Tanker Structure Cooperative Forum

Guidance Notes on High Tensile Steel

SUMMARY

This paper discusses characteristics of high tensile steel, potential problems with the use of this material, and highlights items that may not be addressed in current regulations.

Reference	Revision N°	Revision Date
TSCF IP 004/2013	0	2013/12/20

CONTENTS

1 Introduction

On the topic of high tensile steel, a TSCF member has said “It still amazes me that we are the only industry that discourages the use of a higher quality material.”

High tensile steel (HTS) is commonly used in shipbuilding to reduce steel weight and construction cost. HTS was widely introduced in the 1980s to promote cost savings. HTS was often used without sufficiently accounting for additional potential failure modes which had not been prevalent with predominantly mild steel structures. Many of these vessels encountered significant structural problems, especially with fatigue cracking. As a result, many owners and charterers introduced limits on the maximum percentage of high tensile steel that could be used in the design. Over the past 10 to 20 years, significant progress has been made with the adoption and use of computer-based analysis to evaluate ship structures for buckling and fatigue.

The intent of this paper is to discuss characteristics of HTS, potential problems with the use of this material, and highlight items that may not be addressed in current regulations. The last section of this paper contains suggestions on the rational use of high tensile steel. While this paper is primarily intended for shipowners, it will also be useful for shipyards, designers, and class societies.

2 What is HTS

HTSs have a yield stress not less than 265 N/mm2. Guidance on steel grades comparable to the normal and high strength hull structural steel grades given in classification societies’ rules is summarized in the table below (Table No.1).

Steel grades according to Classification Societies’ rules (ref. 5)							Comparable steel grades			
Grade	Yield stress R_{eH} min. N/mm^2	Tensile strength R_m N/mm^2	Elongation A_5 min. %	Average impact energy Temp. °C	J, min. L	 T	ISO 630-80 4950/2/3 1981	EN EN 10025-93 EN 10113-93	ASTM A 131	JIS G 3106
A B D E	235	400 - 502	22	+20 0 -20 -40	- 27 27 27	- 20 20 20	Fe 360B Fe 360C Fe 360D -	S235JRG2 S235J0 S235J2G3 S275NL/ML	A B D E	SM41B SM41B (SM41C) -
A 27 D 27 E 27	265	400 - 530	22	0 -20 -40	27	20	Fe 430C Fe 430D -	S275J0G3 S275N/M S275NL/ML	- - -	- - -
A 32 D 32 E 32	315	440 - 590	22	0 -20 -40	31	22	- - -	- - -	AH32 DH32 EH32	SM50B (SM50C) -
A 36 D 36 E 36	355	490 - 620	21	0 -20 -40	34	24	Fe 510C Fe 510D E355E	S355N/M S355N/M S355NL/ML	AH36 DH36 EH36	SM53B (SM53C) -
A 40 D 40 E 40	390	510 - 650	20	0 -20 -40	41	27	E390CC E390DD E390E	S420N/M S420N/M S420NL/ML	AH40 DH40 EH40	(SM58) - -

Table 1 Steel grades – Properties of High Tensile Steels[1]

[1] IACS Recommendation No.47, Rev.6, May 2012, “Shipbuilding and Repair Quality Standard”

HTS commonly used in tanker construction comes in six grades of two strengths, AH32, DH32, EH32, AH36, DH36, and EH36.[2] The 32 grades have yield strength of 315 MPa (45,500 psi), and ultimate tensile strength of 440-590 MPa (64,000 - 85,000 psi). The 36 grades have yield strength of 355 MPa (51,000 psi), and ultimate tensile strength of 490-620 MPa (71,000 - 90,000 psi).

Higher strength steel with a minimum yield strength of 460 MPa (HT47) is beginning to be used in the designs of large containerships. Similarly, HT40 steels are available but are not commonly used for tankers.

IACS Unified Requirements W11 covers class society approval, method of manufacture, chemical composition, mechanical properties, freedom from defects, tolerances, material identification, testing, branding, documentation, conditions of supply. This UR W11 addresses A, B, D, and E grade mild, HT32, HT36, and HT40 steel.

A summary of the chemical composition of normal strength and HTSs is given in Tables No.2 and No.3 below.

[2] Steel Vessel Rules 2010, Part 2 - Materials and Welding, American Bureau of Shipping, 2010, Chapter 1, Sections 2 and 3

Grade	A	B	D	E
Deoxidation Practice	For t ≤ 50 mm Any method except rimmed steel (1) For t > 50 mm Killed	For t ≤ 50 mm Any method except rimmed For t > 50 mm Killed	For t ≤ 25 mm Killed For t > 25 mm Killed and fine grain treated	Killed and fine grain treated
Chemical Composition % (4) (7) (8) (ladle samples)	**Carbon plus 1/6 of the manganese content is not to exceed 0.40%**			
C max.	0.21 (2)	0.21	0.21	0.18
Mn min.	2.5 x C	0.80 (3)	0.60	0.70
Si max.	0.50	0.35	0.35	0.35
P max.	0.035	0.035	0.035	0.035
S max.	0.035	0.035	0.035	0.035
Al (acid soluble min)	-	-	0.015 (5) (6)	0.015 (6)

t = thickness

Notes:

1. Grade A sections up to a thickness of 12.5 mm may be accepted in rimmed steel subject to the special approval of the Classification Society.
2. Max. 0.23% for sections.
3. When Grade B steel is impact tested the minimum manganese content may be reduced to 0.60%.
4. When any grade of steel is supplied in the thermo-mechanically rolled condition variations in the specified chemical composition may be allowed or required by the Classification Society.
5. For Grade D steel over 25 mm thick.
6. For Grade D steel over 25 mm thick and Grade E steel the total aluminium content may be determined instead of acid soluble content. In such cases the total aluminium content is to be not less than 0.020%. A maximum aluminium content may also be specified by the Classification Society. Other suitable grain refining elements may be used subject to the special approval of the Classification Society.
7. The Classification Society may limit the amount of residual elements which may have an adverse effect on the working and use of the steel, e.g. copper and tin.
8. Where additions of any other element have been made as part of the steelmaking practice, the content is to be indicated.

Table 2 Chemical Composition and deoxidation practice for normal strength steels[3]

[3] IACS Unified Requirement (UR W11), 1979/Rev.7 2008/Corr.1 2009, “Normal and higher strength hull structural steels”

Grade [1]	A32 D32 E32 A36 D36 E36 A40 D40 E40	F32 F36 F40
Deoxidation Practice	killed and fine grain treated	
Chemical Composition % [5] [7] (ladle samples)		
C max.	0.18	0.16
Mn	0.90 – 1.60 [2]	0.90 – 1.60
Si max.	0.50	0.50
P max.	0.035	0.025
S max.	0.035	0.025
Al (acid soluble min)	0.015 [3] [4]	0.015 [3] [4]
Nb	0.02 – 0.05 [4]) total:	0.02 – 0.05 [4]) total:
V	0.05 – 0.10 [4]) 0.12	0.05 – 0.10 [4]) 0.12
Ti max.	0.02) max.	0.02) max.
Cu max.	0.35	0.35
Cr max.	0.20	0.20
Ni max.	0.40	0.80
Mo max.	0.08	0.08
N max.	-	0.009 (0.012 if Al is present)
Carbon Equivalent [6]		

Notes:

1. The letter “H” may be added either in front or behind the grade mark e.g. HA 32 or AH 32.
2. Up to a thickness of 12.5 mm the minimum manganese content may be reduced to 0.70%.
3. The total aluminium content may be determined instead of the acid soluble content. In such cases the total aluminim content is to be not less than 0.020%.
4. The steel is to contain aluminium, niobium, vanadium or other suitable grain refining elements, either singly or in any combination. When used singly the steel is to contain the specified minimum content of the grain refining element. When used in combination, the specified minimum content of a fine graining element is not applicable.
5. When any grade of higher strength steel is supplied in the thermo-mechanically rolled condition variations in the specified chemical composition may be allowed or required by the Classification Society.
6. When required, the carbon equivalent value is to be calculated from the ladle analysis using the following formula.
   $$Ceq = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} \quad (\%)$$
   This formula is applicable only to steels which are basically of the carbon-manganese type and gives a general indication of the weldability of the steel.
7. Where additions of any other element have been made as part of the steelmaking practice, the content is to be indicated.

Table 3 Chemical Composition and deoxidation practice for higher strength steels[4]

[4] IACS Unified Requirement (UR W11), 1979/Rev.7 2008/Corr.1 2009, “Normal and higher strength hull structural steels”

3 Historical HTS Use

The first single hull VLCC (Very Large Crude Carrier) was developed in the 1960's. At that time, HTS (HT32) use was limited to upper and lower parts of hull girder and struts in wing cargo tanks. In the early 1980's, Thermo Mechanical Control Process (TMCP) steel was developed in Japan. Since the TMCP steel can achieve both higher strength and higher toughness and does not require additional treatment at the welding stage, such as pre-heating or post-heating, the use of TMCP steel by Japanese shipbuilders expanded widely in a short period of time (see Figure 1).

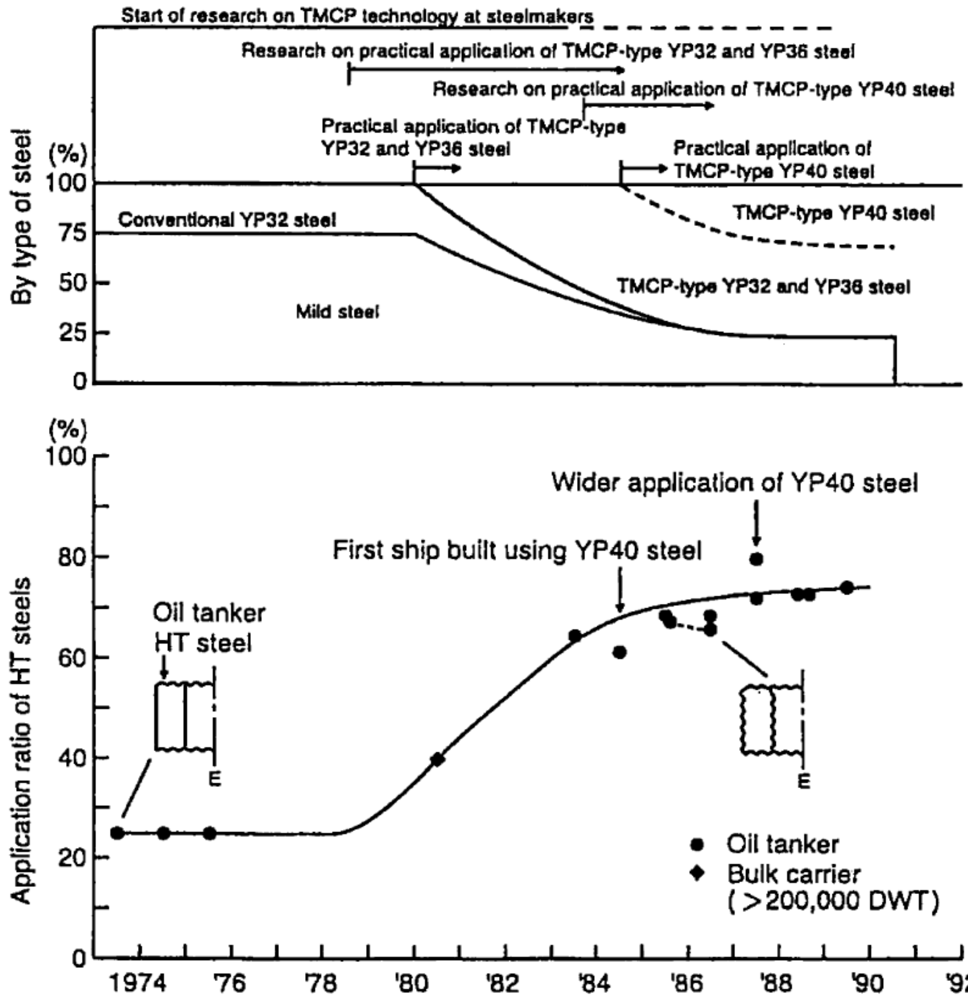
As a result, HTS of HT36 and/or HT40 was widely used for the second generation VLCCs built in the 1980s on not only hull girder strength plates but also longitudinals and transverse members. This led to a reduction in hull steel weight and fabrication cost and an increase in cargo deadweight. The HTS ratio of the second generation VLCCs increased from 30% to approximately 70 to 80%.

In the second generation VLCCs, however, the concept of structural design was almost identical to that of the first generation. The scantlings were determined in accordance with classification societies' rules based on yielding criteria. As a result, a number of serious damage cases by fatigue were found in the side longitudinals. One of the main reasons was the lack of fatigue strength evaluation. Following these problems, classification societies established procedures to analyze fatigue. Between 1995 and 2000, fatigue analysis became a mandatory requirement. However, implementation was not immediate and vessels constructed before fatigue requirements were introduced continued to encounter problems.

After the fatigue issues emerged in the second generation VLCCs, new VLCC designs were divided generally into two groups. One was the mild steel (MS) rich design in which the HTS ratio was limited to around 30%. Another was the HTS rich design, in which the HTS ratio was 70 to 80% or sometimes higher.

The intent of the MS rich designs was to limit the use of HTS to the upper and lower flange of the hull girder, similar to designs common in the 1970s for which there was generally satisfactory service experience. The HTS rich designs were able to increase cargo deadweight, lower steel costs, and, to a lesser degree, reduce fuel consumption. These HTS rich designs would often be subjected to additional fatigue analysis in order to address issues encountered by the second generation VLCC. However, many owners/operators requested MS rich designs.

With the adoption of the class rules that required detail fatigue strength evaluation and later the Common Structural Rules (CSR), which also set clear corrosion margins, structural performance is expected to improve. Initially, CSR designs showed an increase in steel weight. Subsequent to the introduction of CSR, extended use of HTS has been proposed, especially for the MS rich design group, with attention being paid to fatigue requirements of the CSR.



Transition of HT ratio and the rate of TMCP steels in Japan (applied to VLCCs)

Figure 1 Transition of HT Steel Ratio in Japan*

Among TSCF members, 47% of owners/operators had adopted a restriction policy regarding the use of HTS use in the past. After establishment of the CSR only 18% retain such limits. Generally, the HTS target is set at 30% to 55% in weight. Among those owners/operators having a restriction, most of them have alternatives in case the HTS ratio exceeds the restriction, such as improving fatigue details based on fatigue analysis recognized by a classification society, etc.

* Figure 1: Class NK Technical Report 2001, “Application of YP40 steel to hull construction and its performance evaluation”; Author Mr. Tutomu Fukui and Hiroshige Kitada / Material and Equipment Department

4 HTS in Ship Types

We have researched the utilization of HTS primarily in oil tankers complying with CSR. It is difficult to determine the exact amount of steel weight of an individual ship because it is one of a shipbuilder's competitive secrets. For the purpose of this section the HTS ratio has been calculated as:

HTS ratio = HTS weight amidships / total steel weight amidships

To determine the percentage of HTS to be used in hull girder strength members, primary supporting members and secondary members in the hold or tank region, we have investigated the HTS ratio of amidships tanks from the key plan scantling, and then, through the questionnaire method with shipyard personnel, have gathered the HTS ratio of the ship types they have built. Small members such as tripping brackets and buckling stiffeners have been excluded in the investigation. The HTS ratio of a whole ship is lower than that in the midship because the HTS is normally used less for the fore part and aft part including engine room and deckhouse in comparison with the amidships part. This information was collected in 2011.

4.1 CSR VLCC

HTS ratio of no.3 cargo tank within amidships has been investigated for the following VLCC which has three rows and five compartments for cargo tanks and two rows and five compartments for water ballast tanks.

- LBP : 319 m - B : 60 m - D : 30.4 m
- d_{sc} : 22.6 m - Length of no.3 cargo tank : 51 m

The steel weight of plates and stiffeners for longitudinal members and transverse members has been calculated as in the Table 4.

Structural Member	Plate + Stiffener, ton (%)		
	Mild	HTS	Sum
Longitudinal Members	1,025 (23%)	3,495 (77%)	4,520 (100%)
Transverse Members	1,245 (67%)	610 (33%)	1,855 (100%)
Sum	2,270 (36%)	4,095 (64%)	6,375 (100%)

Table 4 Steel weight of no.3 cargo tank of CSR VLCC (2011)

HTS was used a considerable amount for the deck and bottom structural members which mainly contributed to the hull girder longitudinal strength. The HTS ratio of the typical amidship cargo tank of VLCC is 64%.

4.2 CSR 105K Aframax Tanker

HTS ratio of no.4 cargo tank within amidships has been calculated for the following aframax tanker which has two rows and six compartments each of cargo tanks and water ballast tanks.

- LBP : 234 m   - B : 42 m   - D : 21.5 m
- d_{sc} : 15.0 m   - Length of no.4 cargo tank : 29.96 m

Structural Member	Plate + Stiffener, ton (%)		
	Mild	HT	Sum
Longitudinal Members	790 (57%)	600 (43%)	1,390 (100%)
Transverse Members	285 (56%)	220 (44%)	505 (100%)
Sum	1,075 (57%)	820 (43%)	1,895 (100%)

Table 5 Steel Weight of No.4 Cargo Tank of CSR Aframax Tanker (2011)

The portion of HTS of the 105K tanker is 43% for one cargo tank. The HTS ratio of a cargo tank amidships in this case may be affected by the fact that this vessel was built with the limitation of HTS use of 35% for the entire vessel as required by the shipowner.

4.3 CSR 47K MR Tanker

The HTS ratio of no.4 cargo tank with corrugated bulkheads within amidships was calculated for the following MR tanker which has two rows and six compartments each of cargo tanks and water ballast tanks.

- LBP : 174 m   - B : 32.2 m   - D : 18.8 m
- d_{sc} : 12.30 m   - Length of no.4 cargo tank : 21.20 m

Structural Member	Plate + Stiffener, ton (%)		
	Mild	HT	Sum
Longitudinal Members	428 (69%)	192 (31%)	619 (100%)
Transverse Members	121 (40%)	182 (60%)	303 (100%)
Sum	548 (59%)	374 (41%)	922 (100%)

Table 6 Steel Weight of No.3 Cargo Tank of CSR MR Tanker (2011)

HTS was mainly used for the transverse and center longitudinal corrugated bulkheads, their upper and lower stools and inner bottom plates. Other main structures including longitudinal members were made of mild steel. The portion of HTS was 41% for one cargo tank.

4.4 Summary of oil tankers

The following table shows the average HTS ratio for oil tankers in Korean shipyards.

Ship Size	HTS ratio	Shipyard	No. of vessels
VLCC	51%	5	5
Aframax Tanker	52%	5	8
MR Tanker	39%	2	4

Table 7 HTS Ratio of CSR Oil Tankers, Korean Shipyards (2011)

In comparison, it may be noted that the HTS ratios for the three corresponding specific mid-body tank examples considered earlier in this section were 64%, 43%, and 41%, respectively. As previously stated, the corresponding full vessel HTS ratios will probably be lower.

The HTS ratio of oil tankers varies considerably depending on limitations on the usage of HTS given by shipowners or charterers or the lack of such a specification constraint. The ratio in any event can commonly range from 30% to 70% for oil tankers in general based on recent data from Korean shipyards.

At present, oil tankers built in Korea mainly use the HTS with a minimum yield stress of 315N/mm^2 (HT32) rather than those with a minimum yield stress of 355N/mm^2 (HT36), although HT36 tends to be locally used in limited amounts. There appears to be limited experience with usage of HTS with yield strengths greater than 355M/mm^2 (HT36)

5 Use of HTS in Design

As HTS has a higher yield and ultimate strength, structural members are capable of being loaded to higher axial, bending and shear stresses, but more so in tension than under compression because of the possibility of buckling. The yielding strength of HT32 is 34% higher than mild steel, while HT36 has a yield strength 51% higher than mild steel. The material factors adopted by classification societies for HTS in the 1960s included an additional margin of safety. This was intended to provide sufficient margin on ultimate strength and account for failure modes such as buckling which were not extensively analyzed at that time. Therefore, in pre-CSR designs certain structural members could be reduced in thickness by 28% for HT36 and 22% for HT32 when compared to mild steel.

It may also be noted that classification society requirements for hull girder strength have changed over the years. For example, the section modulus requirements for tankers prior to 1970 were higher than they are today.

The International Association of Class Societies (IACS) Unified Requirement S4, originally adopted in 1975, assigns a material factor (k) to each type of HTS, as shown below in Table 8:

Type	Minimum yield stress R_{eH}, in N/mm^2	*k*
Mild	235	1
HT32	315	0.78
HT36	355	0.72
HT40	390	0.68

Table 8 Material Factors for HTS

When either the top or bottom flange of the hull girder, or both, is constructed of HTS, the required hull girder section modulus may be reduced by the factor k. For double hull tankers, the area of the main deck plating and longitudinals contribute the most to the offered top flange of the hull girder section modulus. Therefore, the main deck plating and longitudinals are almost always constructed of HTS. When designing for local loads, the same reduction may generally be made to the section modulus of stiffeners and deep supporting members. For plating, the required thickness may be generally reduced by the square root of k (12% for HT 32, 16% for HT 36)

Classification societies' rules from the 1980s primarily addressed yielding, but the high stresses associated with HTS made additional failure modes more critical. Of primary concern is buckling and fatigue.

5.1 Buckling

A structure incorporating HTS will not only be subject to higher stresses, but will also be constructed of lighter scantlings with a lower buckling capacity. The buckling capacity of structural members does not increase as dramatically as the yielding strength. In the elastic range of behavior, the buckling capacity of a plate panel will reduce proportionately to the square of the thickness.

The IACS CSR for Double Hull Oil Tankers addresses buckling in two ways, proportion requirements (such as spacing to thickness ratios) and detailed stress analysis. The proportion checks will generally limit the critical buckling stress to values lower than those permitted based on yielding. The CSR contain comprehensive proportion requirements (plating, stiffeners, primary support members, web, and flange) that account for the type of member, material strength and location in the hull. These equations lead to more stringent requirements when HTS is used and generally do not directly consider the actual stress in the member being evaluated. Proportion requirements also govern the design of brackets and their stiffened edges. The CSR include moment of inertia requirements for stiffeners and attached plate to help protect against column buckling. There are also prescriptive equations that govern the spacing of tripping brackets that require closer spacing for HTS primary support members.

In addition, structural members subjected to detailed stress analysis will also be checked for buckling. The working stress is calculated using finite element analysis and must be lower than the critical buckling stress. The CSR contain comprehensive equations for details commonly used in shipbuilding, including panels with openings. Both the local working stress and the local critical buckling stress are calculated using the full net thickness (or renewal thickness defined as required thickness with 100% corrosion margin deducted). The CSR for Oil Tankers require finite element analysis of a three cargo hold model with the longest cargo tank in the middle of the model.

In the April 2013 draft of the CSR for Bulk Carriers and Oil Tankers (Harmonized CSR), the extent of FE analysis covers the full cargo block area from the aftmost bulkhead of the cargo block to the collision bulkhead. The Harmonized CSR is scheduled to be finalized by the end of 2013. For HTS-rich vessels constructed to CSR for Oil Tankers, owners may want to specify additional FE buckling checks for the full cargo block area similar to the Harmonized CSR.

5.2 Fatigue

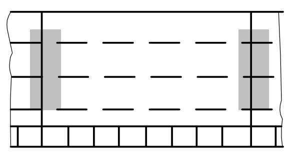
Another concern with the increased use of HTS is fatigue. As HTS allows for lighter scantlings, the resulting stress ranges are increased. The CSR require a 25-year fatigue life based on a North Atlantic wave environment. The finite element models used in the fatigue analysis incorporate net scantlings which have 25% or 50% of the corrosion margin deducted for global and local models respectively. The nominal stress approach is used to check fatigue for longitudinal stiffener end connections within the midship region.

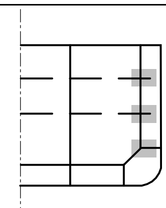
One of the major reasons cited by owners and charterers for limiting the percentage of HTS was to avoid its use for longitudinals at side shell that are subject to higher cyclic loads. Fatigue analysis for these items has been required as part of class Rules since the late 1990s. Vessels built after fatigue analysis was made mandatory have had significantly more care taken in the design of longitudinal end connections. As a result, the performance of side shell longitudinals has improved. The CSR fatigue is based on a 25-year service life and should lead to even better performance when compared to pre-CSR designs with shorter fatigue lives (20 years).

One difference between the pre-CSR and the CSR requirements is the approach taken to address fatigue of main supporting members. The CSR were developed with the understanding that they would apply primarily to oil tankers with well-defined standard structural arrangements. Therefore, requirements have been tailored to allow compliance with prescriptive requirements and screening methods instead of detailed fatigue analysis using finite element methods. This lower level of analysis is permitted only when standard details are used. For example, standard details prescribed for the connection of the horizontal girder to transverse bulkhead are shown in Figure 2. In cases where standard details have been used throughout the vessel, the CSR require only the hopper knuckle be assessed using FE fatigue analysis.

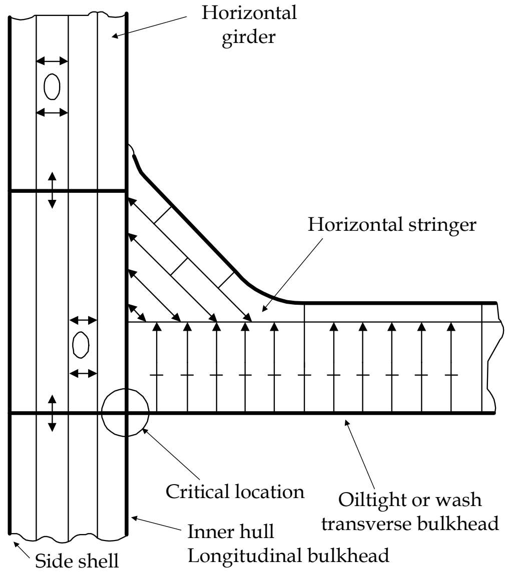
Option: Transverse Bulkhead Horizontal Stringer Heel	
Connections of horizontal girder in double side tanks to transverse bulkheads Connection of horizontal stringer on plane oiltight transverse or wash bulkheads to inner hull longitudinal bulkhead	
CRITICAL AREAS	**DETAIL DESIGN IMPROVEMENT**

CRITICAL AREAS

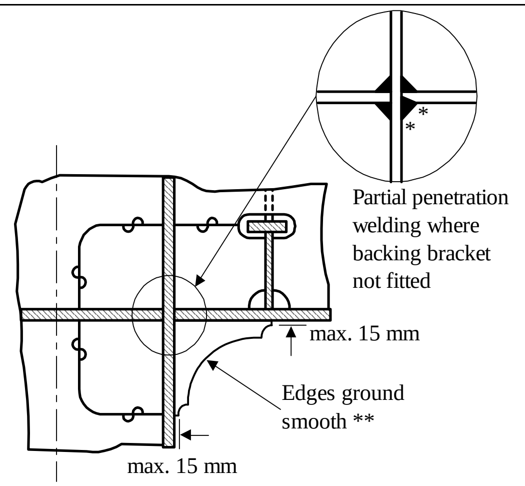




CRITICAL LOCATIONS



DETAIL DESIGN IMPROVEMENT



Note:

* Weld toe to be ground smooth, visible undercuts to be removed where brackets not fitted.

** Where a face plate is considered necessary, it is recommended that design features be adopted to reduce the stress concentration at the face plate termination (e.g., taper and soft nose).

Critical Location	Intersections of webs of transverse bulkhead horizontal stringer and double side tank horizontal girder forming square corners.
Detail Design Improvement	Elimination of scallops in way of cruciform joint and fitting a localized ‘D’ grade steel insert plate, with minimum thickness of 7 mm in addition to the Rule-required thickness, to reduce the peak and range of resultant stresses arising from cyclic cargo inertia pressure and hull girder global loading. In addition, a soft-toed backing bracket of suitable dimension is to be fitted. The following bracket sizes are recommended: • VLCC: 800x800x30 R600 with soft toe as shown in Figure • Suezmax and Aframax tankers: 800x600x25 R550 with soft toe as shown in Figure, where the longer arm length is in way of the inner skin. The actual bracket design is to be verified by fine mesh finite element analysis in accordance with CSR *Appendix B/3.1.3*.
Building Tolerances	Enhanced alignment standard. The nominal distance between the centers of thickness of the two abutting members should not exceed 1/3 of the table member thickness.
Welding Requirements	Fillet welding having minimum weld factor of 0.44, where backing bracket is fitted or partial penetration welding where backing bracket is not fitted. The extent of partial penetration should be of the order of longitudinal spacing. A small scallop of suitable shape, which is to be closed by welding after completion of the continuous welding of bulkhead, should be provided where scallop is eliminated.

Figure 2 Sample CSR Standard Detail

The hot spot stress approach (mesh size t x t) is mandatory for analysis of welded hopper knuckles. Additional discussion on the CSR approach to fatigue may be found in the TSCF *Guidance Note on Fatigue for Double Hull Oil Tankers Complying with the Common Structural Rules*. While the required fatigue life per the CSR is 25 years, for the hopper knuckle, weld improvement such as weld toe grinding may be used to increase the fatigue life so long as a minimum life of 17 years is achieved for the unimproved detail. There is a degree of conservatism introduced as an improvement of 47% is credited whereas the actual increase in fatigue life should exceed 100%.

Prescriptive requirements in the CSR cover details including bracket toes, drain holes, etc. In addition, critical locations such as bracket toes are subjected to finite element stress analysis. They are not however required to be analyzed using hotspot fatigue analysis unless the details do not comply with prescriptive requirements.

The draft Harmonized CSR requires hot spot (mesh size t x t) finite element fatigue analysis for both welded and bent lower hopper knuckles as well as welded upper hopper knuckles. In addition, the connection of transverse bulkhead lower stools to the inner bottom is to be assessed.

The Harmonized CSR also requires the fatigue life of other locations be calculated using finite element analysis. If the detail passes the fatigue screening (fine mesh 50 x 50 mm), hot spot analysis need not be carried out. The locations to be checked with fatigue screening are the toes of transverse web frames and horizontal stringers.

Similar to CSR, other critical locations are need only pass stress screening if built in accordance with design details.

5.3 Net Thickness Approach

One of the main principles of the CSR was to “provide a direct link between the thickness used for strength calculations during the new building stage and the minimum thickness accepted during the operational phase.” Previous classification society rules typically provided an allowable wastage in terms of percentage of as-built scantlings. Where a net scantling approach was used for design, the deductions were typically in numerical terms based on expected corrosion rates. As a result, some inconsistencies developed between the analysis and allowable wastage. The CSR list the allowable wastage in numerical terms.

Figure 3 depicts the as-built, owners, gross, gross required, corrosion and net required thickness. In general, scantling requirements are calculated based on the net thickness; however, global finite element analysis is carried out at thicknesses between net and gross. Figure 3 also shows important values of ships in service. The renewal thickness is the same as the net thickness. Annual surveys are required when the gauged thickness is below the reserve thickness (renewal thickness plus 0.5 mm).

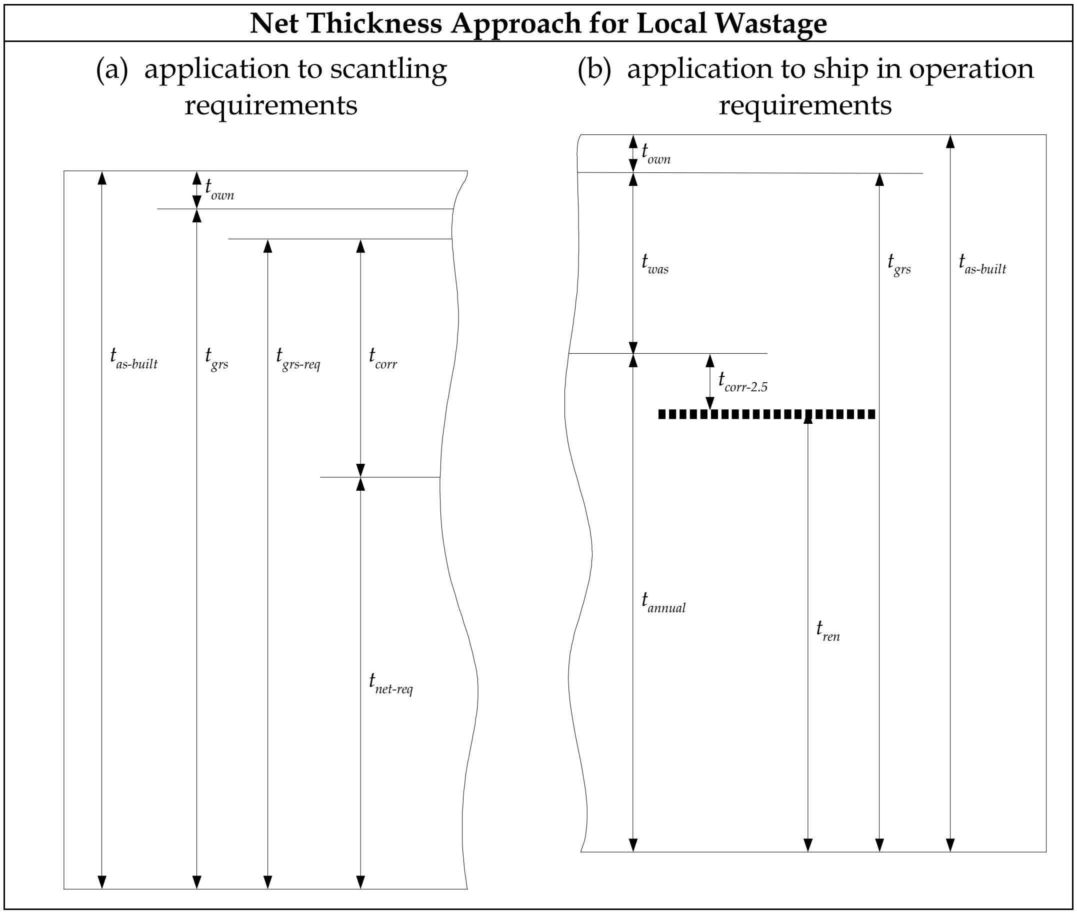


Figure 3 Net Thickness Approach

5.4 Vibration

As HTS structures tend to be more flexible, they also are more prone to vibration. Class requirements for certain structures, including the deckhouse, do not have reduction factors for HTS. As the deckhouse typically sits directly above the engine room and is a freestanding item, it is more susceptible to vibration. Excessive deckhouse vibration is known to have a negative effect on crew comfort.

In addition to crew comfort, vibration may lead to structural and mechanical failures. In general, HTS is not widely used in the engine room. Use of HTS should be minimized in the engine room. Where it is used, the extent of HTS should be kept to service proven levels. Where additional extent of HTS is proposed, additional attention is to be given to the stiffness of structural members near the source of vibration.

For example, sniped end stiffeners should be avoided in the engine room.

Vibration analysis is not a requirement of the CSR; however, it is typically checked by shipyards using their own internal procedures. Where HTS is widely used in either the engine room or deckhouse, it is recommended that a more extensive vibration analysis be carried out.

5.5 Cross-Ties

Several members have experienced damages in cross-tie structure. These problems have been attributed to a number of factors. A VLCC recently experienced cracking in cross ties towards the aft end of the cargo block. After detailed study, it was determined that the cracks could be attributed to vibration. Typically, the ship structure has a higher natural frequency than the most common sources of vibration, the main engine and propeller. When HTS is used to reduce the scantlings of the cross ties it will typically lower the natural frequency which could make them more prone to vibration-induced damages.

Damages have also been reported in cross ties due to uneven loadings when center tanks may have been loaded and wing tanks empty. CSR contain load cases to address both wing tank and center tank cross-ties. In addition, CSR require analysis of the cross tie subjected to sloshing pressures within cargo tanks.

5.6 Summary

Since the issues encountered by the HTS-rich designs of the 1980s, significant advances have been made regarding the design and analytical requirements for fatigue and buckling which lends more confidence to an HTS-rich design built under CSR.

6 Traceability of Material

The more grades of material introduced in the design, the greater the potential for shipyard errors during construction. Furthermore, shipyard supply chains have become increasingly complex. It is possible that a yard has more than one design under construction and obtains steel from several different mills. This steel may be sent to a number of cutting shops which each may be also be supplying multiple yards. In addition, yards may subcontract entire blocks. Therefore, it is critical that the shipyard have a robust procedure in place to cover traceability at each stage between the mill and the primary yard. An appendix to this paper outlines key aspects of an effective shipyard procedure.

To facilitate effective material traceability procedures, it is recommended that the steel mill put a final color tint that will identify mild and HTS. Mills should have the capability to introduce a final contrasting color scheme shine on HTS that would better distinguish it from mild steel.

Similarly, where nominally similar looking structural components may occur but with different material and perhaps thicknesses, traceability implementation for purposes of block fabrication and assembly is important.

Structural areas or locations that are critical to safety or operational reliability and uptime may need to be specifically addressed for more stringent design, traceability and inspection requirements by an owner or operator through appropriate specification requirements. Such items also may require specific traceability procedures. The latter can be implemented by appropriate identification and marking, cross-referenced to related material certificates, inspection and test records. The related information will then become part of the vessel's documentation for operation, and will be used in service as needed, such as for permanent repairs.

7 Welding and Heating Procedures

Most of the potential issues related to welding will be the same from mild to high strength steel. However, due to the lower thicknesses and higher stresses, weld design and welding procedures can become relatively more important for HTS usage. It is important that welders working in HTS have certification appropriate for the base material, consumables and work procedures to be used. To enhance awareness and understanding of potential quality issues when applying HTS for shipbuilding, the following issues shall be discussed:

- Welding and preheating procedure
- Straightening by open flame

In addition, the yield strength of TMCP-steel could be irreversibly reduced if the material temperature is increased above 580°C. In order to minimize the deterioration of the mechanical and metallurgical properties of TMCP-steel, welding and heating procedures must be approved by the class society.

7.1 Welding and Preheating Procedures

The relatively high content of alloy elements necessary to achieve the fine grain microstructure of HTS may lead to a deterioration of important strength properties in case of fast cooling down after welding, e.g. when applying small welds on thick parts. To counteract the unwanted fast cooling, all plates of 25 mm thicknesses and above shall generally be preheated prior to any welding being carried out. The necessary preheating temperature has to be determined on the basis of the actual material properties as shown in the material certificate submitted by the steel supplier. In order to avoid rapid cooling after welding, the preheating of voluminous cast pieces has to be carefully considered. The same applies to welding in low ambient temperatures ($T_a<5°C$), e.g. in winter conditions. Reference is made to the standard EN 1011-2. Appropriate preheating should be specified in the approved welding procedures.

7.2 Straightening by Line Heating

Line heating is a common practice used to straighten structures by surface heating using open flame. In this practice the heating is limited to the surface. The use of too much heat may cause a certain loss of yield strength in high tensile and TMCP-steels. IACS Recommendation No. 47 addresses the maximum heating temperature for short duration heating of both material types.

8 Alignment of Critical Areas

Due to the relatively higher stress levels permitted for HTS, misalignment of abutting parts subject to dynamic loads may increase the risk of fatigue cracks and yielding due to stress concentrations at the respective geometrical discontinuity. To address the increased risk, especially for hull members affecting longitudinal strength, the permissible limits for imperfections of welding joints is lowered by class society requirements when compared to the corresponding requirements for mild steel structure.

IACS requires that vessels be built in accordance with a recognized standard for workmanship and quality control. One widely referenced standard is IACS Recommendation No. 47 Shipbuilding and Repair Quality Standard.

Section 7 of Recommendation No. 47 contains alignment requirements for butt welds, fillet welds, and other connections. In general, the alignment requirements are given as a percentage of the thickness of thinner member. For example, the standard alignment for butt welds is to be within 15% of the thinner member and 33% for fillet welds. Therefore, alignment becomes more critical when working with thinner HTS members as the alignment thresholds will be smaller in terms of the whole number.

Typically, critical areas are identified in a construction monitoring plan. These will be identified based on analysis and experience, and will place more emphasis on locations where fabrication is difficult.

9 Availability for Repairs

AH-32 and AH-36 are in some cases readily available in even numbered thicknesses. This means that in such cases, greater rounding up is frequently required to obtain a satisfactory scantling. For large repair jobs (renewal of underdeck longitudinals in cargo tanks), there is value in early ordering steel so as to minimize the steelweight and cost penalty. D and E grades are sometimes more difficult to obtain and failure to advise the repair yard in time can lead to delays in procuring the material. Such consideration becomes significant when repairing collision or grounding damage where speed is of the essence.

For the particular case of high tensile rolled sections, it may well be that the original rolled section or equivalent is not available and longitudinals will need to be fabricated. Again this needs advance notice to the shipyard and may impact slot, collar and lug dimensions.

There are cases where AH grade material has been accepted as DH after satisfactorily passing Charpy testing; however, TSCF would advise against this as it complicates established practice around plate classification and material traceability. Verification of certification is vital for HTSs and every effort should be made to verify that the steel in the yard is the steel on the certificate. There are cases on record of fraudulent altering of steel to match certificates and this is of course not acceptable.

A side effect of reduced availability can be that in some cases shipyards and their workers are not fully familiar with handling HTS. This means that inspection and verification efforts must be increased, particularly for pre-heat and consumables. Also, while care always needs to be taken with color coding and marking, in special cases such as one where naval and commercial shipbuilding are conducted in the same yard, consistency of marking becomes vital.

10 Corrosion and Coatings

Pre-CSR class Rules generally limited local wastage based on a percentage of the as built thickness. Therefore, if HTS was used to reduce the thickness of a particular structural member, the corrosion margin was also reduced by the same percentage. Since corrosion generally occurs on a thickness per year rate basis, and not a percentage of thickness basis, the use of HTS resulted in a reduction in the in-service “life” of the structural member before it has to be renewed.

For example, if a ballast tank bulkhead was constructed using 16 mm mild steel, it may have an allowable wastage of 25% or 4 mm. If the same bulkhead is constructed of HT36 material to a thickness of 11.5 mm (reduced thickness due to HTS), the corrosion margin at 25% drops to 2.9 mm. If the corrosion rate in this location is 0.14 mm per year, the use of HTS would reduce the in-service “life” from 28.5 to 20.7 years. In addition, the requirements related to substantial corrosion, defined as 75% of the allowable wastage, may make this issue even more pronounced.

The CSR corrosion margins are based on a thickness amount instead of a percentage of as built. The margins were developed based on experience as well as statistical analysis of data collected from classification societies. The additions are intended to provide for a 25-year service life and have an additional 0.5 mm for substantial corrosion. The CSR corrosion margins correlate well with those contained in the paper “Corrosion Protection of Cargo Tanks” presented by Chevron Shipping Company on behalf of TSCF at the 2000 Shipbuilders Meeting.

Corrosion is directly linked to the effectiveness of coatings, where applied. Increased use of HTS and higher yield HTS will increase the flexibility of the vessel. If coatings are not sufficiently flexible, failures may occur. The “Performance Standard for Protective Coatings for Dedicated Seawater Ballast Tanks in all Types of Ships and Double-Side Skin Spaces of Bulk Carriers” (PSPC) specifies a test to measure the flexibility of coatings, but does not does not make this test mandatory. Reference should be made to

PSPC Appendix 1 Section 2.2.4 and ASTM D4145:1983, "Standard Test Method for Coating Flexibility of Prepainted Sheet." This topic becomes more complex since the flexibility of coatings may change due to ageing, exposure to extreme temperatures, and other factors.

11 Enhanced Survey

High strength steel as used in ships generally is perceived to have a lower margin for corrosion and buckling, and as being more susceptible to fatigue than mild steel. This may or may not be, depending on the particular case and the standard of care (including stress, buckling and fatigue analyses) exercised in a particular design. Also, as previously noted, there are additional considerations related to HTS usage that are pertinent for the construction and during service as well. As such, a more rigorous survey plan may be indicated.

The standard survey requirements for ships are given in the applicable class Rules. These survey requirements have been based on experience with ships constructed of mild steel. In order to address the possibility of HTS premature failure due to corrosion, fatigue and buckling, the special survey scope utilized during each special and intermediate inspection may need to be altered.

Special survey requirements for the first 5 and 7.5 years of the ship's life are limited in the number of tanks and details, but a broader survey scope should be considered. Areas that have been identified through analysis or industry experience as being susceptible to buckling or fatigue should be closely inspected, as well as any typical areas where fatigue or buckling has previously been identified. In all areas where coating failure and corrosion have been noted, close attention should be paid to verify that the lower corrosion margin as compared to mild steel is not in danger of being exceeded. Typical failure details are listed in TSCF papers.

12 Considerations for Use

Some owners have in the past used or specified HTS limits in new construction, as well as for purposes of chartering. Discussions within TSCF indicate that the practice may be decreasing, particularly with the advent of CSR and increasing use of advanced analyses. While it is correct that the physics of HTS usage (e.g. increased stresses, thinner scantlings, fatigue, construction, and in service concerns) has not in principle changed, its use still needs to be considered in individual cases by stakeholders including owners and operators, shipyards and Class.

Generally, the present study indicates that with CSR, and even perhaps earlier in the case of some class societies, class Rules have over time included consideration of issues particular to HTS in their Rules and practice. This practice on the part of Class will certainly continue and future refinements may be expected as experience is generated, accumulated and fed back under the relatively new CSR regime. These and other recent statutory developments including those related to coating of cargo tanks will continue to improve fleet structural reliability levels worldwide over time.

Vessel owners and operators also bear important responsibilities for adequate care regarding shipyard new construction specifications, monitoring of construction by their site teams, and of course ongoing lifecycle care after construction; care that needs to be adequate for the individual vessel and particular circumstances, including trade routes, the degree of HTS (in the context of the present paper), and various other factors.

Regarding feedback of experience into specifications, standards and practice, Class has access to significant owner and operator experience which will help facilitate their ongoing and continuous refinements and improvements.

Considering the various pertinent factors, TSCF suggests that in place of specific HTS ratio limits, the following technical considerations are among those that are of greater importance where use of HTS may be of concern:

- For vessels reviewed to the CSR for Oil Tankers, finite element analysis based buckling calculations should be carried out for the full cargo block region. Reference may be made to the Harmonized CSR.*
- Additional fatigue analysis should be carried out at critical locations not covered by the CSR.
- It is preferable for cross ties to be constructed with mild steel. Where HTS is used in greater quantities, the vibration analysis should consider the cross ties.
- For locations where credit is taken for weld improvement in the fatigue calculation and design, an appropriate construction monitoring program should be put in place.
- Owners may consider specifying an additional corrosion margin in locations they have experienced coating breakdown and wastage.
- Where HTS is used throughout the engine room or deckhouse, a more extensive vibration analysis should be carried out.
- Appropriate procedures to address traceability are to be in place in mills, subcontractors, cutting shops, and shipyards; additional traceability needs of critical components should also be addressed.
- Straightening of TMCP-steel is only to be carried out where carefully monitored and with specific approval by the class society
- The coating is to be subjected to the flexibility test recommended by the IMO Performance Standard for Protective Coatings.
- Additional planning is required before a vessel enters drydock for repairs as availability of certain grades of HTS may not be widely available.

* At the time this paper was published, the Harmonized CSR was under industry review and subject to change before final adoption.

APPENDIX

Traceability from the Steel Mill to Construction

A.1 Terms and Definitions

A.1.1 Mill

A steel maker which produces rolled plates or profiles.

A.1.2 Mill Certificate (Inspection Certificate)

A certificate which records the information and test results including the chemical compositions and the mechanical properties of plate or profile. A mill certificate is issued to a bundle of rolled plates.

A.1.3 Heat No. (Charge No. or Cast No.)

A heat number is given to the plates by a steel maker for their own purpose. It is a serial number of a slab from a furnace which is a semi-finished product used to produce a plate or a profile by rolling. It is specified in a mill certificate.

A.1.4 Lot No.

A lot number is an identification number assigned by a mill to a bundle of rolled plates that are of equal sizes and properties. It is specified in the mill certificate.

A.1.5 Product No.

A product number is an identification number assigned by a mill to every single plate. For example, if two plates have the same size and properties, they will be assigned the same lot number; but will have different product numbers.

A.1.6 Plate No.

A plate number is assigned by a yard to every single plate according to the yard’s coding system. It is necessarily used to find a mill certificate in the yard’s plate data base. It is usually specified in cutting drawings.

A.1.7 Piece No.

All the pieces cut from a plate have their unique piece number at the production design stage based on the yard’s coding system. This number is specified in the production drawing and cutting drawing. It is also marked on the piece plate, usually by hand before cutting.

A.1.8 Production drawing

A production drawing is a drawing used for assembly. It is based on a structural drawing and includes additional information for production methods (e.g. welding details, plate margin by welding shrinkage and holes, the order of assembly, etc.). A production drawing contains every piece number for all structural members presented in the drawing.

A.1.9 Cutting drawing

A cutting drawing is the drawing for a plate to be cut by an N/C machine. It describes the cutting arrangement for a plate. The plate is cut by the N/C machine exactly as shown on the cutting drawing. It contains the piece number for each piece cut from the plate as well as the plate number (refer to A.1.6)

Name of number	assigned by	marked on				used in
		Mill Cert.	Plate	Production dwg	Cutting dwg	
Heat No.	Mill	O	-	-	-	-
Lot No.	Mill	O	O *	-	-	finding mill cert.
Product No.	Mill	O	O *	-	-	-
Plate No.	Yard	-	-	-	O	finding Lot number in the data base
Piece No.	Yard			O	O	finding cut'g dwg

*It is erased after blasting and priming, then marked on the plate normally by stenciling

Table A.1 Summary of Numbers Marked on Plates

A.2 Process of Hull Manufacturing

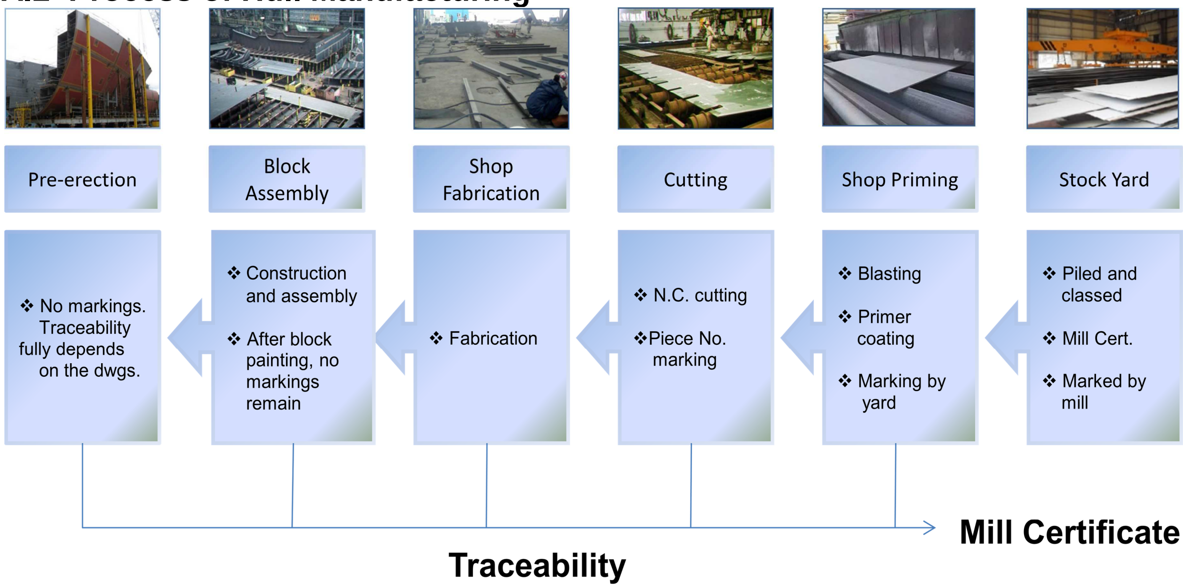


Figure A.2 Process of Hull Material and Traceability

The building process from stock yard to pre-erection stage is summarized in Fig. A.2. Proper implementation will ensure traceability from the mill certificate to any point during construction. To this end, most yards have their own material control system and manage it effectively.

A.2.1 Stock Yard (Incoming raw materials)

The requested plate materials would be piled and classified according to a project (hull no.), steel grade and yard's standards at a steel stock yard.

A raw plate has various markings that are assigned by a yard or mill for the convenience of efficient control and classifying of the material. It may be different according to a yard or mill's coding system. However, basic information is similar. Fig. 3 shows an example used in various mills and shipyards.

Figure A.3 Markings by a Mill on a Plate in a Stock Yard

The first row is a product number assigned by a mill. The fifth row is a lot number assigned based on a yard's request. It is generally a combination of hull number, block number, etc.

A.2.2 Shop priming

A project number, dimension and grade, etc. are marked on the primer-coated plate by an automatic stencil marking system because the information on a plate marked by a mill gets erased during blasting and primer coating, as shown in Fig.3 and Fig. 4. Usually, the grade marking of mild steel may be omitted.

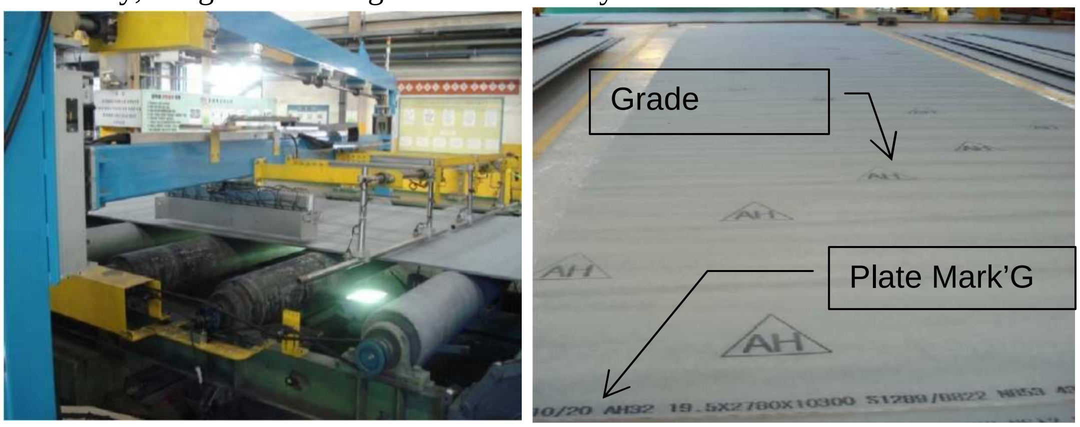


Figure A.4 Automatic Stencil Marking System

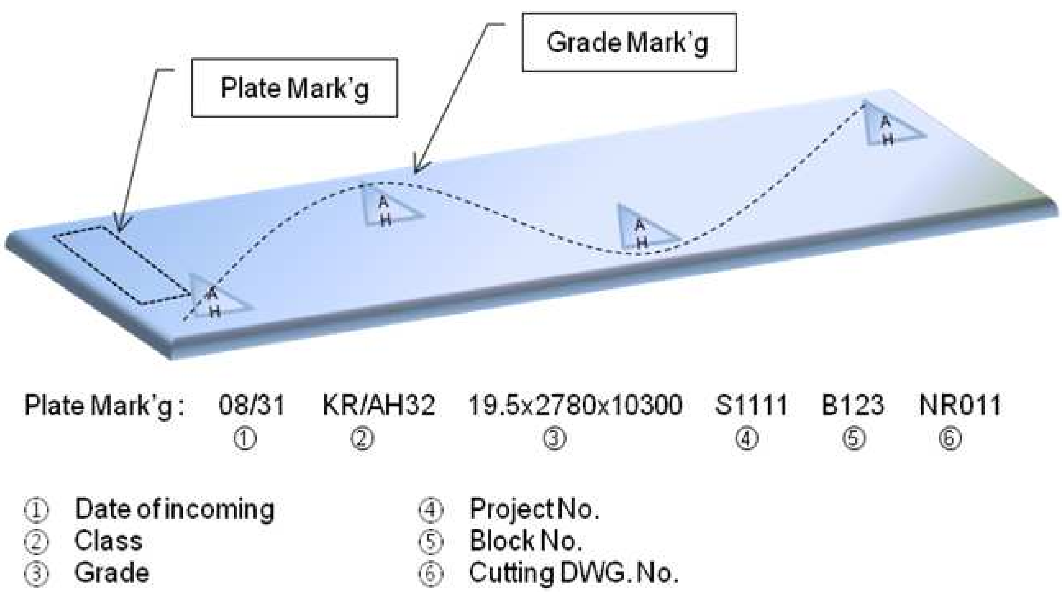


Figure A.5 Stencil Marking Arrangement

A.2.3 Cutting, fabrication, block assembly and pre-erection

After priming, the plate is transferred to a cutting machine. Before cutting the plate, the worker confirms that the plate number matches the cutting drawing.
A pre-marking for cutting lines is carried out automatically by the cutting machine.
After the pre-marking operation, all the cut materials are to be clearly marked with

piece numbers and grade. The piece number marking is normally done by hand writing before the plate is cut by the machine.
After cutting, each piece with a unique piece number is transferred to the relevant fabrication shop and then transferred to block assembly and pre-erection stages, as shown in Fig. A.2

A.3 Material Traceability

A.3.1 Material Traceability before block painting

A piece number is the unique code number assigned according to a yard's coding system. Its contents are similar among most yards. It contains a variety of information such as a project (hull no), block, assembly, sending package numbers, and steel grade as shown in Fig. 6. The sending package number indicates the assembly location where the piece is assembled.

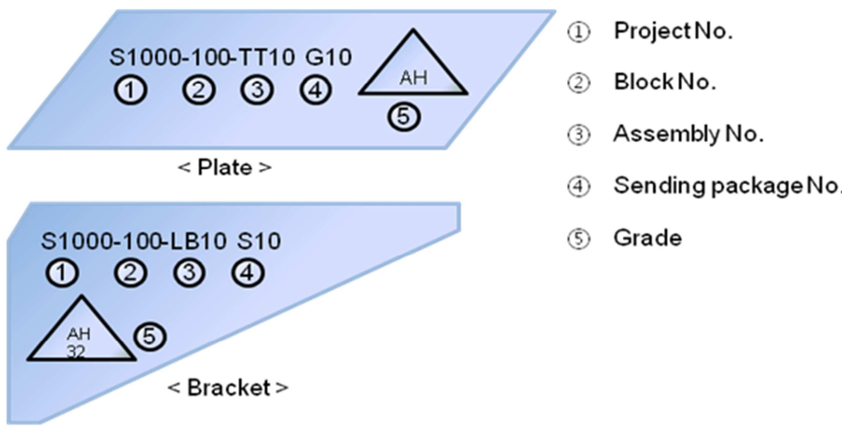


Figure A.6 Piece Number and Information for Plate and Bracket

Fig. A.7 shows a piece number, which is similar to that of Fig.A.6, marked on both a collar plate in the double bottom structure and a production drawing.

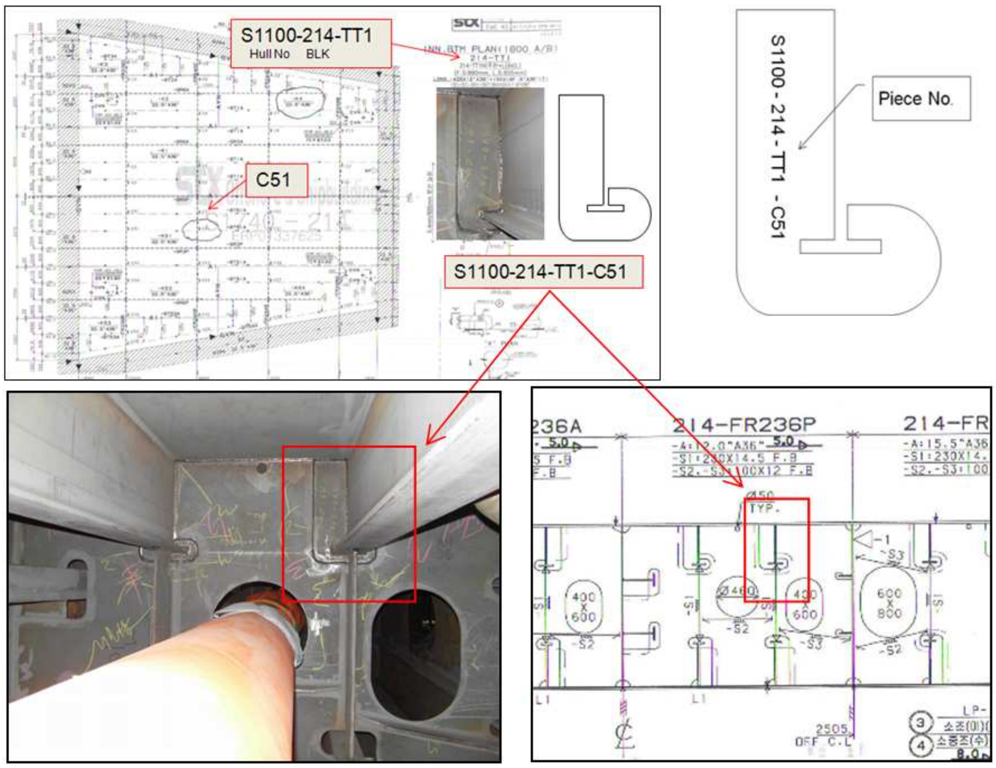


Figure A.7 Piece of Collar Plate (left) and Production Drawing Containing the Piece (above and right)

The same piece number can be found in a cutting drawing as shown in Fig. A.7. In the cutting drawing, a plate number is also specified by the hull production design staff. A lot number can be found by inputting this plate number in the computerized data base as shown Fig. A.7. The mill certificate can then be searched with the lot number shown in Fig.A.7 on the right-hand side.

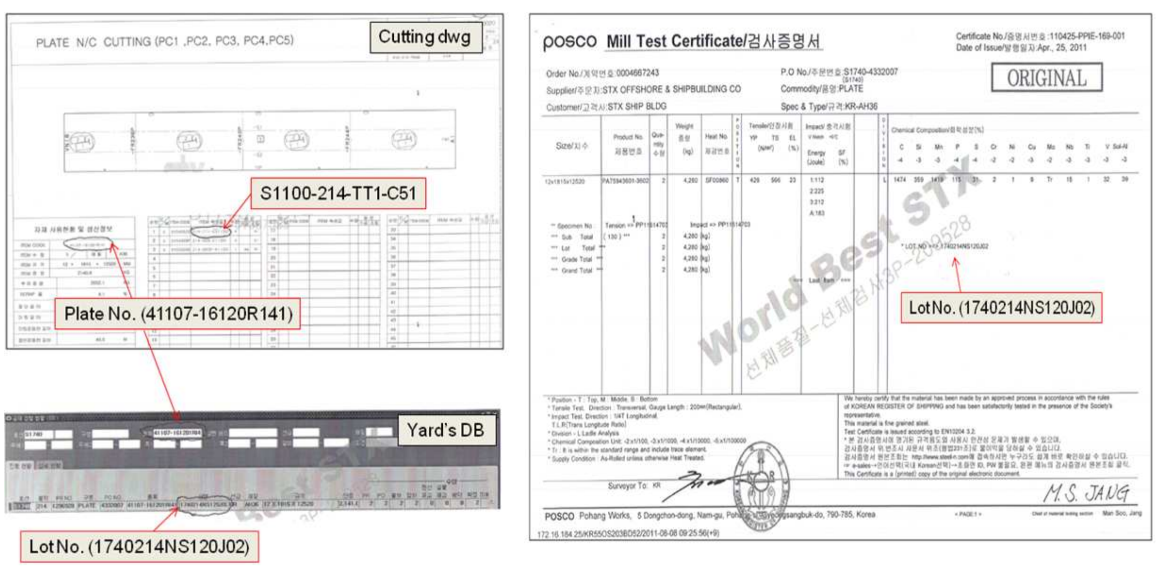


Figure A.8 Cutting Dwg (left, up), Computerized Database (left, low) and Mill Certificate (right)

A.3.2 Material Traceability after block painting

A piece number marking will be completely erased during the block painting process. There is no way to determine the path from the piece to the mill certificate without depending on the structural drawings, block division, production drawings and cutting drawings.