THE DEVELOPMENT OF RULES
FOR BUILDING AND CLASSING ALUMINUM VESSELS

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4th Pan-American Congress of Naval Engineering, Ports Engineering and Maritime Transportation. 16-22 November 1975 - Lima, Peru.

AMERICAN BUREAU OF SHIPPING

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INTRODUCTION

Aluminum has been a shipbuilding material for about 85 years during which time an appreciable number of aluminum vessels have been either classed or have been subject to design review by the American Bureau of Shipping. With the continuing trend towards this use of aluminum it was decided that as a service to industry the American Bureau of Shipping would develop Rules for the Building and Classification of Aluminum Vessels. These Rules were developed to provide requirements by which vessels constructed of aluminum would be as structurally reliable as those constructed of steel. The Rules for the Building and Classification of Aluminum Vessels were completed in May 1974 and were published for general distribution earlier this year.

The aim of this paper is to describe the development of the Rules for aluminum vessels from those for steel vessels and the measures taken, directly and indirectly, to account for the differences between aluminum and steel that might have a bearing on the structural reliability of the vessel. For the benefit of those interested, reference is also made to the service experience with aluminum vessels. And although not a part of the development of Rules for aluminum vessels, Appendix A includes some design features of aluminum vessels which may be of general interest or assistance to owners, builders and designers.

BACKGROUND

It is 85 years since the 5.16 meter (17 foot) aluminum launch "Zephyr" was built in Zurich. Seven or eight other aluminum vessels of up to about 12.2 meter (40 foot) in length were built prior to the beginning of this century. Throughout this century all-alumimun vessels have continued to be built although until some twenty-five years ago they were generally the exception and were to some extent regarded as experimental. Aluminum has also been used for the upper structures of large commercial and naval vessels where its weight-strength properties were used to advantage by improving the vessels' stability while retaining adequate strength. For naval vessels, its use in upper structures permitted increased armament or protection elsewhere while keeping the displacement within treaty limits.

More recently aluminum has become a conventional building material for vessels in certain types of service. For pleasure boats, aluminum has fast replaced wood as a construction material while the last decade or so has seen aluminum become both feasible and popular for the construction of competitive racing yachts.

Perhaps the most notable advances to date of aluminum in the construction of commercial vessels have been in the fishing industry where, by the end of the 1950's, a modern fleet of aluminum fishing vessels was in service. The economic advantages of these vessels soon led to their more widespread use and since the early 1960's numerous aluminum fishing vessels of up to 18.3 meters (60 foot) in length have gone into service. These vessels have by all accounts proven most satisfactory.

While not as numerous as fishing vessels there are quite a number of aluminum hydrofoil ferries in the length range 18.3-27.43 meters (60-90 foot) now in service and several larger, more conventional, ferryboats of up to 45.73 meter (150 foot) in length are operating in U.S. coastal service.

To date the largest all-welded aluminum commercial vessel in service is an ABS classed 91.46 meter (300 foot) ocean-going vehicle carrier. This is followed in size by the 67.98 meter (223 foot) 1959 German-built oil tanker "Aluminia" and an ABS classed 66.46 meter (218 foot) ocean-going survey vessel. There are also quite a number of ocean-going supply vessels in service in the length range 30.5-36.6 meter (100-120 foot).

It is of interest to note that the only aluminum cargo vessel to have refrigerated cargo spaces, for which aluminum construction would seem most suitable, is a 32.32 meter (106 foot) vessel built in 1966 in Guyana.

No doubt there are a number of factors contributing to the progress of aluminum as a shipbuilding material, among which are the possibility of a maintenance-free long life and increased deadweight. However, the more recent availability of improved aluminum alloys and advances in aluminum welding technology have probably contributed more than any other single factors to establish aluminum as a more conventional shipbuilding material. Quite recently an investigation was completed into the feasibility of constructing a 152.44 meter (500 foot) bulk carrier of aluminum. This gives some further idea of the extent to which alumimum is being considered.

The services of the American Bureau of Shipping have been used very often in the design, construction and survey of aluminum vessels throughout the years in which these vessels have developed. For reference, a list is shown in Table 1 of all-aluminum vessels either classed by the Bureau or having had designs reviewed by the Bureau. The records of the service experience of the ABS classed vessels, which cover all the current services in which aluminum vessels are employed, indicate aluminum to be a satisfactory shipbuilding material.

DEVELOPMENT OF RULES

The decision to develop Rules for the construction and classification of aluminum vessels was made in 1969. At the time the Bureau was also developing Rules for small steel vessels, much needed because of the different characteristics of vessels under 45.73-61 meters (150-200 foot) in length. In view of this it was felt that the Rules for aluminum vessels should cover the length range 45.73 to 152.43 meters (150 to 500 foot) and that requirements for aluminum vessels under 45.73 meters (150 foot) in length could be obtained using the conversion factors in the Rules for aluminum vessels together with the requirements for steel vessels under 45.73 meters (150 foot).

The experience to date with Bureau classed aluminum vessels indicated it was feasible to use the Rules for Building and Classing Vessels as a basis from which, by suitable conversion factors, scantlings of comparable structural reliability could be derived. The Rules for steel vessels express scantling requirements in several ways. In all cases, however, whether apparent or not there is in the requirement equation an allowable stress which is in turn the product of the failure stress and a safety factor. Presuming the actual applied load in service to be unaffected by the use of aluminum it was considered most feasible to establish conversion factors by which the steel scantling requirements are adjusted for the failure stress differential of the two materials, to give aluminum scantlings providing the same reliability against failure as those of steel vessels. Thus the development of the Rules for aluminum vessels became to a considerable extent, but not entirely, a question of determining conversion factors based on the difference in those properties of aluminum and steel which affect their resistance to the various possible modes of failure in service.

As such conversion factors presume no variation in applied loads, the possible effects of the use of aluminum on the applied loads also needed to be investigated.

Another aspect to be accounted for was to ensure that where, by virtue of structural arrangement or extreme differences in material properties, additional requirements became necessary for aluminum construction they were included in the Rules and where those for steel construction became redundant they were omitted.

It seems appropriate here to also acknowledge the valuable assistance provided by the Aluminum Association of America, particularly in developing the sections of the Rules on materials, welding and corrosion protection.

ESTABLISHMENT OF CONVERSION FACTORS FOR SCANTLINGS OF ALUMINUM VESSELS

The possible modes of failure for a steel vessel are tensile yield, shear yield, fatigue fracture, instability in compression and brittle fracture. Understandably the Rules for aluminum vessels should provide at least the same reliability against structural failure in any of these modes as do the Rules for steel vessels. The following consideration was given to this in the development of the Rules for aluminum vessels. Unless specifically mentioned otherwise the reference to steel throughout is to ordinary strength Rule steel.

Tensile strength

The basic tensile strength conversion factor established to ensure that the aluminum structure has tensile strength equivalent to that of steel is:

$$Q_o = \frac{Ys + Us}{Yal + Ual}$$

where

Ys = the minimum tensile yield strength of ordinary-strength Rule steel

Us = the ultimate tensile strength of ordinary-strength Rule steel

Yal = the minimum tensile yield strength of the welded aluminum alloy at 0.2% offset

Ual = the minimum ultimate tensile strength of the welded aluminum alloy

The form of this conversion factor is similar to that used to derive higher strength steel requirements from those of ordinary strength steel and it is considered equally appropriate to express the equivalent tensile strength requirement for aluminum.

Although the initial failure mode would be yield, the conversion factor gives equal prominence to ultimate strength for the following reasons. For many years ultimate tensile strength was the only tensile strength test property on which material approval was based and therefore that on which much experience was acquired. Its use also serves to provide some degree of equivalent strength, load carrying capacity, beyond the yield strength and ultimate strength is more closely related to the fatigue strength of the material than is the yield strength.

With the use of a fatigue strength conversion factor for aluminum the two former reasons for including ultimate strength in the equation still remain valid.

The requirements in the aluminum Rules for all structural members which may be subject to tensile stress are given by the product of this factor and the requirement for the same structural member in the Rules for steel vessels, except for plate thickness requirements for loading normal to the plate where the stress varies with t^2 and $\sqrt{Qo}$ is used.

Shear Strength

Structural casualty due to shear yield is extremely uncommon in steel vessels, particularly those in the length range concerned, i.e., 150 to 500 feet. Nevertheless, it was felt appropriate to give attention to this mode of failure in developing the Rules for aluminum vessels.

It was concluded adequate to confine this consideration to the webs of primary and secondary structural supporting members. The ratio of shear yield strength to tensile yield strength of aluminum is similar to that of steel but the ratio of ultimate shear strength to ultimate tensile strength of aluminum is somewhat less than that of steel. Conversion factors for shear strength would therefore be about 12% greater than those for tensile strength, Q_o, when expressed in the same form.

The required thickness of the webs of primary structural members of aluminum, such as girders, transverse floors, etc., is obtained by use of the conversion factors Q or Qo. However, an additional correction factor is introduced in the aluminum Rules by which the required web depth for aluminum members is increased 15% above that for steel members. The product of this increased web depth and the web thickness given by use of Q or Qo results in web areas and shear stresses comparable to those for steel in terms of resistance to shear failure.

Secondary structural members such as beams, stiffeners, etc. are usually rolled sections and requirements for them in the Rules for steel vessels are given only in terms of section modulus. Provided openings in the webs are kept within reasonable limits experience has shown the steel manufacturers' standards to be such that compliance with the section modulus requirement ensures adequacy against other possible modes of failure due to loading normal to the plating which member stiffens. It is thought that aluminum manufacturers standards for rolled sections would be similarly designed but as a precautionary measure further reference is made to this later in the form of guidance information in Appendix A. It will also be explained later how in deriving aluminum fillet weld sizes from those given in the steel Rules, minor correction is made for the lower ratio for aluminum of ultimate shear strength to ultimate tensile strength.

Fatigue Strength

Fatigue fracture in steel vessels has not been found to be a failure mode on which scantlings need to be based. The limited occurrence has been confined generally to the welded connections of internal structural members and the prevention brought about by revised details. Nevertheless, in recognition of the lower fatigue strength of aluminum compared with that of steel it was considered necessary to derive a conversion factor with the intention of providing the aluminum vessel with a fatigue strength comparable to that of a steel vessel. The conversion factor established is

$$Q = 0.91 + \frac{Ys}{2\ Yal}$$

where

Ys = the minimum yield strength or ordinary-strength Rule steel

Yal = the minimum yield strength of the welded aluminum alloy at 0.2% offset

The requirements in the aluminum Rules for all structural members subject to fluctuating stress of significant frequency are given by the product of this factor and the requirement for the same structural item in the Rules for steel vessels. However, as with the conversion factor Qo, the plate thickness requirement for loading normal to the plate is obtained by use of the conversion factor $\sqrt{Q}$. The factor Q is generally greater than Qo, the static tensile strength conversion factor.

The conversion factor, Q, was developed so that the aluminum vessel sea load stress (wave induced, hull girder bending stress plus bottom shell stress due to local pressure) resulting from its application would at any frequency at least ensure the same margin to fatigue failure stress as exists between the sea load stress and the fatigue failure stress for a steel vessel. An example of the derivation of this relationship is shown in Figure 1.

The sea load stresses in the bottom shell for steel vessels were estimated to be those due to wave induced hull girder bending and local wave induced pressure. The wave induced hull girder bending stresses at the various probability levels were taken from long-term predictions. It was assumed that local wave induced pressures would follow the same trend and could be estimated from a wave height of 48 foot (a 24 foot single amplitude) at 10^2 cycles and would be zero at 10^8 cycles for a ship life of about 20-25 years. It should be emphasized that these values are used for comparative purposes only.

The suitability of the conversion factor so derived was checked by Miner's Rule comparing the resulting $\sum n_{al}/N_{al}$ for the aluminum alloy vessels with $\sum n_s/N_s$ predicted for steel vessels. In the foregoing n is the number of cycles of a particular sea load stress in service during the ship life and N is the number of cycles to fatigue failure at the same stress level. The results of this are shown in Table 2. These values should also be regarded as being comparative only.

It can be seen from the predicted fatigue lives of the structures, given by the reciprocal of $\sum n/N$, that the conversion factor for fatigue strength, $Q = 0.91 + \frac{Ys}{2\,Yal}$ when used to derive aluminum scantlings from those of a steel member can be considered to provide the aluminum structure with as suitable a fatigue life as a steel structure.

Plate Stability in Compression or Shear

As the value of the modulus of elasticity of aluminum does not vary with the alloy or temper it was thought unnecessary to introduce an additional conversion factor to ensure the buckling strength of the aluminum vessel be comparable to that of a steel vessel. Rather the conversion factors Q or Qo could be given minimum values to do this.

For the equivalent resistance to elastic buckling in compression for the strength deck, bottom and side shell plating.

$$Es \cdot \left(\frac{ts}{s}\right)^2 \times \frac{SMs}{M} = Eal \cdot \left(\frac{tal}{s}\right)^2 \times \frac{SMal}{M}$$

in the Rules for aluminum vessels

$tal = Qts$

and for hull girder section modulus

$SMal = Q\ SMs$

and

$$\frac{Es}{Eal} \left(\frac{ts}{s}\right)^2 \times \frac{SMs}{M} = \left(\frac{Qts}{s}\right)^2 \times \frac{Q\ SMs}{M}$$

or where $1.401 \leq Q$, the aluminum deck, bottom shell or side shell has buckling strength equivalent to that of the steel vessel.

For equivalent resistance to elastic buckling due to shear in the webs of primary members

$$Es \cdot \left(\frac{ts}{s}\right)^2 \times \frac{As}{SF} = Eal \cdot \left(\frac{tal}{s}\right)^2 \times \frac{Aal}{SF}$$

in the Rules for aluminum vessels

$tal = Qts$

& $d\ al = 1.15\ d_s$

& $A\ al = 1.15\ Q\ A_s$

then

$$\frac{E_s}{E_{al}} \left(\frac{ts}{s}\right)^2 \times \frac{As}{SF} = \left(\frac{Qts}{s}\right)^2 \times \frac{1.15\ Q\ As}{SF}$$

or where $1.34 \leq Q$, the web of the aluminim primary member has buckling strength equivalent to that of the steel member.

Es = modulus of elasticity of steel

Eal = modulus of elasticity of aluminim

ts = required minimum thickness for ordinary-strength Rule steel

tal = required minimum thickness for aluminum alloy

SM = required hull girder section modulus, ordinary strength Rule steel vessel

SMal = required hull girder section modulus, aluminum vessel

Q = aluminum scantling conversion factor for fatigue strength equivalent to ordinary-strength steel

ds = required minimum depth of web of primary member, ordinary-strength steel

dal = required minimum depth of web of primary member, aluminim

As = ts x ds   M = Hull Girder Bending Moment

Aal = tal x dal   SF = Shear force in primary member web

The present requirements in the Rules for steel vessels for bottom shell, side shell, strength deck and the webs of primary structural members are shown by service experience to be most adequate. Accordingly, it was considered reasonable to establish a minimum value of conversion factor, Qo or Q, of

1.30 for deriving from the requirements for steel vessels, aluminum, bottom shell, side shell, strength deck and primary web scantlings adequate in resistance to buckling.

Stability of Internal Stiffening Members in Compression

Service experience of steel vessels indicates no evidence of instability of the complete member due to sea loads or internal hull loads. The members subject to the highest compressive stresses are probably bottom shell and deck longitudinals. It was concluded that for aluminum vessels the hull girder bending stresses reduced by the coefficient Q and the section modulus (and consequently inertia) of the internal stiffening member increased by the conversion factor Q would ensure aluminum internal stiffening members to have adequate stability under compressive loads.

Strength of Pillars and Stanchions in Compression

The allowable compressive load on aluminum pillars and stanchions is given by

$$Wa = \left(1.02 - 5.93\times10^{-3} \ (l/r)\right) \frac{A.Yal}{17} \text{ metric tons}$$

$$\text{or } Wa = \left(6.49 - 0.452 \ (l/r)\right) \frac{A.Yal}{24000} \text{ long tons}$$

where

Wa = allowable load

l = unsupported span in cm or ft

r = least radius of gyration in cm or in

A = cross-sectional area of pillar or stanchion in cm^2 or in^2

Yal = minimum yield strength of welded aluminum-all[illegible]
at 0.2% offset

This requirement is derived from the critical load curve and is based on providing the same factor of safety for aluminum pillars and stanchions as presently given in the Rules for steel pillars and stanchions.

Derivation of this requirement is illustrated in Figure 2.

<u>Brittle Fracture</u>

The fact that aluminum remains ductile even at low temperatures gives aluminum advantages over steel in this respect. Provided suitable attention is given to detail and workmanship it was considered there was no need for any requirements addition to those in the Rules for steel vessels.

<u>Resistance of Aluminum to Corrosion</u>

In recognition of the superior resistance of aluminum to corrosion compared with steel, a 10% reduction was given to all the requirements for aluminum derived from the Rules for steel vessels.

<u>Effect of Welding on Strength of Aluminum</u>

As there is a definite reduction in strength due to welding, the minimum yield and minimum ultimate tensile strengths of aluminum used to obtain conversion factors are for welded aluminum specimens. Minimum expected values for the various alloys are given in Section 30, Table 30.1, with the provision there that higher minimum values may be adopted where they can be verified by test.

Conversion Factors

The conversion factors developed in accordance with the foregoing, to ensure the reliability against failure of an aluminum vessel is comparable to that of a steel vessel, are shown in Table 2 for various aluminum alloys.

EFFECT OF ALUMINUM CONSTRUCTION OF INTERNAL HULL LOADS

Still Water Bending Moment (SWBM)

For vessels with identical form, dimension, draft and arrangement the internal load distribution of an aluminum vessel will in most cases differ from that of a steel vessel because of its reduced lightweight and increased deadweight. This can in certain circumstances result in an increase in SWBM and in general it makes the aluminum vessel more sensitive than a steel vessel to change in SWBM for change in cargo distribution. The numerical effect on the SWBM of this change in internal load distribution was investigated and showed an aluminum vessel could have a SWBM of up to 40% greater than that of a steel vessel of identical form, dimension, draft and arrangement. For steel vessels under 400 feet, of normal form and loading, SWBM calculations are not required since the SWBM is not expected to be critical. However, with the possibility of up to a 40% increase in SWBM for some aluminum vessels it was found that critical values of SWBM could occur at lengths much less than 400 feet. Accordingly, it is required in the Rules for aluminum vessels that SWBM calculations be submitted for vessels of length 200 feet or more. It seems worthwhile to mention that the greater sensitivity to change of the aluminum vessel SWBM for change in cargo distribution need not always result in a value of SWBM greater than for a similar steel vessel. If not in conflict with other design requisites advantage may be taken of it in certain cases to reduce the SWBM below that of a similar steel vessel. In determining the SWBM, caution should be taken in the use of lightweight LCG values which might have be determined for steel vessels as they may not therefore be accurate enough.

There will most probably be higher still water shearing forces with the higher SWBM's that may occur in aluminum vessels. For homogeneously loaded steel vessels of 500 feet in length and less, SWSF has not to our knowledge been a governing design parameter and it is very probable that the side shell increased by the conversion factor Q, would ensure the same for uniformly loaded aluminum vessels. However, it is felt prudent, although not a requirement in the Rules, that for larger aluminum vessels the SWSF be determined and side shell scantlings verified accordingly. Where cargo or ballast is distributed non-uniformly, paragraph 6.9 of the aluminum Rules requires investigation of SWSF and resulting shear stresses.

<u>Local Internal Cargo Loading due to Increased Deadweight</u>

For vessels of identical form, length, breadth, draft and arrangement, the aluminum vessel will have a greater cargo deadweight and consequently a greater cargo load on inner bottom and tween decks.

As inner bottom longitudinals and reverse frames are based on depth of vessel to freeboard deck and tween deck scantlings on height of tween deck, these members would be automatically corrected for capacity cargoes.

However, for deadweight cargoes there are no requirements in the Rules for steel general cargo vessels to account for the considerable variation in cargo loads and as this variation may be greatly in excess of that resulting from the increased deadweight of an aluminum vessel it is concluded that additional correction for the latter need not be made.

Local Internal Loading due to Different Hull Proportions

It is quite possible that the optimum design aluminum vessel may, for compliance with the hull girder inertia and section modulus requirements, have a lesser L/D ratio than do steel vessels.

In the Rules for steel vessels the required thickness of tank end floors is based on vessel length although in double bottom tanks the actual load is related to the tank overflow height. Presuming the overflow to extend to the upper deck the present requirements for tank end floors become deficient by tank standards when the depth of vessel exceeds about L/9.5. While this depth is rarely if ever exceeded in steel cargo vessels, it may be for aluminum vessels. Consequently, in the aluminum Rules reference is made to the tank end floor requirements that they comply also with the requirements for tanks.

Stiffness of Structural Members

There appears to be a relationship between the value of hull girder inertia and the value of high frequency wave induced bending (springing) stresses although for ocean-going vessels requirements recognizing this have not so far been developed. As there is a minimum required hull girder inertia for steel vessels it was concluded the same should be developed for aluminum vessels. The requirement developed is comparable to the minimum value for steel vessels, allowing deflection slightly greater than permitted for higher strength steel vessels.

The required standard for the stiffness of aluminum primary structural members given by the increase of the steel section modulus by the factor Q or Qo and the 15% increase in minimum depth of the member above that required for steel, results in a deflection about 50% greater than for steel members.

The stiffness of secondary stiffening members, frames, beams and stiffeners, for aluminum vessels is obtained indirectly by increasing the section modulus by the conversion factor Q or Qo.

It was concluded that for aluminum vessels the stiffness of the various interconnected structural members were, in relation to each other, similar to those for a steel hull. Consequently, the structural response of the hulls would be comparable and no appreciable change in actual applied load was anticipated in this respect due to the use of aluminum.

SPECIAL REQUIREMENTS FOR THE RULES FOR ALUMINUM VESSELS

Special Material

Because of the superior characteristics of aluminum in remaining ductile at low temperatures it was not considered necessary to retain the requirements in the Steel Rules for special notch materials for the bilge, sheerstrake and stringer plates.

End Attachments

Although aluminum has the advantage over steel of being ductile even at low temperatures, experience has shown fractures to have occurred where the ends of double bottom tank boundary stiffeners have terminated on unstiffened shell plating. Provision is made in the Rules for aluminum vessels to prevent this type of end connection.

Service

It was not anticipated that aluminum vessels would be designed for service involving cargo discharge by grabs, navigation in ice or alternate hold loading. Consequently, requirements for these features were not included in the Rules for aluminum vessels.

As the requirements for liquefied gas carriers are to soon undergo complete revision they were also excluded.

Corrosion

Where this would be unavoidable, as in the case of steel anchor chain in chain and hawse pipes, the latter are required in the equipment section to be constructed of steel. The boundaries of aluminum chain lockers, considering both avoidance of dissimilar metal contact and impact damage, are required to be suitably sheathed internally.

Welding

Fillet weld requirements were taken directly from the Rules for steel vessels, it being considered all necessary corrections for material properties already reflected in the plate thickness. Minor increase was made, however, to the required fillet weld size to correct for the lower ratio for aluminum of ultimate shear strength to ultimate tensile strength. Fillet weld requirements are given for continuous welding as it was thought that in general it would be preferred both to minimize crater cracking, notches formed at end of welds are particularly critical in view of reduced strength properties in way of welding, and to minimize crevice corrosion in moist environments.

The welding section was rewritten to cover aluminum welding procedures and techniques. In general it is expected that metal inert gas (MIG) process will be preferred to the tungsten inert gas (TIG) process, the former being faster, requiring less experienced welders, no preheat and involving less distortion.

Service Experience

With some 10 classed aluminum vessels representing about 65 ship years service, service experience is very small compared with steel vessels. However, it nevertheless provides a valuable means of assessing to date the service performance of aluminum vessels.

The resistance to corrosion has been verified where care is given to the choice of material for pipes and fittings and the measures outlined in the section in the Rules covering corrosion are complied with.

Scattered minor corrosion on the foils of hydrofoil vessels and local hull wastage on other vessels, where the insulation between dissimilar metals had deteriorated, has been recorded.

There have been some casualties in service with aluminum vessels, none have been major and by far most have been local fractures originating near welds in undesirable details.

The indications are, therefore, that in the design and construction of aluminum vessels attention to detail is at least as equally important as it is for steel vessels. Some of the details which have resulted in local casualties are illustrated in Figures 3 to 7 together with the recommended details. It should be noted that the same details on a steel vessel would probably have resulted in fracture in the same circumstances. Of equal importance is the fact that in no case did the recorded fractures propagate to any extent after their initiation and that after repair and improvement of detail most have been subject to an additional six years service in which the corrected details have proven satisfactory.

ALUMINUM VESSELS LESS THAN 150 FEET IN LENGTH

The scantlings for aluminum vessels under 150 feet may be obtained from the Rules for Building and Classing Steel Vessels under 61 meters (200 feet) in Length by use of the conversion factors given in the Rules for Building and Classing Aluminum Vessels.

FIRE PROTECTION

The approval of insulation of aluminum structures to prevent fire propagation is the responsibility of the Administration of the country of registry. For those seeking some guidance on this aspect of aluminum construction, reference may be made to the new SNAME Bulletin 2-21 "Aluminum Fire Protection Guidelines".

CONCLUSION

There has been little doubt from past experience that aluminum is an excellent material for building vessels of up to about 100 feet in length. Recent experience has shown that this is not the limit to vessel size, with vessels of 300 foot now in service and an experience in service of ABS classed aluminum vessels of all sizes and types which is satisfactory. It is hoped the development and publication by the American Bureau of Shipping of

Rules for the Building and Classing of Aluminum Vessels will, in keeping with all the other Bureau Rules, provide industry with the services it may need to be able to take full advantage of the progress in the manufacture of shipbuilding materials. Appendix A, while not a part of the paper to be delivered, is attached herewith and includes some design features of aluminum vessels which may be of interest or assistance to owners, builders or designers.

In closing, thanks is given to my colleagues in the New York Hull Technical Staff for their most valuable time and advice in editing this paper. Reference to the following sources of information is also acknowledged:

ABS Rules for Building and Classing Steel Vessels.

ABS Rules for Building and Classing Aluminum Vessels.

"Design Considerations for Aluminum Hull Structures" by C.J. Altenburg and R.J. Scott. Gibbs & Cox

"Aluminum and its Use in Fishing Vessels" by C.W. Leveau.

Paper No. 4 Part 1 "Aluminum for Small Craft" by W.J. Allday - RINA Symposium on Small Craft.

ALUMINUM VESSELS

TABLE 1

L Ft	B Ft	D Ft	Built	Vessel Type	Classification
291.75	44.0	13.0	1967	Vehicle Carrier	✠ A1
218.52	50.0	11.5	1971	Survey Vessel	✠ A1
141.25	26.83	8.81	1970	Ferry	✠ A1
120.0	25.0	11.3	1969	Supply Vessel	ABS Reviewed Design
120.0	24.0	10.0	1967	Supply Vessel	ABS Reviewed Design
111.0	24.2	10.3	1966	Supply Vessel	ABS Reviewed Design
102.0	25.0	12.0	1966	Supply Vessel	ABS Reviewed Design
98.5	26.0	7.2	1967	Supply Vessel	ABS Reviewed Design
96.4	22.96	13.25	1962	Hydrofoil Ferry	ABS Reviewed Design
92.3	22.0	9.9	1964	General Cargo	ABS Reviewed Design
91.33	21.58	9.5	1972	Launch	✠ A1
90.25	22.0	10.58	1965	Launch	✠ A1
85.7	21.6	10.6	1963	Supply Vessel	ABS Reviewed Design
80.83	21.5	9.75	1972	Launch	✠ A1
68.4	15.67	7.0	1962	Hydrofoil Ferry	✠ A1
68.4	15.67	7.0	1962	Hydrofoil Ferry	✠ A1
64.5	17.7	10.25	1969	Yacht	✠ A1 Yachting Service
60.0	16.16	7.58	1969	Launch	ABS Reviewed Design
57.0	18.5	7.6	1964	Fishing Vessel	ABS Reviewed Design

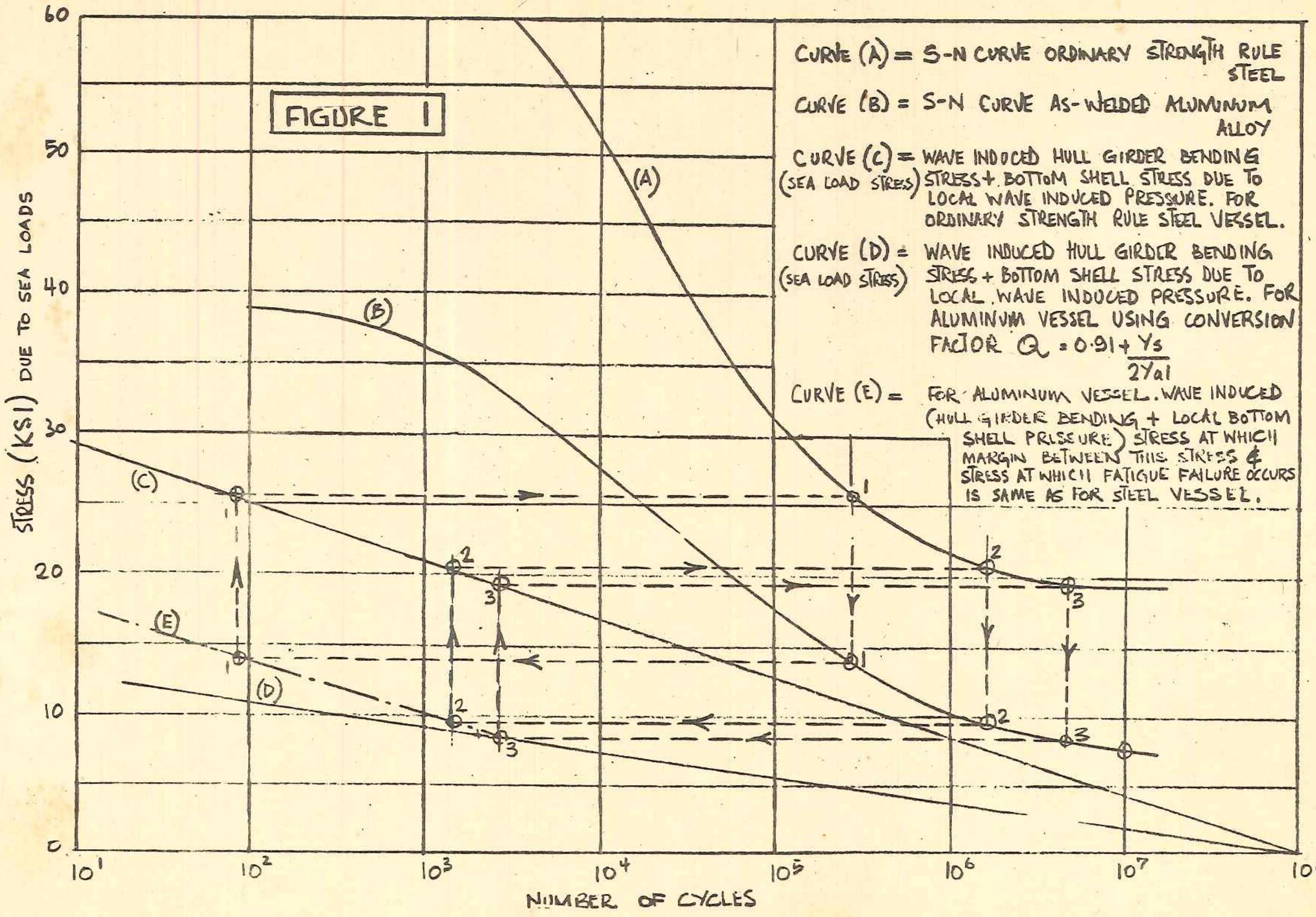


FIGURE 1
CURVE (A) = S-N CURVE ORDINARY STRENGTH RULE STEEL
CURVE (B) = S-N CURVE AS-WELDED ALUMINUM ALLOY
CURVE (C) = WAVE INDUCED HULL GIRDER BENDING STRESS + BOTTOM SHELL STRESS DUE TO LOCAL WAVE INDUCED PRESSURE. FOR ORDINARY STRENGTH RULE STEEL VESSEL.
(SEA LOAD STRESS)
CURVE (D) = WAVE INDUCED HULL GIRDER BENDING STRESS + BOTTOM SHELL STRESS DUE TO LOCAL WAVE INDUCED PRESSURE. FOR ALUMINUM VESSEL USING CONVERSION FACTOR Q = 0.91 + Ys/2Yal
(SEA LOAD STRESS)
CURVE (E) = FOR ALUMINUM VESSEL. WAVE INDUCED (HULL GIRDER BENDING + LOCAL BOTTOM SHELL PRESSURE) STRESS AT WHICH MARGIN BETWEEN THIS STRESS & STRESS AT WHICH FATIGUE FAILURE OCCURS IS SAME AS FOR STEEL VESSEL.
(A)
(B)
(C)
(D)
(E)
STRESS (KSI) DUE TO SEA LOADS
0
10
20
30
40
50
60
NUMBER OF CYCLES
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
10⁸

TABLE 2

Predicted Stress Curve Sub-Range Cycles	Ordinary-Strength Rule Steel For scantlings $Q = 1.0$	Aluminum 5083 As-Welded For scantlings $Q = 0.91 + \frac{Y_s}{2Y_{al}}$	Aluminum 5086 As-Welded For scantlings $Q = 0.91 + \frac{Y_s}{2Y_{al}}$	Higher Strength Steel H-36 For scantlings, Q $= \frac{49.92}{Y_{HTS} + 2/3\,U_{HTS}}$ metric $= \frac{70900}{Y_{HTS} + 2/3\,U_{HTS}}$ inch/lb	Aluminum 5456 As-Welded For scantlings $Q = 0.91 + \frac{Y_s}{2Y_{al}}$
0-4	0.0000547	0.000019	0.0000148	0.0002	0.0000258
4-6	0.00002	0.0000071	0.000057	0.00008	0.0000111
6-8	0.0000181	0.0000068	0.000054	0.00007272	0.0000105
8-10	0.0000153	0.0000066	0.0000051	0.00006779	0.0000097
10-40	0.0001818	0.0000731	0.0000545	0.0007142	0.000109
40-60	0.0000952	0.0000333	0.0000243	0.0003076	0.0000487
60-80	0.0000833	0.0000307	0.0000222	0.0002597	0.0000416
80-100	0.00008	0.000025	0.000021	0.0002352	0.00004
100-400	0.00075	0.0002727	0.0002142	0.002	0.0004
400-600	0.0002857	0.0001176	0.0001052	0.000888	0.00016
600-800	0.0002222	0.0001111	0.0001	0.0007272	0.0001538
800-1000	0.000202	0.0001	0.00009521	0.0006451	0.0001333
1000-4000	0.0008571	0.0008823	0.0008571	0.005454	0.00125
4000-6000	0.0000666	0.0002857	0.0002222	0.0018018	0.0004761
6000-8000	0.	0.0002222	0.0002105	0.001333	0.0004
8000-10000	0.	0.0002105	0.000203	0.0011428	0.000333
10^4 - 4×10^4	0.	0.0005	0.0006	0.008571	0.001875
4×10^4 - 6×10^4	0.	0.	0.0002	0.002	0.
6×10^4 - 8×10^4	0.	0.	0.	0.0008	0.
	$\sum \frac{n_s}{N_s} = 0.002932$	$\sum \frac{n_{al}}{N_{al}} = 0.0029037$	$\sum \frac{n_{al}}{N_{al}} = 0.00295$	$\sum \frac{n_s}{N_s} = 0.0273$	$\sum \frac{n_{al}}{N_{al}} = 0.005477$

Estimated fatigue life, $\sum N/n$ is comparative only.

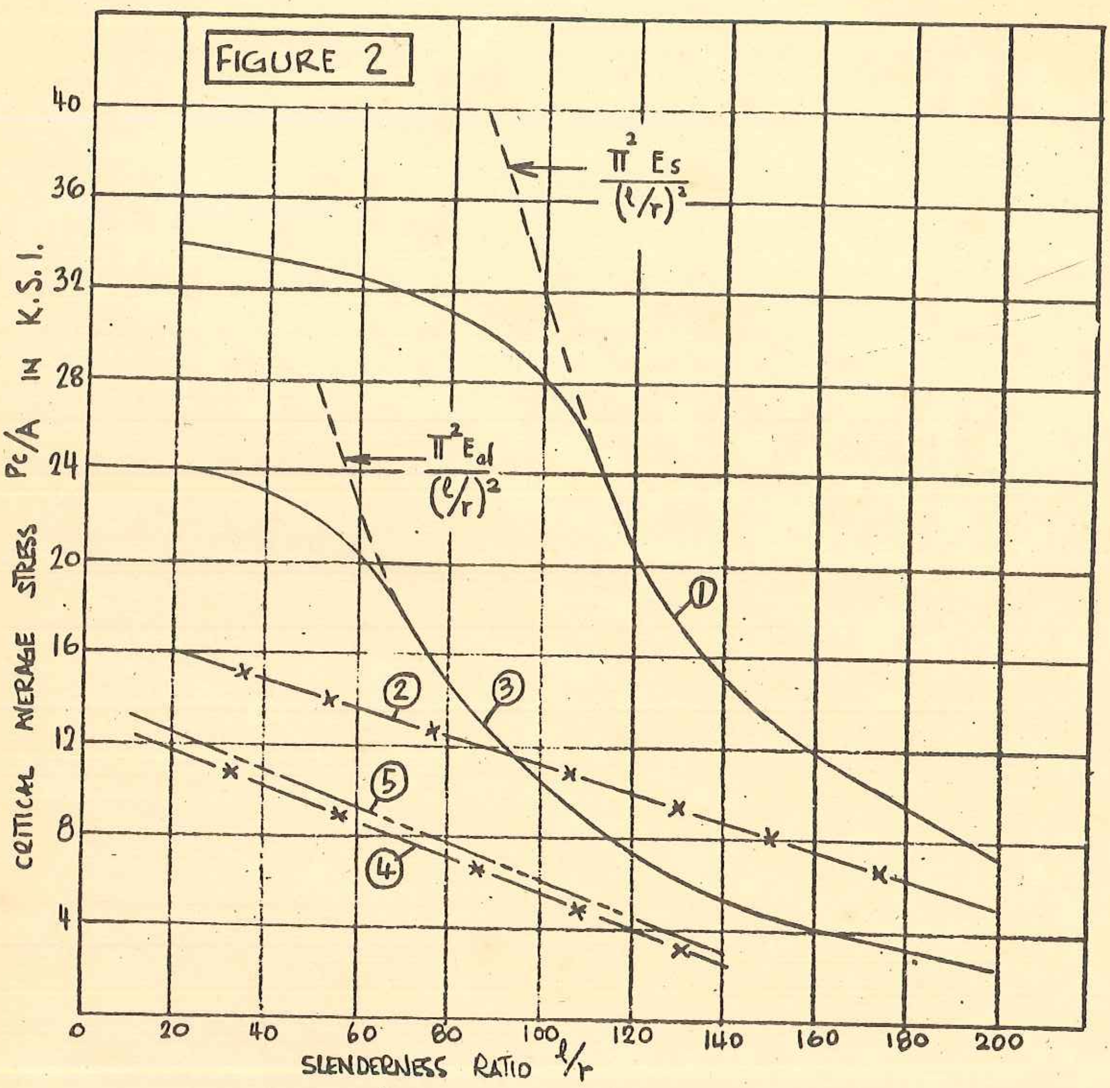


FIGURE 2

CURVE ①	CRITICAL LOAD FOR STEEL PILLAR
CURVE ②	PERMISSABLE LOAD FOR STEEL PILLAR IN ACCORDANCE WITH RULES FOR STEEL VESSELS
CURVE ③	CRITICAL LOAD FOR ALUMINUM PILLAR (5083-H321)
CURVE ④	PERMISSABLE LOAD FOR ALUMINUM PILLAR TO PROVIDE SAME FACTOR OF SAFETY AS GIVEN BY CURVES ① AND ②
CURVE ⑤	CURVE ④ CORRECTED FOR SUPERIOR RESISTANCE OF ALUMINUM TO CORROSION. IS EXPRESSED IN ALUMINUM RULES AS $W_a = (1.02 - 5.93\times10^{-3}\, l/r)\frac{A.Y_{al}}{17}$ METRIC TONS AND $W_a = (6.49 - 0.452\, l/r)\frac{A.Y_{al}}{24000}$ LONG TONS

TABLE 3

Aluminum Alloy	Conversion Factors for Estimated As-Welded Aluminum Properties ※		Value Obtained Indirectly by Use of 0.9Q+ / Value Required to Give Standards Comparable with Steel Standard				
			Web of Primary Structural Member		Shell & Deck Plate	Deflection	
	Tensile Strength 0.9.Q.	Fatigue Strength 0.9.Q	Shear Strength $\frac{1.15 \times 0.9 \times Q}{1.12Q}$ ✓	Plate Stability $\frac{1.15 \times 0.9 \times Q^3}{2.78}$ ✓	stabili $\frac{0.9 \times (Q^3)}{2.78}$ ✓✗	Primary Structural Member	Hull
5083	1.38	1.55	0.93 (min)	0.92 (min) 1.385	1.69Q(min) 1.21	2.083	1.078
5086	1.69	1.91	"	2.58	2.26	"	"
5454	1.97	2.09	"	3.4	2.97	"	"
5456	1.38	1.62	"	1.58	1.38	"	"
6061	2.12	1.84	"	3.53	3.09	"	"
Ordinary Strength Steel	1.0	1.0	1.0	1.0	1.0	1.0	(HTS) 1.0

※ Values of Aluminum Ultimate Tensile and Yield Strengths Higher than Estimated May be Used if Verified by Test. This Would Permit Use of Conversion Factors Less than those Indicated.

✓ Rules do not permit Q to be taken as less than 1.30, Q = 1.3 gives (Min)

✓✗ Rules do not permit to be taken as less than 1.69Q, Q^3 = 1.69Q gives (Min)

\+ Using minimum allowable value of Q = 1.3, where applicable in Aluminum Rules

FIG 3

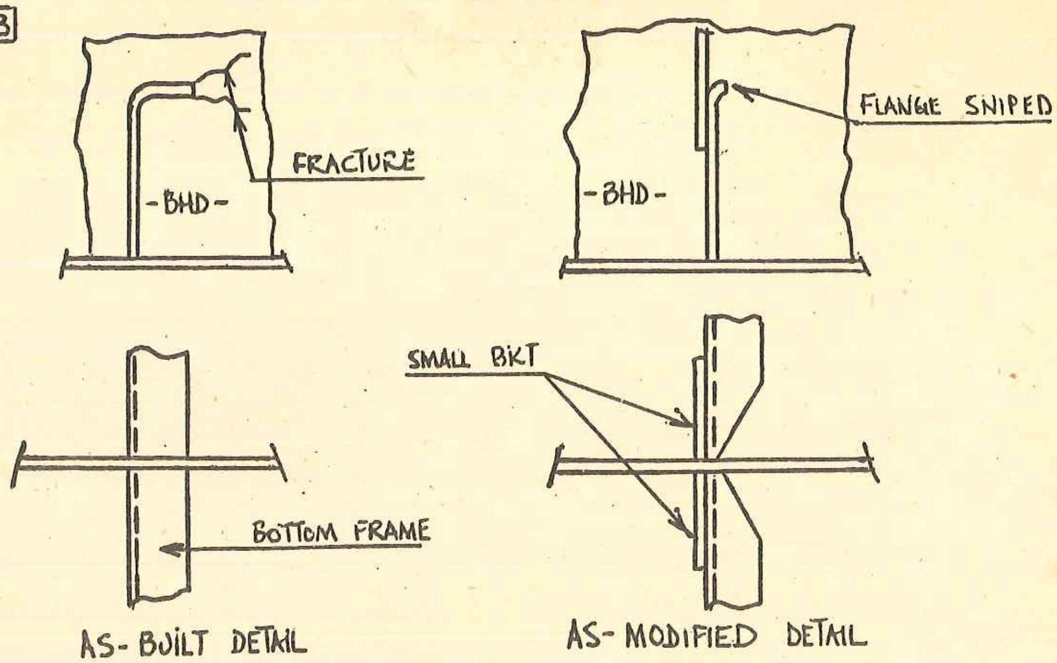


FIG 4

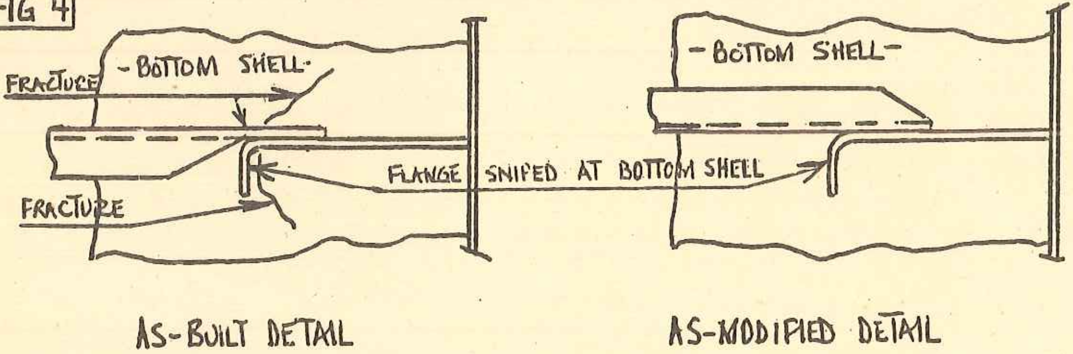


FIG 5

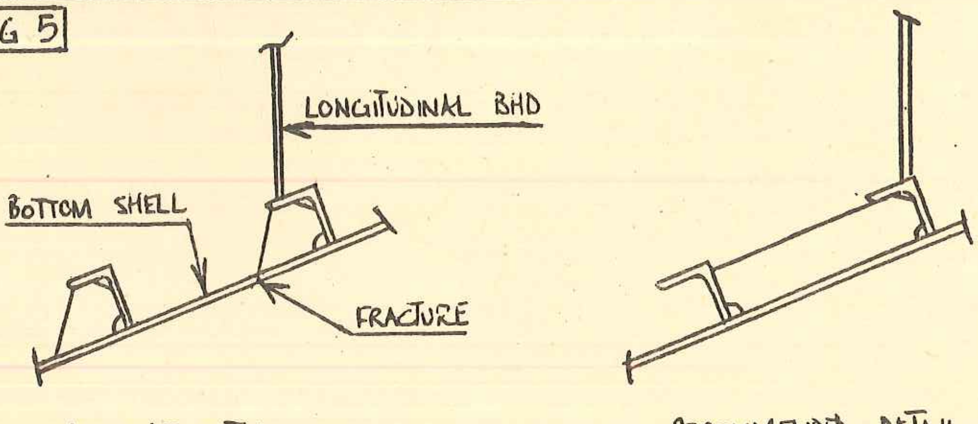
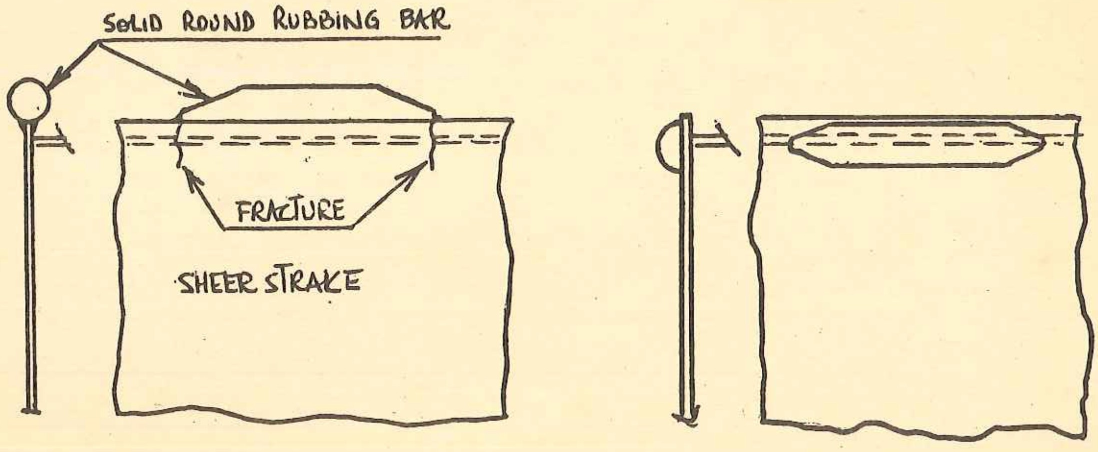


FIG 6

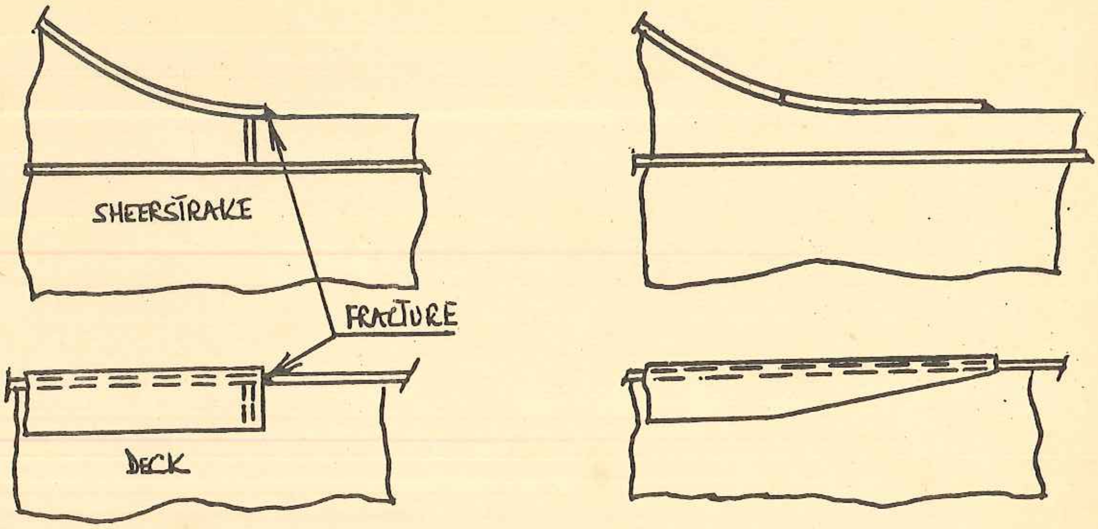


AS- BUILT DETAIL.

DETAIL WAS MODIFIED BY REMOVING RUBBING BAR AND RENEWING SHEER STRAKE LOCALLY. RUBBING BAR WAS NOT REPLACED.

WHERE UNAVOIDABLE, RUBBING BAR AS SHOWN ABOVE WOULD BE ACCEPTABLE PROVIDED ATTENTION TO MATERIAL AND WELDING QUALITY IS APPROPRIATE TO THE STRUCTURAL IMPORTANCE OF LOCATION.

FIG 7



AS-BUILT DETAIL

AS- MODIFIED DETAIL

APPENDIX A

Particular Design Considerations

There are with Rule development generally by-products of investigations which, while not always having a direct bearing on classification requirements, are often most useful to designers builders or owners. For this reason some items coming into this category are mentioned below.

Rudders

With the exception of hydrofoil vessels, it appears that spade rudders are preferred for aluminum vessels. For the former, lower end support of the rudder is provided by the stern foil. Steel rudders with stainless steel stocks or forged steel stocks having stainless steel sleeves from top of rudder to just below the tiller have been used, as have stainless steel rudders with stainless steel stocks. Steel rudders have been coated externally by zinc chromate paints or provided with zinc anodes.

Quite recently on smaller vessels approval has been given to the use of aluminum rudders and aluminum rudder stocks. For the latter, suitable conversion factors based both on shear strength and tensile strength need to be used and attention needs to be given to any dissimilar material properties at the stock to tiller keyed connection.

Prevention of Corrosion

The following is in addition to the contents of the general requirements in the Rules for aluminum vessels.

External underwater surfaces, including sea chests, are usually coated for anti-fouling purposes. As paints containing mercury in any form and copper under certain circumstances should not be used, the paint manufacturers recommendations need to be sought for the suitability of the paint.

Uncoated aluminum fresh water tanks, even without dissimilar metal fittings, have been known to be subject to rapid corrosion and it seems advisable they be coated internally with epoxy paint or similar.

In wet spaces such as bilges or chain lockets, etc., heat treated aluminum needs to be used to prevent exfoliation corrosion, i.e., intergranular corrosion caused by excess magnesium precipitation into grain boundaries.

It appears that the 5000 series of aluminum alloys can be exposed uncoated to marine grade fuel oils, salt water and sewage without corrosion problems.

It should be emphasized that the foregoing, particularly for uncoated aluminum, is valid provided careful attention is given to selection of piping and fitting materials.

Use of the same aluminum alloy as the hull or tank is of course, most preferable, however, plastic and stainless steel have been used.

External cathodic protection is very often used. Zinc anodes are generally fitted on steel rudders and on both aluminum and steel struts as well as locally to the aluminum hull at the forward and aft ends.

It should be mentioned that in the foregoing, where reference is not made to a particular material or arrangement, it is not intended to indicate its unsuitability.

Shafts and Shaft Struts

Propeller shafts have generally been of stainless steel, with, in a few cases, steel shafts with stainless steel sleeves. Shaft struts have been of stainless steel or alumimum.

Secondary Stiffening Members

For secondary stiffening members such as beams, stiffeners and frames, provided web openings were kept within reasonable limits, it would seem that shear strength equivalent to steel members would be obtained if the depth for beams and stiffeners were not less than about length/34 and for frames not less than about length/25.

PAN-AMERICAN CONGRESS OF NAVAL ENGINEERING, PORTS ENGINEERING AND MARITIME TRANSPORTATION, 16-22 NOVEMBER 1975 - LIMA, PERU

Paper "The Development of Rules for Building and Classing Aluminum Vessels" Robert Curry, Principal Surveyor, Hull Technical Staff, American Bureau of Shipping, 45 Broad Street, New York, NY

Errata Page 4, last two lines

Change: "Rules for Building and Classing Vessels"

To: "Rules for Building and Classing Steel Vessels"

Page 13, after definition of A_{aL}

Add: "s = stiffener spacing"

Page 16, sixth line

Change: "Effect of Aluminum Construction of Internal Hull Loads"

To: "Effect of Aluminum Construction on Internal Hull Loads"

Page 20, 12th line

Change: "special notch materials"

To: "special notch tough materials"