using a computer code HULLST [1,2]. Then, some discussions are made on the basis of the calculated results by different methods.

2. Methods of Calculation

2.1 JTP methods

According to the JTP document, three methods are recommended to evaluate the ultimate hull girder strength, which are:
(1) single step procedure for sagging;
(2) alternative method applying Smith's method [3];
(3) alternative method applying nonlinear FEM.
For the alternative methods, only a fundamental concept is described. On the other hand, single step procedure to evaluate the ultimate hull girder strength in sagging is specified as follows:

(1) Deck plating is divided into stiffened plate elements.

(2) Net area of individual element is calculated.

(3) Ultimate compresive strength of each stiffened plate element is evaluated applying the computer code, PULS

(4) Effective net area of each element in deck plating is calculated. The effectiveness ratio is defined by the ratio of its compressive ultimate strength to yielding strength.

(5) For the cross-section with deck plating of reduced scantling, location of the neutral axis and the moment of inertia of the cross-section of a hull girder for vertical bending are calculated.

(6) The ultimate hull girder strength is calculated as the initial yielding strength of the cross-section with reduced deck plating.

2.2 JBP method

According to the JBP document, two methods are recommended to evaluate the ultimate hull girder strength under both sagging and hogging conditions, which are:
(1) progressive collapse analysis applying Smith's method;
(2) progressive collapse analysis applying nonlinear FEM.
For the FEM analysis, only a fundamental concept is described. On the other hand, concrete procedure is specified for the application of Smith's method as follows:

(1) Divide the transverse section of hull into stiffened plate elements.

(2) Define stress-strain relationships for all elements as shown in Table 1.

(3) Initialise curvature and neutral axis for the first incremental step with the value of incremental curvature as:

$$\chi = \chi_0 = 0.01\varepsilon_{Yi}$$

where ε_{Yi} is yield strain of the element.

(4) Calculate for each element the corresponding strain, $\varepsilon_i = \chi z_i$, and the corresponding stress, σ_i.

(5) Determine the neutral axis, z_{NA-cur}, at each incremental step by establishing force equilibrium over the whole transverse section as:

$$\sum A_i\sigma_i = \sum A_j\sigma_j$$

where i-th element is under compression and j-th element is under tension.

(6) Calculate the corresponding moment by summing the contributions of all elements as:

$$M_U = \sum \sigma_{Ui}A_i(z_i - z_{NA-cur})$$

(7) Compare the moment in the current incremental step with the moment in the previous incremental step. If the slope in $M-\chi$ relationship is less than a negative fixed value, terminate the process and define the peak value as M_u. Otherwise, increase the curvature by the amount of χ_0 and go to **Step 4**.

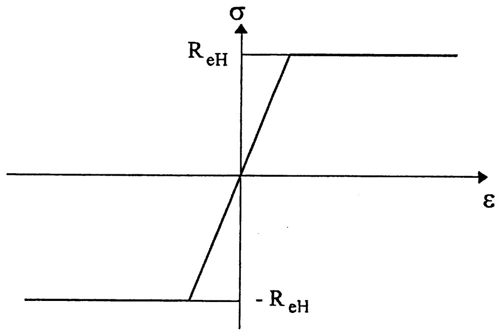

Fig. 1 Average stress-average strain relationship for elastic-plastic element

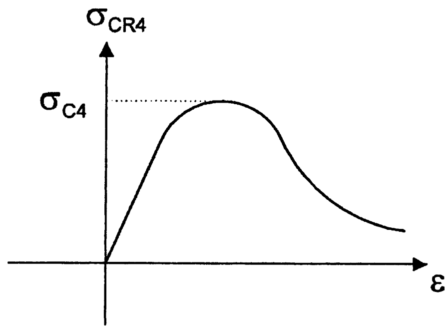

Fig. 2 Average stress-average strain relationship in compression for element collapsing by buckling

Table 1 Modes of failure of plating panel and ordinary stiffeners

Element	Mode of failure	Curve σ–ε defined in
Lengthened transversely framed plating panel or ordinary stiffeners	Elasto-plastic collapse	[2.2.3]
Shortened ordinary stiffeners	Beam column buckling Torsional buckling Web local buckling of flanged profiles Web local buckling of flat bars	[2.2.4] [2.2.5] [2.2.6] [2.2.7]
Shortened transversely framed plating panel	Plate buckling	[2.2.8]

In the JBP document, concrete description is given to derive the average stress-average strain relationships of individual elements, which is based on the method proposed in Ref.[4]. Modes of failure of plating panel and ordinary stiffeners are summarised in Table 1, where "lengthened" and "shortened" imply "tensed" and "compressed," respectively.

Figure 1 shows the average stress-average strain relationship for elasto-plastic collapse both in tensile and compressive ranges. On the other hand, average stress-average strain relationship for other failure modes in compression is represented by the curve in Fig. 2. These curves for individual failure modes are obtained by the closed-form equations specified in the document.

For the progressive collapse analysis, HULLST is used. For this analysis, the original part to derive average stress-average strain of elements in HULLST is replaced by the method specified in the JBP document.

2.3 HULLST

HULLST is an in-house code developed at Hiroshima University and Osaka University for the progressive collapse analysis of ship's hull girder subjected to longitudinal bending moment [1, 2]. This code follows the Smith's method, and its applicability has been confirmed through benchmark calculations in the Special Task Committee (STC) established in the ISSC (International Ship and Offshore Structures Congress) held at Nagasaki, Japan in 2,000 [5]. In HULLST, the average stress-average strain relationships of structural components (stiffened plate elements) composing a hull girder cross-section is constructed by semi-analytical method.

3. Ship Hull Girders for Analyais and Calculated Results

The characteristics of the analysed twentyfour ships are indicated in Tables 2 through 7 together with the calculated results. The cross-section of individual ships are also shown in Fig. 3 in a same scale. They include four ships used for benchmark calculation in the ISSC Special Task Committee [5]. The calculated results are summarised in Tables 2 through 7. Explanation of individual item in the tables is as follows:

L: length of ship

B: breadth of ship

D: depth of ship

a: length of local panel in deck plating

b: breadth of local panel in deck plating

t_p: thickness of local panel in deck plating

Longl. size and type of deck longitudinals

${\sigma_Y}^{DK}$: yielding stress of deck plating

${\sigma_Y}^{BTM}$: yielding stress of bottom plating

I_{int}: moment of inertia of the cross-section with gross scantling

e_{int}: distance between keel and neutral axis of the cross-section with gross scantling

$\sigma_u^*/{\sigma_Y}^{DK}$: ultimate strength of deck plating calculated by HULLST as reference strength

${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$: ultimate strength of deck plating calculated by PULS

I_{red}: moment of inertia of the cross-section with reduced scantling at deck plating

e_{red}: distance between keel and neutral axis of the cross-section with reduced scantling at deck plating

M_{IYS}: initial yielding strength of hull girder at deck in sagging
($M_{IYS} = \sigma_Y^{DK} \cdot I_{int}/(D - e_{int})$)

M_{uS}^{JTP}: ultimate hull girder strength in sagging according to JTP method
($M_{uS}^{JTP} = {\sigma_Y}^{DK} \cdot I_{red}/(D - e_{red})$)

M_{uS}^{JBP}: ultimate hull girder strength in sagging according to JBP method
(by progressive collapse analysis using specified average stress-average strain relationships of elements)

M_{uS}^*: ultimate hull girder strength in sagging calculated by direct application of HULLST performing progressive collapse analysis as reference strength

M_{IYH}: initial yielding strength of hull girder at bottom in hogging
($M_{IYH} = \sigma_Y^{BTM} \cdot I_{int}/e_{int}$)

M_{uH}^{JBP}: ultimate hull girder strength in hogging according to JBP method
(by progressive collapse analysis using specified average stress-average strain relationships of elements)

M_{uH}^{*}: ultimate hull girder strength in hogging calculated by direct application of HULLST performing progressive collapse analysis as reference strength

4. Discussions

Calculated ultimate hull girder strength by JTP method is compared with that by HULLST in Fig. 4. On the other hand, that by JBP method is compared with that by HULLST in Figs. 5 (a) and (b). Furthermore, initial yielding strength is compared with the ultimate hull girder strength obtained by direct application of HULLST in Fig. 6, and the ultimate compressive strength of deck plating calculated by PULS is compared with that by HULLST in Fig. 7.

It is known from Fig. 4 that the ultimate hull girder strength obtained by the JTP method has relatively good correlations with that obtained by HULLST, but is a little un-safe side.

Looking over Figs. 4, 5 (a) and 5 (b), it could be said that the ultimate hull girder strength obtained by JBP shows better agreement with that obtained by HULLST than that by JTP.

Here, the initial yielding strength in sagging shows almost the same with or better agreement than the ultimate hull girder strength obtained by JTP and/or JBP methods when it is compared to the ultimate hull girder strength obtained by the direct application of HULLST. This suggests that very simple method to multiply yielding strength by elastic section modulus of the cross-section with intact deck plating may give more accurate result than a single step procedure specified in JTP document. On the other hand, the initial yielding strength of bottom plating can not be a good measure of the ultimate hull girder strength in hogging. This is because the inner bottom plating can sustain furher bending moment after the collapse of bottom plating.

At the end, Fig. 7 indicates that the ultimate compressive strength of deck plating obtained by PULS is a little conservative compared to that obtained by HULLST. This may be because the initial yieklding condition determines the ultimate strength in PULS. However, it should be noticed that PULS gives a higher estimation of the ultimate strength in some cases, that is six cases among twenty-four cases.

5. Conclusions

The followings are the conclusion obtaind in the present report.

(1) JTP method to evaluate the ultimate hull girder strength seems to give good estimation but in many cases in the un-safe side.

(2) JBP method to evaluate the ultimate hull girder strength seems to give good estimation.

(3) The initial yielding strength calculated by multiplying the yielding strength of deck plating by the elastic section modulus of the deck plating could be a good measure of the ultimate hull girder strength under the sagging condition.

References

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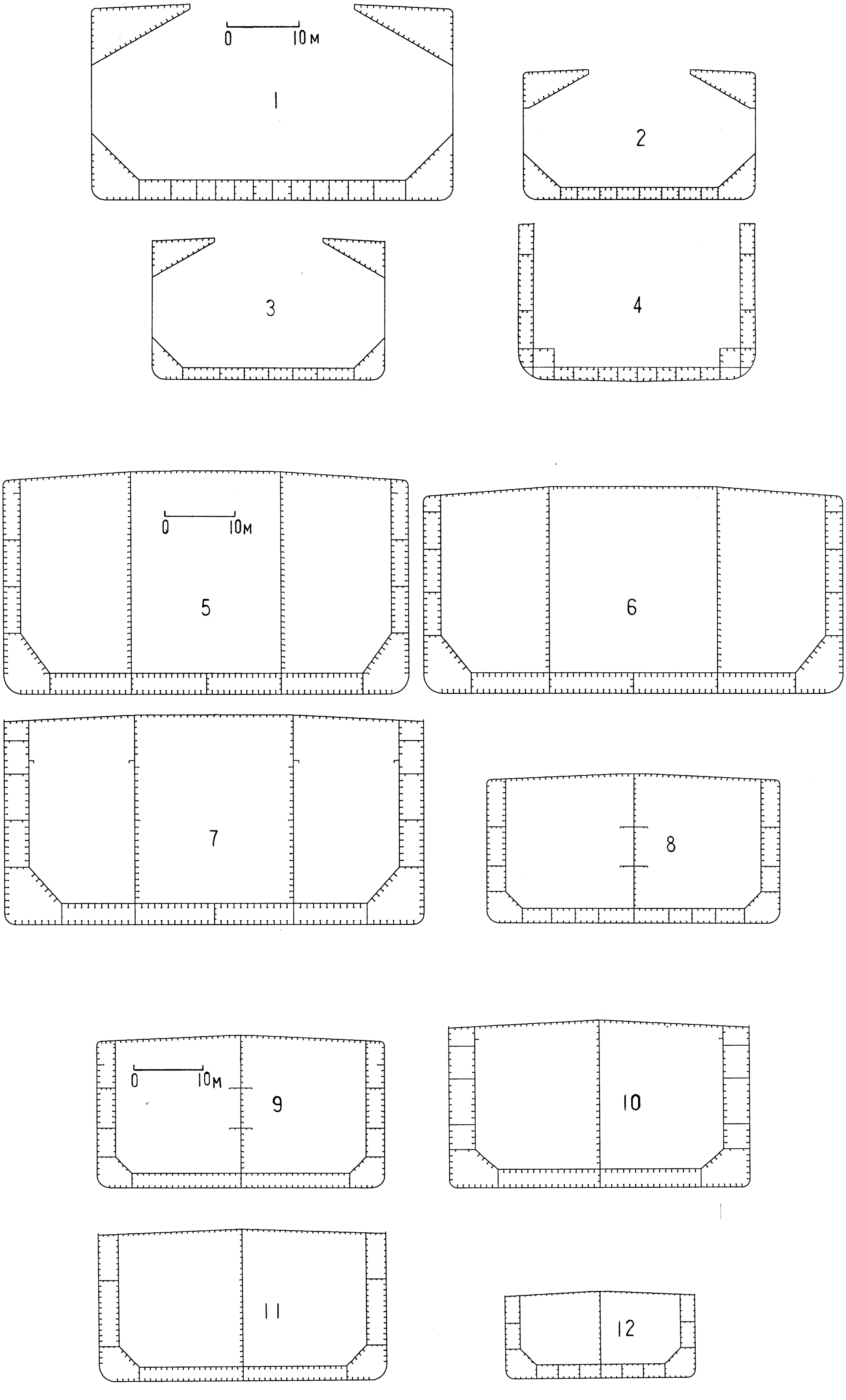


Fig. 1 Hull girder cross-sections of Ships No.1 through 12

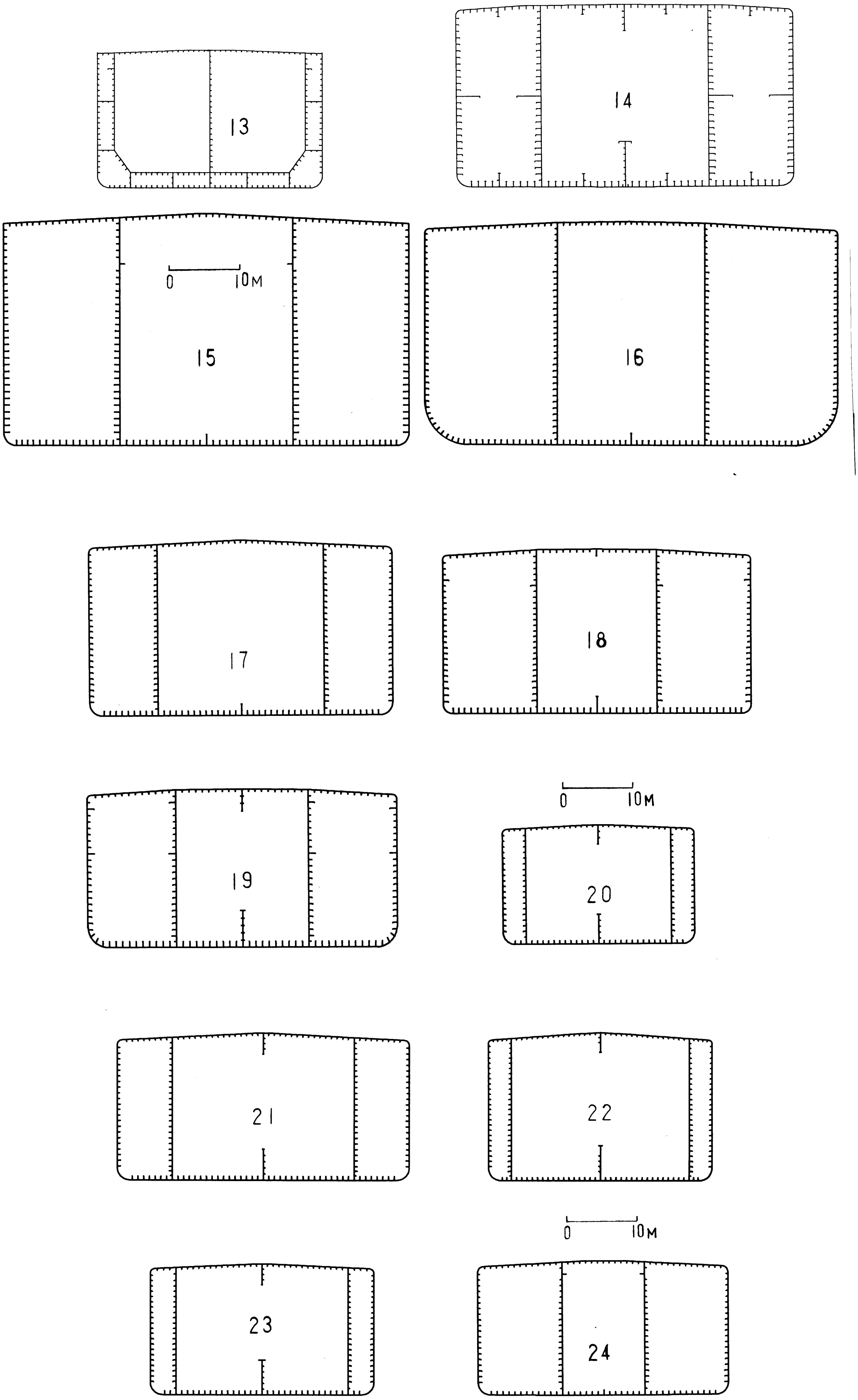


Fig. 2 Hull girder cross-sections of Ships No.13 through 24

Table 2 Ultimate hull girder strength of Ships No.1 through 4

ID No.	1	2	3	4
Ship type	Bulk Carrier*	Bulk Carrier	Bulk Carrier	Container Ship*
L(mm)	285,000	215,000	217,000	230,000
B(mm)	50,000	32,200	32,260	32,200
D(mm)	26,700	17,800	18,300	21,500
a(mm)	5,220	3,440	4,275	3,270
b(mm)	800	780	836	383
t_p(mm)	24.5	19	19.5	38
Longl.	390×27 (flat-bar)	330×25 (flat-bar)	300 × 90 × 13/17 (invert angle-bar)	300 × 38 (flat-bae)
${\sigma_Y}^{DK}$(MPa)	392	313.6	352.8	352.8
${\sigma_Y}^{BTM}$(MPa)	313.6	235.2	313.6	313.6
I_{int}(mm^4)	0.6788436×10^{15}	0.1844383×10^{15}	0.1952175×10^{15}	0.2382061×10^{15}
e_{int}(mm)	10,935.44	7,289.86	7,810.48	8,633.93
$\sigma_u^*/{\sigma_Y}^{DK}$	0.9036	0.8794	0.8297	0.9299
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.8418	0.8737	0.8022	0.9354
I_{red}(mm^4)	0.6400843×10^{15}	0.1771493×10^{15}	0.1830182×10^{15}	0.2360429×10^{15}
e_{red}(mm)	10,506.63	7,096.24	7,479,69	8,590.43
${\sigma_u}^{PLS}/\sigma_u^*$	0.9316	0.9935	0.9669	1.0059
M_{IYS}(kN·m)	0.1525299×10^8	0.4839318×10^7	0.5447766×10^7	0.6073957×10^7
${M_{uS}}^{JTP}$(kN·m)	0.1423752×10^8	0.5190141×10^7	0.5462501×10^7	0.6450712×10^7
${M_{uS}}^{JBP}$(kN·m)	0.1382760×10^8	0.4918620×10^7	0.4945080×10^7	0.6072080×10^7
M_{uS}^*(kN·m)	0.1446941×10^8	0.4767304×10^7	0.4716267×10^7	0.6759824×10^7
M_{IYS}/M_{uS}^*	1.0542	1.0151	1.1551	0.8985
${M_{uS}}^{JTP}/M_{uS}^*$	0.9840	1.0887	1.1582	0.9543
${M_{uS}}^{JBP}/M_{uS}^*$	0.9556	1.0317	1.0485	0.8983
M_{IYH}(kN·m)	0.1946747×10^8	0.5951159×10^7	0.7436701×10^7	0.8652077×10^7
${M_{uH}}^{JBP}$(kN·m)	0.177720×10^8	0.5527200×10^7	0.6632640×10^7	0.6728680×10^7
M_{uH}^*(kN·m)	0.1714020×10^8	0.5710460×10^7	0.6574820×10^7	0.6977600×10^7
M_{IYH}/M_{uH}^*	1.1358	1.0151	1.1551	1.2400
${M_{uH}}^{JTP}/M_{uH}^*$	1.0372	1.0887	1.1582	0.9643

*: ships used for benchmark calculation at ISSC [3]

Table 3 Ultimate hull girder strength of Ships No.5 through 8

ID No.	5	6	7	8
Ship type	Tanker*	Tanker	Tanker	Tanker
L(mm)	315,000	320,000	316,000	232,000
B(mm)	58,000	60,000	60,000	42,000
D(mm)	30,300	28,000	28,900	20,400
a(mm)	4,950	5,000	5,000	4,800
b(mm)	830	860	950	840
t_p(mm)	20	19.5	19.5	17
Longl.	$300 \times 90 \times 13/17$ (invert angle-bar)	$300 \times 90 \times 13/17$ (invert angle-bar)	$276 \times 11 + 124 \times 14$ (tee-bar)	$300 \times 90 \times 10/16$ (invert angle-bar)
${\sigma_Y}^{DK}$(MPa)	313.6	352.8	352.8	313.6
${\sigma_Y}^{BTM}$(MPa)	313.6	313.6	313.6	313.6
I_{int}(mm^4)	0.1344807×10^{16}	0.1144940×10^{16}	0.1214744×10^{16}	0.3232758×10^{15}
e_{int}(mm)	12,837.02	12,093.27	12,373.22	9,261.00
$\sigma_u^*/{\sigma_Y}^{DK}$	0.8939	0.8487	0.7376	0.8304
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.8036	0.7795	0.7143	0.7717
I_{red}(mm^4)	0.1245207×10^{16}	0.1048427×10^{16}	0.1088630×10^{16}	0.2937218×10^{15}
e_{red}(mm)	12,278.89	11,492.67	11,637.29	8,761.55
${\sigma_u}^{PLS}/\sigma_u^*$	0.8990	0.9185	0.9684	0.9293
M_{IYS}(kN·m)	0.2158826×10^8	0.2155185×10^8	0.1912821×10^8	0.7557305×10^7
M_{uS}^{JTP}(kN·m)	0.2154928×10^8	0.2240732×10^8	0.2224846×10^8	0.7914383×10^7
M_{uS}^{JBP}(kN·m)	0.2239300×10^8	0.2098180×10^8	0.2184420×10^8	0.8311940×10^7
M_{uS}^*(kN·m)	0.2031839×10^8	0.2002754×10^8	0.1917082×10^8	0.7268214×10^7
M_{IYS}/M_{uS}^*	1.0625	1.0761	0.9978	1.0398
M_{uS}^{JTP}/M_{uS}^*	1.0605	1.1188	1.1605	1.0889
M_{uS}^{JBP}/M_{uS}^*	1.1021	1.0476	1.1361	1.1436
M_{IYH}(kN·m)	0.3285276×10^8	0.2969033×10^8	0.3078766×10^8	0.1094691×10^8
M_{uH}^{JBP}(kN·m)	0.2925300×10^8	0.2907660×10^8	0.3041920×10^8	0.8398600×10^7
M_{uH}^*(kN·m)	0.2833180×10^8	0.2702840×10^8	0.2762620×10^8	0.8530900×10^7
M_{IYH}/M_{uH}^*	1.1596	1.09849	1.1144	1.2832
M_{uH}^{JBP}/M_{uH}^*	1.0325	1.0758	1.1011	0.9845

*: ships used for benchmark calculation at ISSC [3]

Table 4 Ultimate hull girder strength of Ships No.9 through 12

ID No.	9	10	11	12
Ship type	Tanker	Tanker	Tanker	Tanker
L(mm)	232,000	232,000	235,000	150,000
B(mm)	42,000	44,000	42,000	27,700
D(mm)	21,200	23,200	19,100	12,000
a(mm)	4,800	4,350	6,3400	2,280
b(mm)	840	875	800	780
t_p(mm)	17	17	17	14.5
Longl.	$300 \times 90 \times 10/16$ (invert angle-bar)	$300 \times 90 \times 11/16$ (invert angle-bar)	$290 \times 90 \times 9/14$ (invert angle-bar)	$180 \times 32.5 \times 9.5$ (flat bulb-bar)
${\sigma_Y}^{DK}$(MPa)	313.6	313.6	352.8	352.8
${\sigma_Y}^{BTM}$(MPa)	313.6	313.6	313.6	352.8
I_{int}(mm^4)	0.3478694×10^{15}	0.4811652×10^{15}	0.3500881×10^{15}	0.5038692×10^{14}
e_{int}(mm)	9,766.79	10,187.55	9,208.72	5,643.81
$\sigma_u^*/{\sigma_Y}^{DK}$	0.8335	0.7602	0.7578	0.6912
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.7717	0.7844	0.6859	0.6973
I_{red}(mm^4)	0.3168372×10^{15}	0.4420025×10^{15}	0.3067287×10^{15}	0.4376707×10^{14}
e_{red}(mm)	9,253,22	9,707.38	8,516.64	5,211.11
${\sigma_u}^{PLS}/\sigma_u^*$	0.9261	1.0318	0.9051	1.0088
M_{IYS}(kN·m)	0.7857836×10^7	0.8814937×10^7	0.9462775×10^7	0.1933153×10^7
M_{uS}^{JTP}(kN·m)	0.8316894×10^7	0.1027317×10^8	0.1022491×10^8	0.2274454×10^7
M_{uS}^{JBP}(kN·m)	0.8667120×10^7	0.9679460×10^8	0.8737680×10^7	0.2203040×10^7
M_{uS}^*(kN·m)	0.7592276×10^7	0.8593408×10^7	0.7800904×10^7	0.1927706×10^7
M_{IYS}/M_{uS}^*	1.0350	1.0257	1.2130	1.0028
M_{uS}^{JTP}/M_{uS}^*	1.0954	1.1955	1.3703	1.1799
M_{uS}^{JBP}/M_{uS}^*	1.1416	1.1264	1.1201	1.1428
M_{IYH}(kN·m)	0.1116967×10^8	0.1481155×10^8	0.1192213×10^8	0.3149735×10^7
M_{uH}^{JBP}(kN·m)	0.937140×10^7	0.1343580×10^8	0.1119160×10^8	0.2994880×10^7
M_{uH}^*(kN·m)	0.8929760×10^7	0.1271060×10^8	0.1048600×10^8	0.2849840×10^7
M_{IYH}/M_{uH}^*	1.2508	1.1653	1.1370	1.1052
M_{uH}^{JBP}/M_{uH}^*	1.0495	1.0571	1.0673	1.0509

Table 5 Ultimate hull girder strength of Ships No.13 through 16

ID No.	13	14	15	16
Ship type	Tanker	Tanker*	Tanker	Tanker
L(mm)	172,000	313,000	319,000	315,000
B(mm)	32,200	48,200	58,000	59,000
D(mm)	19,100	25,200	31,500	30,530
a(mm)	3,740	5,100	5,630	4,850
b(mm)	760	1,000	955	890
t_p(mm)	13	25	20.5	19.5
Longl.	$200 \times 90 \times 9/14$ (invert angle-bar)	480×32 (flat-bar)	$400 \times 11 + 100 \times 16$ (tee-bar)	$400 \times 100 \times 11.5/16$ (invert angle-bar)
${\sigma_Y}^{DK}$(MPa)	313.6	313.6	313.6	352.8
${\sigma_Y}^{BTM}$(MPa)	313.6	313.6	313.6	313.6
I_{int}(mm^4)	0.1854321×10^{15}	0.8402836×10^{15}	0.1269913×10^{16}	0.1111114×10^{16}
e_{int}(mm)	9,766.79	12,244.59	14,468.09	14,197.93
$\sigma_u^*/{\sigma_Y}^{DK}$	0.6504	0.9426	0.8833	0.8005
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.7111	0.8801	0.7876	0.8078
I_{red}(mm^4)	0.1656119×10^{15}	0.8006295×10^{15}	0.1160246×10^{16}	0.1023764×10^{16}
e_{red}(mm)	7,740.84	11,866.86	13,686.79	13,465.37
${\sigma_u}^{PLS}/\sigma_u^*$	1.0937	0.9937	0.8917	1.0091
M_{IYS}(kN·m)	0.3484672×10^7	0.1917328×10^8	0.2065355×10^8	0.1707856×10^8
M_{uS}^{JTP}(kN·m)	0.4572159×10^7	0.1781820×10^8	0.2042602×10^8	0.2116565×10^8
M_{uS}^{JBP}(kN·m)	0.4718700×10^7	0.1803200×10^8	0.2125620×10^8	0.2162860×10^8
M_{uS}^*(kN·m)	0.3752283×10^7	0.1852960×10^8	0.1997377×10^8	0.1905145×10^8
M_{IYS}/M_{uS}^*	0.9287	1.0347	1.0325	0.8964
M_{uS}^{JTP}/M_{uS}^*	1.2185	0.9616	1.0226	1.1110
M_{uS}^{JBP}/M_{uS}^*	1.2576	0.9731	1.0642	1.1353
M_{IYH}(kN·m)	0.5954004×10^7	0.2152076×10^8	0.2752573×10^8	0.2454198×10^8
M_{uH}^{JBP}(kN·m)	0.6156360×10^7	0.2021740×10^8	0.2510760×10^8	0.2424520×10^8
M_{uH}^*(kN·m)	0.5782980×10^7	0.2004100×10^8	0.2470501×10^8	0.2279480×10^8
M_{IYH}/M_{uH}^*	1.0296	1.0738	1.1142	1.0766
M_{uH}^{JBP}/M_{uH}^*	1.0646	1.0088	1.0163	1.0636

*: ships used for benchmark calculation at ISSC [3]

Table 6 Ultimate hull girder strength of Ships No.17 through 20

ID No.	17	18	19	20
Ship type	Tanker	Tanker	Tanker	Tanker
L(mm)	265,000	260,000	265,000	195,000
B(mm)	43,200	44,000	44,200	27,400
D(mm)	23,800	22,400	21,500	16,300
a(mm)	5,095	5,000	4,900	4,000
b(mm)	850	950	950	795
t_p(mm)	20.5	23.5	27	18.5
Longl.	$350 \times 100 \times 12/17$ (invert angle-bar)	450×30 (flat-bar)	400×30 (flat-bar)	300×25 (flat-bar)
${\sigma_Y}^{DK}$(MPa)	313.6	235.2	235.2	235.2
${\sigma_Y}^{BTM}$(MPa)	313.6	235.2	235.2	235.2
I_{int}(mm^4)	0.4687907×10^{15}	0.5731469×10^{15}	0.5696742×10^{15}	0.1371160×10^{15}
e_{int}(mm)	11,370.03	10,629.61	10,386.31	8,102.24
$\sigma_u^*/{\sigma_Y}^{DK}$	0.8533	0.9329	0.9130	0.8005
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.8259	0.8844	0.8588	0.8461
I_{red}(mm^4)	0.4346083×10^{15}	0.5449059×10^{15}	0.5365085×10^{15}	0.1289689×10^{15}
e_{red}(mm)	19,821.70	10,261.61	9,961.96	7,790.55
${\sigma_u}^{PLS}/\sigma_u^*$	0.9679	0.9480	0.9406	1.0570
M_{IYS}(kN·m)	0.1009219×10^8	0.1068383×10^8	0.1100939×10^8	0.2799834×10^7
${M_{uS}}^{JTP}$(kN·m)	0.1150162×10^8	0.1055899×10^8	0.1093659×10^8	0.3564682×10^7
${M_{uS}}^{JBP}$(kN·m)	0.1100540×10^8	0.1083880×10^8	0.1090740×10^8	0.3538780×10^7
M_{uS}^*(kN·m)	0.9768844×10^7	0.1084102×10^8	0.1108365×10^8	0.3491936×10^7
M_{IYS}/M_{uS}^*	1.0331	0.9855	0.9933	0.8018
${M_{uS}}^{JTP}/M_{uS}^*$	1.1774	0.9740	0.9867	1.0283
${M_{uS}}^{JBP}/M_{uS}^*$	1.1266	0.9998	0.9841	1.0134
M_{IYH}(kN·m)	0.1292985×10^8	0.1268195×10^8	0.1290038×10^8	0.3980342×10^7
${M_{uH}}^{JBP}$(kN·m)	0.1064480×10^8	0.1206380×10^8	0.1262240×10^8	0.3913140×10^7
M_{uH}^*(kN·m)	0.1296540×10^8	0.1210300×10^8	0.1259300×10^8	0.3724980×10^7
M_{IYH}/M_{uH}^*	0.9973	1.0478	1.0244	1.0686
${M_{uH}}^{JBP}/M_{uH}^*$	0.8210	0.9968	1.0023	1.0505

Table 7 Ultimate hull girder strength of Ships No.21 through 24

ID No.	21	22	23	24
Ship type	Tanker	Tanker	Tanker	Tanker
L(mm)	222,000	215,000	219,000	200,000
B(mm)	42,000	32,200	32,200	36,000
D(mm)	20,300	20,400	18,300	18,700
a(mm)	5,015	4,550	4,500	4,500
b(mm)	820	760	825	850
t_p(mm)	17	15	18.5	15.5
Longl.	$300 \times 90 \times 11/16$ (invert angle-bar)	$250 \times 90 \times 10/15$ (invert angle-bar)	$300 \times 90 \times 11/16$ (invert angle-bar)	$285 \times 10 + 100 \times 12$ (tee-bar)
${\sigma_Y}^{DK}$(MPa)	352.8	352.8	313.6	313.6
${\sigma_Y}^{BTM}$(MPa)	352.8	352.8	313.6	313.6
I_{int}(mm^4)	0.2899034×10^{15}	0.2211081×10^{15}	0.1940469×10^{15}	0.1889537×10^{15}
e_{int}(mm)	9,706.44	9,735.40	8,858.07	8,947.92
$\sigma_u^*/{\sigma_Y}^{DK}$	0.7769	0.7590	0.8239	0.7096
${\sigma_u}^{PLS}/{\sigma_Y}^{DK}$	0.7568	0.7370	0.7972	0.7334
I_{red}(mm^4)	0.2613493×10^{15}	0.1997006×10^{15}	0.1792050×10^{15}	0.1686438×10^{15}
e_{red}(mm)	9,071.69	9,161.50	8,432.68	8,326.02
${\sigma_u}^{PLS}/\sigma_u^*$	0.9741	0.9710	0.9676	1.0335
M_{IYS}(kN·m)	0.7501398×10^7	0.5514929×10^7	0.5310101×10^7	0.4311660×10^7
M_{uS}^{JTP}(kN·m)	0.8211750×10^7	0.6269017×10^7	0.5695439×10^7	0.5098017×10^7
M_{uS}^{JBP}(kN·m)	0.8008560×10^7	0.6193600×10^7	0.5773180×10^7	0.5368440×10^7
M_{uS}^*(kN·m)	0.7263328×10^7	0.5306056×10^7	0.5216485×10^7	0.4524133×10^7
M_{IYS}/M_{uS}^*	1.0345	1.0394	1.0179	0.9530
M_{uS}^{JTP}/M_{uS}^*	1.1306	1.1815	1.0918	1.1070
M_{uS}^{JBP}/M_{uS}^*	1.1026	1.1672	1.1067	1.1268
M_{IYH}(kN·m)	0.1053712×10^8	0.8012710×10^7	0.6869793×10^7	0.6622308×10^7
M_{uH}^{JBP}(kN·m)	0.9574600×10^7	0.7342160×10^7	0.6511120×10^7	0.6057380×10^7
M_{uH}^*(kN·m)	0.8791580×10^7	0.6655180×10^7	0.5950560×10^7	0.5425280×10^7
M_{IYH}/M_{uH}^*	1.1985	1.2040	1.1545	1.2206
M_{uH}^{JBP}/M_{uH}^*	1.0891	1.1032	1.0942	1.1165

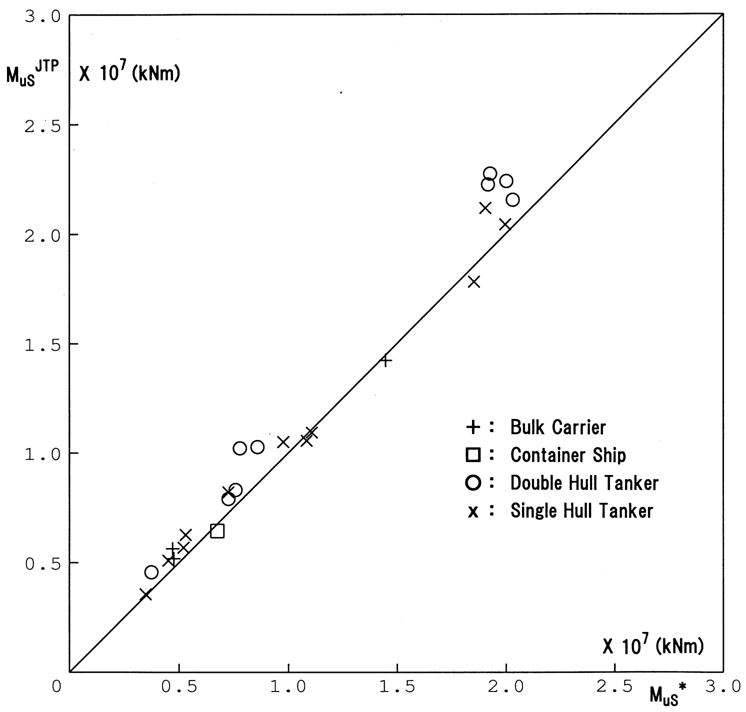
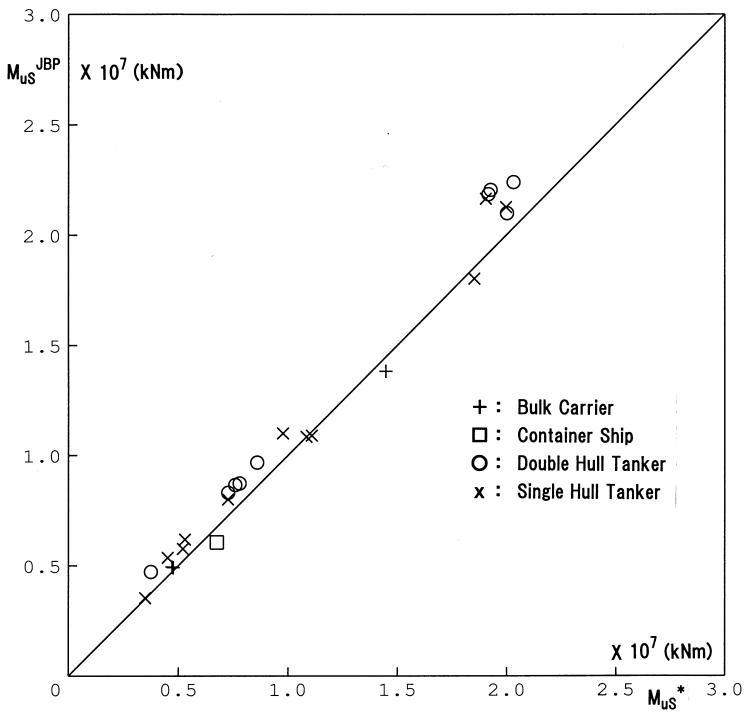
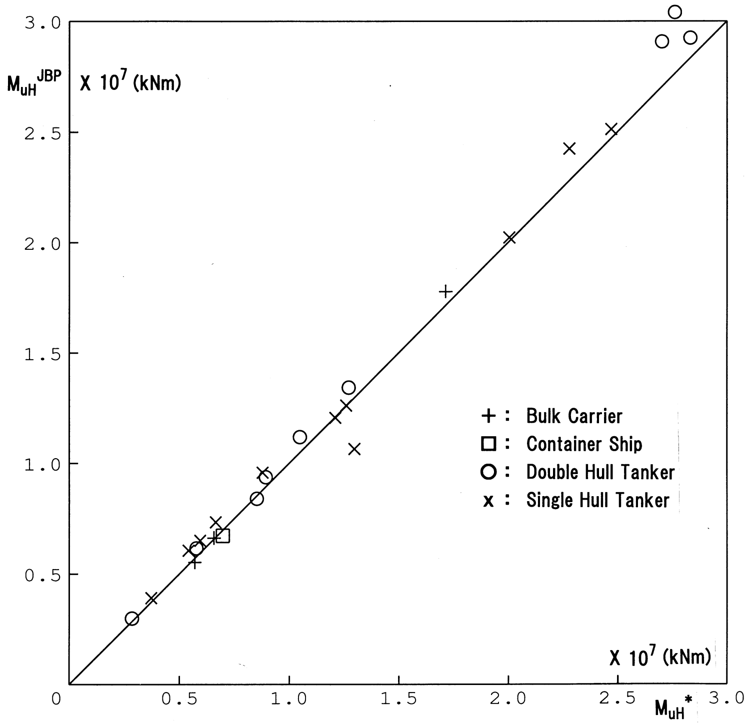


Fig. 4 Comparison of hull girder strength by JTP method and HULLST (M_{uS}^{JTP} vs. M_{uS}^{*}; sagging)



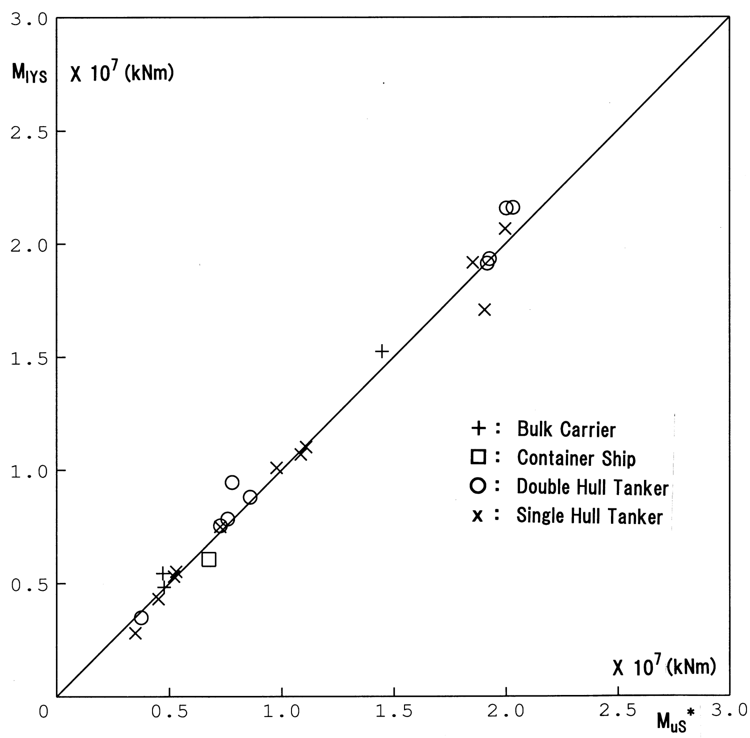
(a) M_{uS}^{JBP} vs. M_{uS}^{*}; Sagging

Fig. 5 Comparison of hull girder strength by JBP method and HULLST



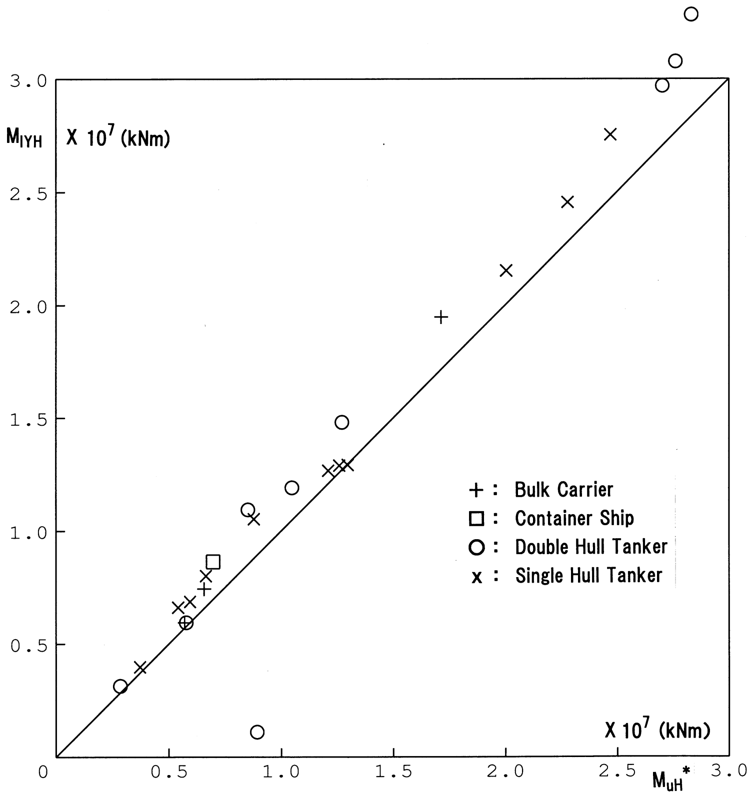
(b) M_{uH}^{JBP} vs. M_{uH}^*; Hogging

Fig. 5 Comparison of hull girder strength by JBP method and HULLST (continued)



(a) M_{IYS} vs. M_{uS}^*; Sagging

Fig. 6 Comparison of initial yielding strength with ultimate hull girder strength



(b) M_{IYH} vs. M^*_{uH}; Hogging

Fig. 6 Comparison of initial yielding strength with ultimate hull girder strength (continued)

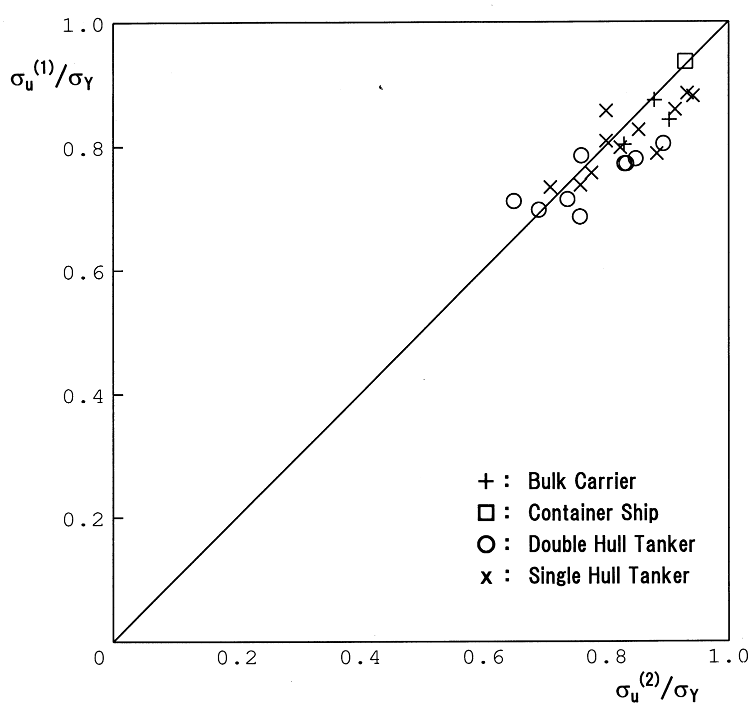


Fig. 7 Comparison of deck ultimatye strength by different methods