Structural Design of Large Aluminium Alloy High-Speed Craft☆

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Based on three decades of experience in Mitsubishi Shimonoseki Shipyard of the construction of a number of all-aluminium alloy craft such as torpedo boats and patrol boats, guidelines for the structural design of large light alloy craft are presented. Special emphasis is laid on the development of a suitable framing system and panel structure to withstand the low fatigue strength of light alloy material. Technical efforts in the development of panels extruded with stiffeners and extruded sections of various shapes together with efforts in the development of an automatic welding system have made it possible to construct large all-aluminium alloy craft with satisfactory strength and service performance.

The economical comparison of various aluminium alloy passenger boats was also referred to.

1. Introduction

Escalation of the cost of fuel oil demands that we develop ships of lower operating costs. Lighter hull weight is one of the essential design considerations for high-speed craft of improved performance. For this purpose, the use of aluminium alloy structure in high-speed craft is appropriate because the hull weight is much less than that of an equivalent structure of mild steel(1).

A brief historical review of the problems we met in the course of development of aluminium alloy craft in the last three decades in the Mitsubishi Shimonoseki Shipyard is first given and is followed by explanation of the efforts devoted to developing large size aluminium alloy craft with satisfactory structural strength. Special emphasis is placed on the framing system and panel structure to withstand the low fatigue strength of light alloy.

Various full-scale data on the strength of torpedo boats and fast patroll boats constructed by Mitsubishi have contributed to the establishment of the design standards of light structure craft in Japan. Recently, three large aluminium alloy high-speed passenger boats of 45 m and 48 m in length were constructed in view of their high economical service performance. Results of full-scale measurements of longitudinal bending moment and water pressure in these craft are presented.

2. Historical review of light alloy high-speed craft constructed by Mitsubishi

A 15 metre patrol boat ARAKAZE owned by the Japanese Maritime Safety Agencies was the first light alloy high-speed craft which entered into service in Japan. She was constructed in 1954 in the Mitsubishi Shimonoseki Shipyard. Before this construction, light alloy materials had been used only for superstructures and fittings.

In 1949 The Committee of Light Metals for the Shipbuildings Industry was organised consisting of representatives from the Japanese Government, material manufacturers and shipyards. The committee initiated basic studies on light alloy material for marine use. Under the leadership and guidance of the committee, Mitsubishi Heavy Industries, which was one of the most enthusiastic builders making use of light alloy, was encouraged to build the first light alloy craft in Japan, ARAKAZE. She was successfully constructed based on a variety of studies made by various technical groups which cooperated in the development of light alloy materials for marine use(2).

As a result of satisfactory service performance, the Japan Defense Agency ordered Mitsubishi to construct two 27 m torpedo boats. At that time, two wooden boats and two steel boats were also constructed for comparison under conditions of the same payload and approximately the same dimensions. It transpired that the light alloy boats were superior to the other craft with respect to speed and maintenance.

Since then the Japanese Defense Agency decided to use light alloy materials for their high-speed craft. In 1957 and 1958 two 33.5 m light alloy torpedo boats, in 1959 two 23 m aeroplane rescue boats, in 1967 a 25 m aeroplane rescue boat and from 1972 to 1975 five 35 m torpedo boats were constructed for the Japan Defense Agency. From 1962 to 1965, 21 hydrofoil boats were constructed in the Shimonoseki Shipyard. Some of these were of the fully submerged foil type with automatic control systems.

On the other hand, the Japanese Maritime Safety Agencies, who owned the first light alloy patrol boat ARAKAZE, constructed two 26 m all-alluminium alloy patrol boats in 1966, 12 years after the construction of ARAKAZE. Though the Japanese Maritime Safety Agencies have recognised the superiority of light alloy materials for high-speed craft, the cost of such material was much higher than others, and it was not convenient at the time to dispense entirely with the use of wood as a building material. Therefore, aluminium-wood composite construction was used for patrol boats of this length.

Meanwhile, it became evident that the cost of construction using light alloy material could be reduced appreciably by improving the framing system and hull forms. It then became possible to construct all-light alloy 26 m boats within the planned budget.

In 1969 one 26 m boat, from 1971 to 1974 ten 21 m patrol boats and since 1974 eleven 26 m patrol boats have been constructed. The expansion of the patrol area due to the declaration of a 200 mile exclusive economic zone has given rise to a requirement for seaworthy high-

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Table 1 Aluminium alloy high-speed craft constructed by Mitsubishi

Craft	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Kind of craft	PC	PT	PC	PT	AH	HF	PT	HF	PC	PC	AH	PT	PC	L	PC	PB	PC	PB	PB
No. of construction	1	2	2	2	2	16	1	5	2	1	1	5	10	1	11	1	10	1	1
Year of construction	1954	1956	1957	1957–58	1959	1962–65	1962	1962–65	1966	1969	1967	1972–75	1971–73	1971	1973–80	1977	1978–81	1980	1980
Length o.a. (m)	15.0	27.00	21.00	33.50	23.00	8.00	32.0	21.00	26.00	26.00	25.00	35.00	21.00	18.80	26.00	45.00	31.0	48.30	45.00
Beam (m)	4.20	6.75	6.00	7.50	5.50	2.50	8.50	4.80	5.60	5.60	6.20	9.20	5.30	4.20	6.30	7.80	6.30	8.20	7.80
Depth (m)	2.20	3.15	2.60	3.50	2.45	1.10	3.40	2.50	2.70	26.76	3.30	3.80	2.70	2.20	3.00	3.90	3.30	3.90	3.90
Power of main engine (PS)	220x2	2000x2	1000x3	2000x3	800x3	280	3140x3	1500	570x2	1100x2	2300x1 285x2	3300x2 2300x2	1100	1000	1000x3	2205x2	2400x2	2420x2	2420x2
Max. speed (Knots)	20.62	29.95	37.74	33.10	40.36	40	47.72	40	23.0	26.76	30	40	27.49	26.00	22.10	28.75	33.25	29.79	29.46

Where PC: Patrol boat, PT: Torpedo boat, AH: Airplane rescue boat, L: Motor Launch, HF: Hydrofoil, PB: Passenger boat.

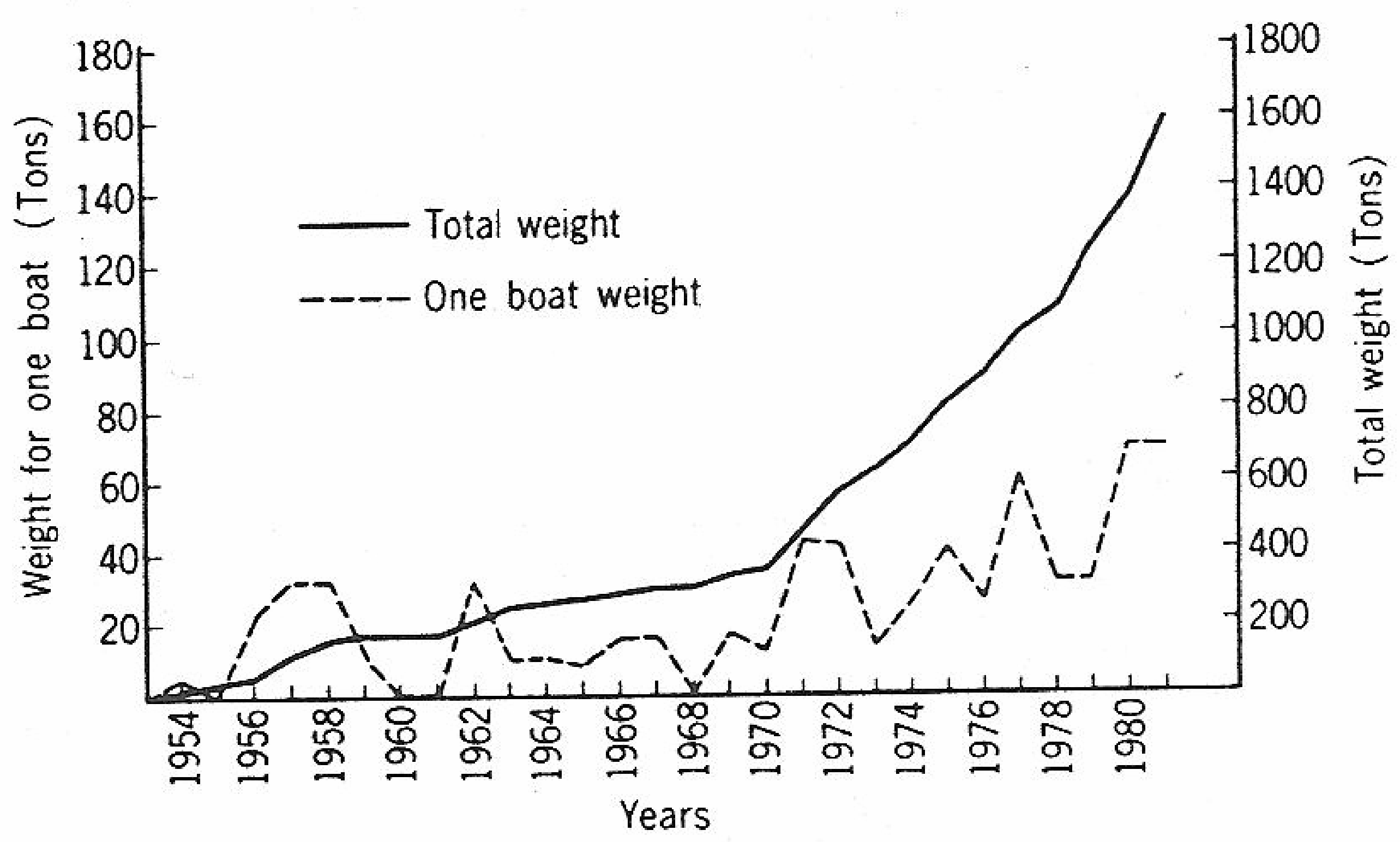

Fig. 1 Trend of aluminium used for hull construction

speed patrol boats. To meet this demand, a 31 m patrol boat with a speed in excess of 30 knots at continuous rating was developed at the Mitsubishi Shimonoseki Shipyard. Since 1978 ten patrol boats of this type have been constructed.

The above-mentioned light alloy high-speed boats constructed by Mitsubishi are for military or surveillance use with the exception of some hydrofoil boats for use as passenger carriers. Therefore the propulsive performance of these craft rather than the economics, was given prominence in order to maintain the mission.

In 1977 an all-light alloy passenger craft of 45 m length was constructed in view of the economic features. As a result of satisfactory achievement in both performance as a passenger carrier and economical running costs, another slightly larger passenger craft of 48 m was ordered by the same customer and a 45 m craft by another customer. At the time of construction, both boats were the largest all-aluminium alloy craft ever built in Japan.

Table 1 lists the above mentioned light alloy craft constructed by Mitsubishi. The hull is of vee bottom form with chines. Sine the 26 m patrol boats constructed in 1966, use has been made of the so-called deep vee type with a large deadrise angle at the entrance but rather small deadrise angle at the transom.

Fig. 1 shows a trend of weight of aluminium alloy used for high speed boats built by Shimonoseki Shipyard. Total weight of aluminium alloy will reach about 2000 tons. This figure seems not so big for about 30 years. However, there are some periods of reduced number of building of light aluminium boats. Size of the boat grows bigger year by year steadily.

Fig. 2 shows a 31 m patrol boat developed at the Mitsubishi Shimonoseki Shipyard for the Japanese Maritime Safety Agencies. **Fig. 3** shows a 48 m high speed passenger boat delivered to the Tokai Kisen Co., Ltd.

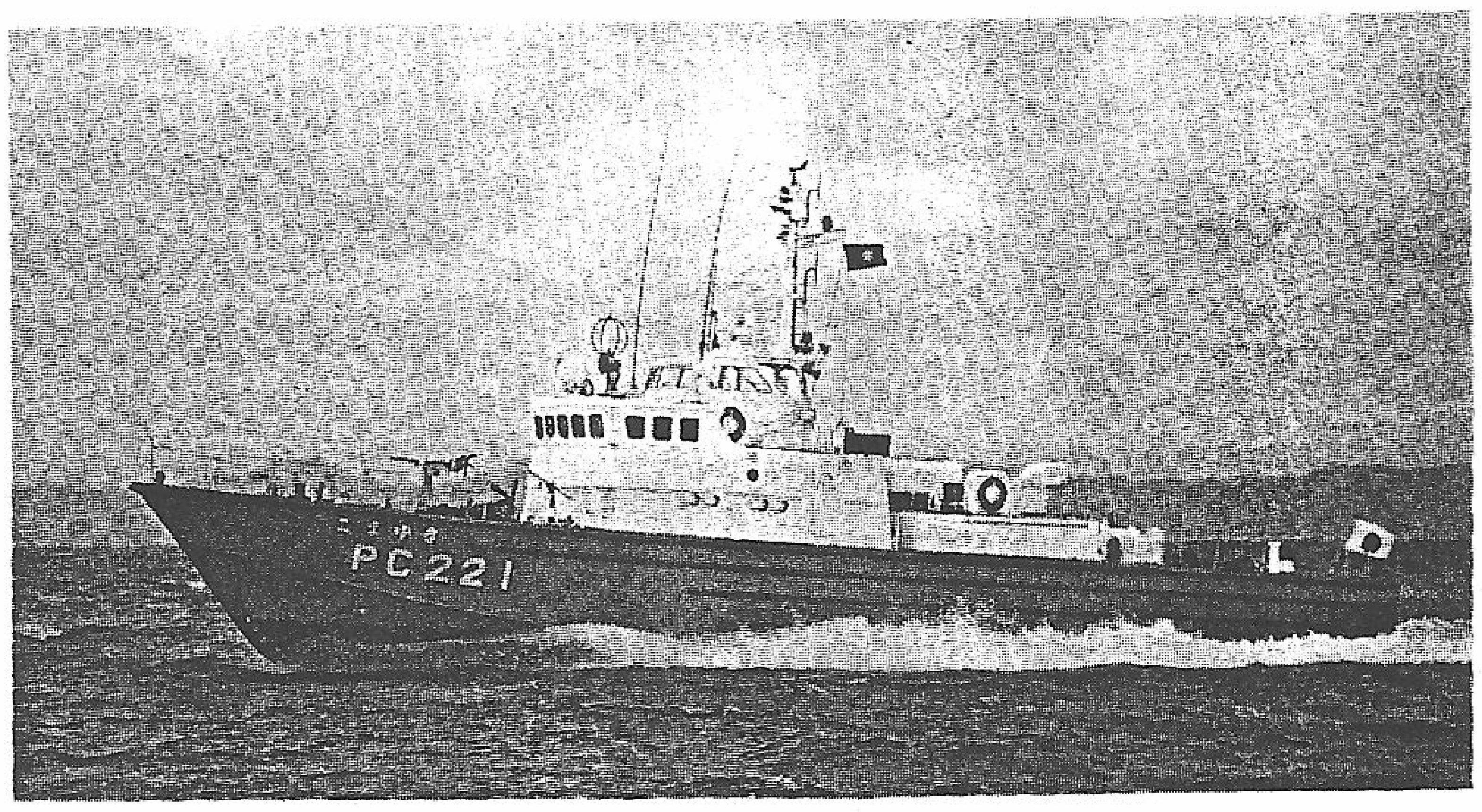

Fig. 2 A 31 meter patrol boat

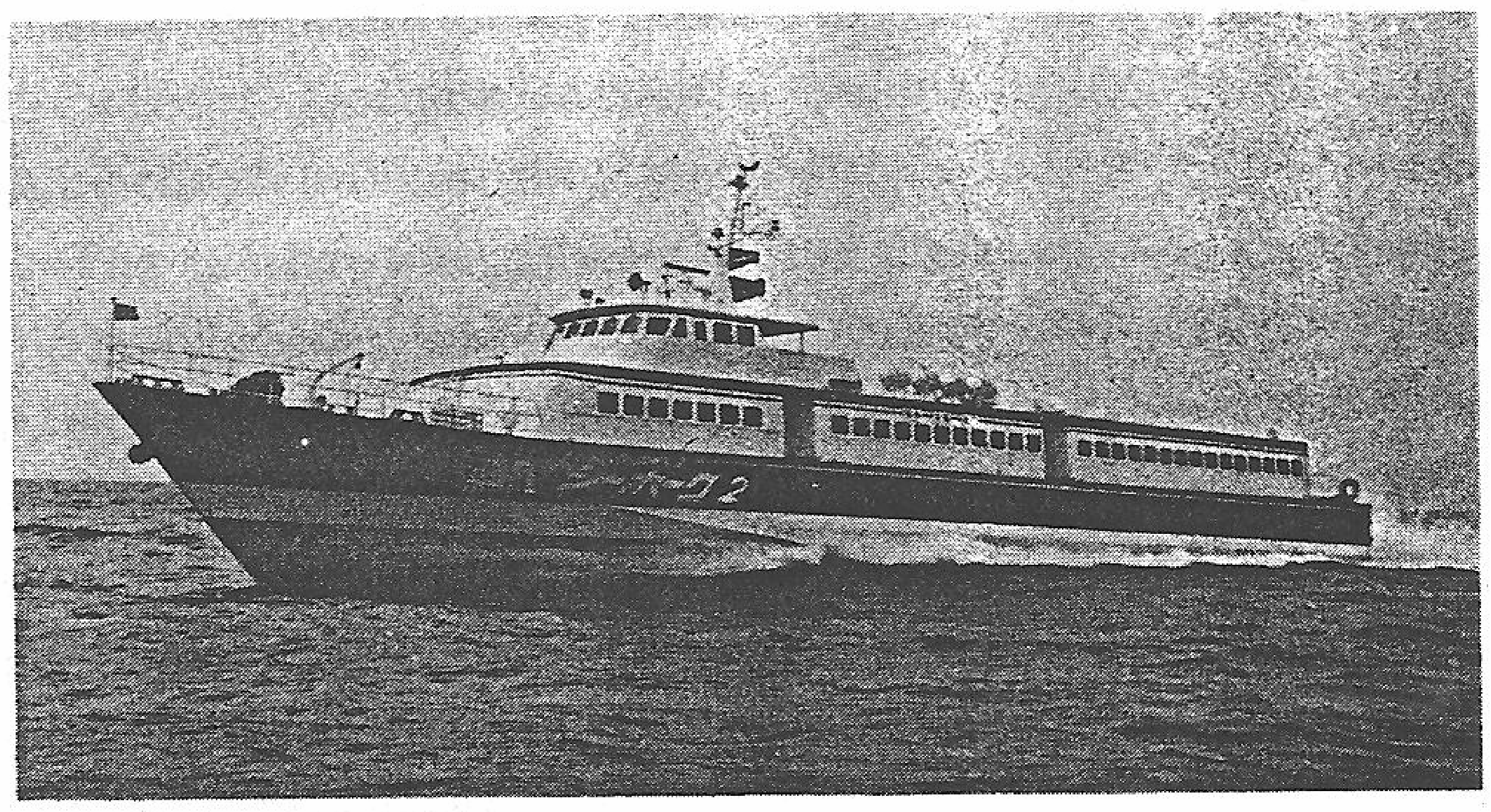

Fig. 3 Passenger boat SEAHAWK 2

3. Development of structural design of light alloy high-speed craft at Mitsubishi

3.1 Construction of ARAKAZE

In Japan, the study of the structure of all-aluminium alloy craft was initiated in 1949. By that time it had become possible to produce the anti-corrosive aluminium alloy 5083, and there was a demand for the construction of light alloy boats for the improvement of performance of high-speed craft belonging to the Japan Defense Agency. It was the first step in the construction of aluminium alloy craft when Mitsubishi built ARAKAZE, a 15 m patrol boat for the Japanese Maritime Safety Agency.

At that time data on wave loads for the structural design of high-speed craft made of light metal were not available. The structural design of ARAKAZE was based on the

Table 2 Chemical composition of test pieces and tensile test results for ARAKAZE after 20 years service

	Chemical composition (%)								
	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ti	Al
Test piece from ARAKAZE after 20 years service	0.012	0.14	0.28	0.47	4.33	0.009	0.18	0.072	Remainder
Original material NP 5/6-0	less than 0.1	0.4	0.4	1.0	3.4–4.7	–	less than 0.5	0.2	Remainder
JIS H 4000 5083	less than 0.1	0.4	0.4	0.3	4.0–4.9	less than 0.25	0.25	0.15	Remainder

	Tensile test			Bending test
	Tensile stress (N/mm²)	Proof stress (N/mm²)	Elongation (%)	Inner radius (180° bend)
Test piece from ARAKAZE after 20 years service	309 (313)	170 (183)	19.7 (20.7)	1.5 *t* (1.5 *t*)
Original material NP 5/6-0	above 265		above 15	2.0 *t*
JIS H 4000 A 5083 P-0	275–353	127–196	above 16	3.0 *t*

( ): Tensile test results after 27 years service *t* : thickness of plate

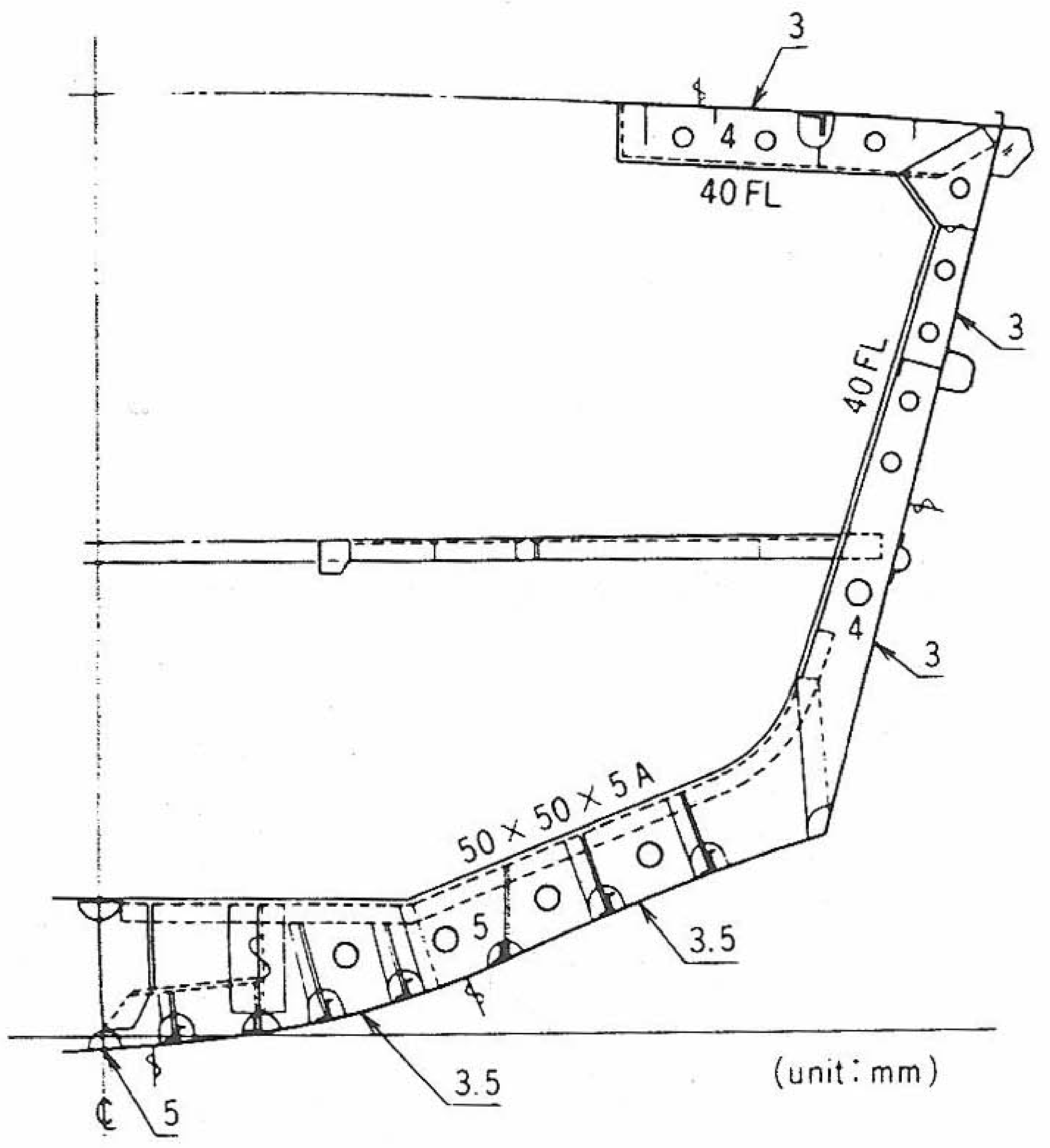

Fig. 4 Midship section of 15 m patrol boat ARAKAZE

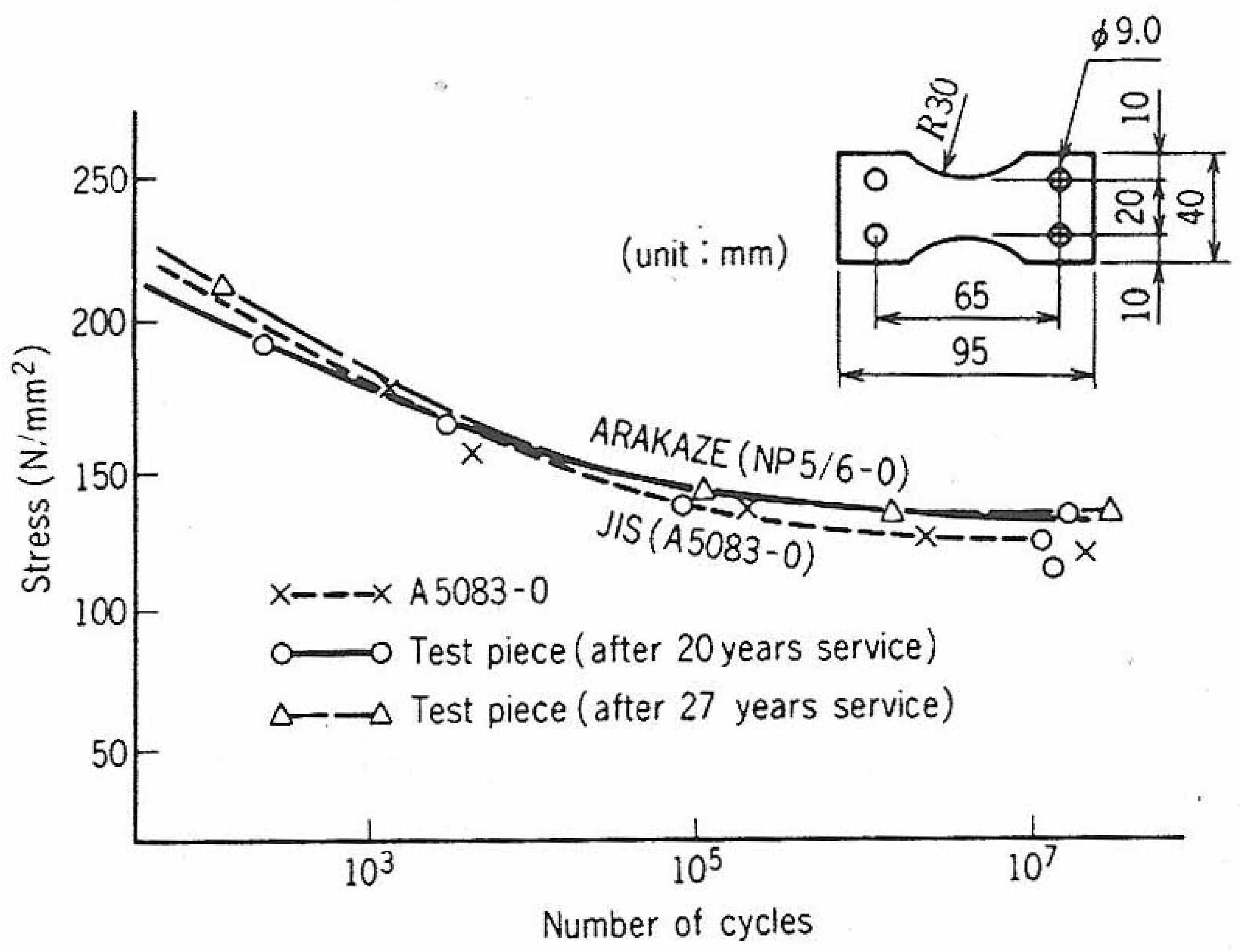

Fig. 5 Fatigue test results of ARAKAZE's test pieces

design data for Japanese wooden craft and steel hull torpedo boats of World War II.

Slamming loads were estimated based on the assumed ship motions in waves with the wave length taken to be the same as boat length and wave height as 1/10th of the wave length. It was further assumed that at the maximum speed, pitch and heave motions have the same phase. Under these assumptions the maximum pressure at the hull surface was estimated as 0.5 kgf/cm^2 (49 kN/m^2).

A longitudinal framing system was adopted for this boat which has the advantage of withstanding buckling of the shell plating with lighter hull weight than that of a transverse framing system, since the strengths of the local panels and the longitudinal frames can be combined.

Fig. 4 shows the midship section of ARAKAZE. Longitudinal frames are fixed to the shell plating by rivets and the transverse webs are fillet welded to the deck and shell plating. The shell and deck plating are butt welded. This framing system has been applied to the designs of torpedo boats hereafter. The extent of welding has been gradually expanded.

3.2 Examination of material strength after twenty years operation of ARAKAZE

After 20 years of hard rescue service, material tests of the hull plating of ARAKAZE were carried out to examine the reliability of aluminium alloy for marine use(3). Four test pieces of 100 x 600 mm were taken from the stern bottom plate. From the analysis of chemical components it was found that the material had not changed from its original composition as shown in **Table 2** which satisfies the recent Japanese Industrial Standards JIS H 4000, A 5083 for aluminium alloy materials.

The tensile strength tests of hull plates showed that both the tensile and proof strengths satisfied JIS H 4000,A 5083 P, and little change was observed from the original strength at the time of construction as shown in Table 2. In the table, additional test data are shown which were taken on the occasion of retirement of ARAKAZE in 1981 after 27 years service. These data also satisfy the recent Japanese Industrial Standards.

Fig. 5 shows the result of fatigue strength tests using a 4 kgf-m Schenck Fatigue Strength Test Machine. It was shown that the fatigue strength was almost the same as that of material A 5083 P which satisfies the present Japanese Industrial Standards.

These examinations demonstrated the reliability of aluminium alloy as hull structure material for high-speed craft.

3.3 Construction of 45 knots torpedo boat

At the time of delivery of ARAKAZE, full scale measurements of stress and ship motions in rough waves were conducted. The data thus obtained became the basis for the structural design of light alloy high-speed crafts thereafter. Such full scale measurements in waves have been continued for every new type of craft in order to explore the limit design of hull structure and performance.

In 1962 a 32 m torpedo boat with speed exceeding 45 knots was constructed for the Japan Defense Agency. In the design process of this boat every effort was made to reduce hull weight, and a design method based on elastic and plastic characteristics of the material was introduced for the first time. A partial structural model of a bottom

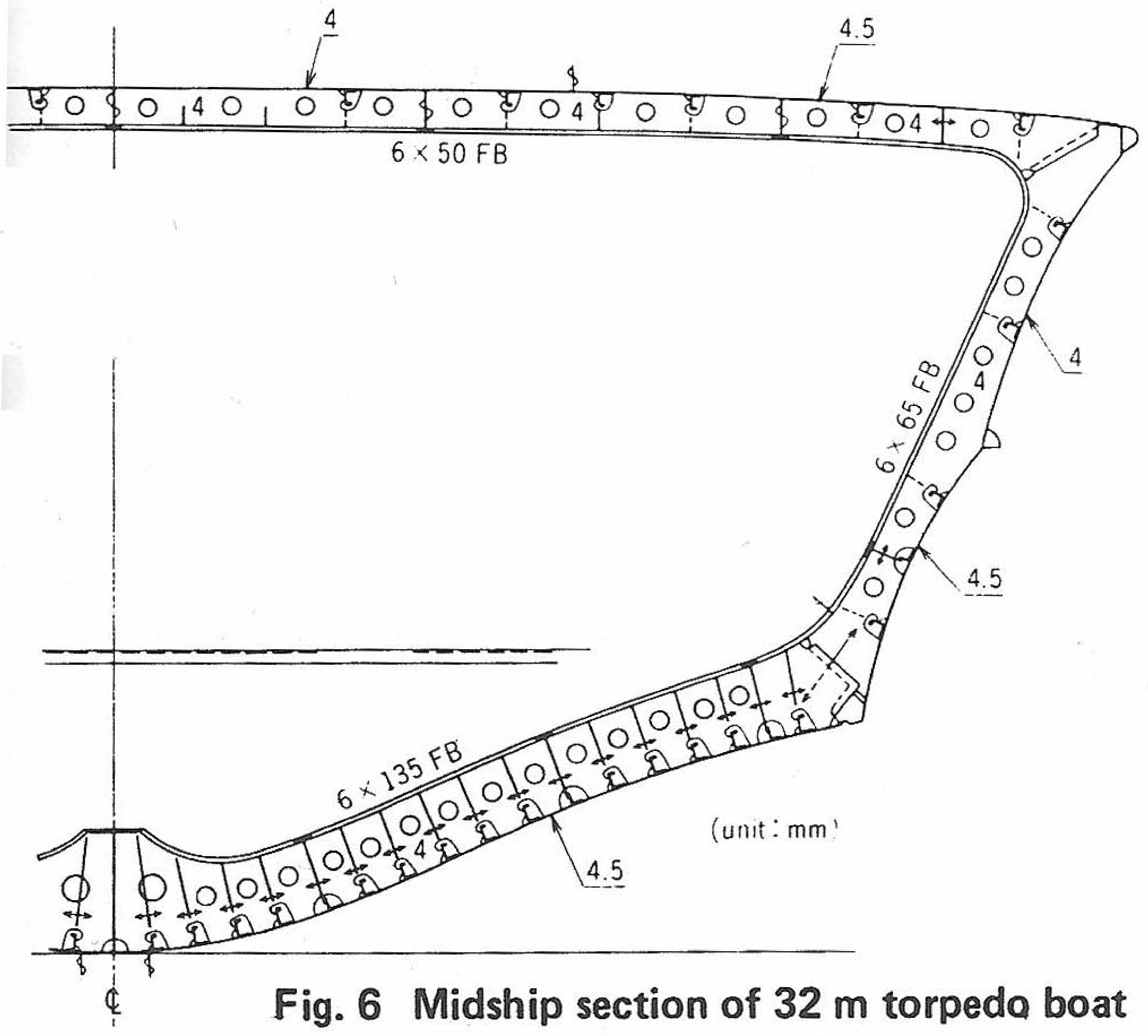

Fig. 6 Midship section of 32 m torpedo boat

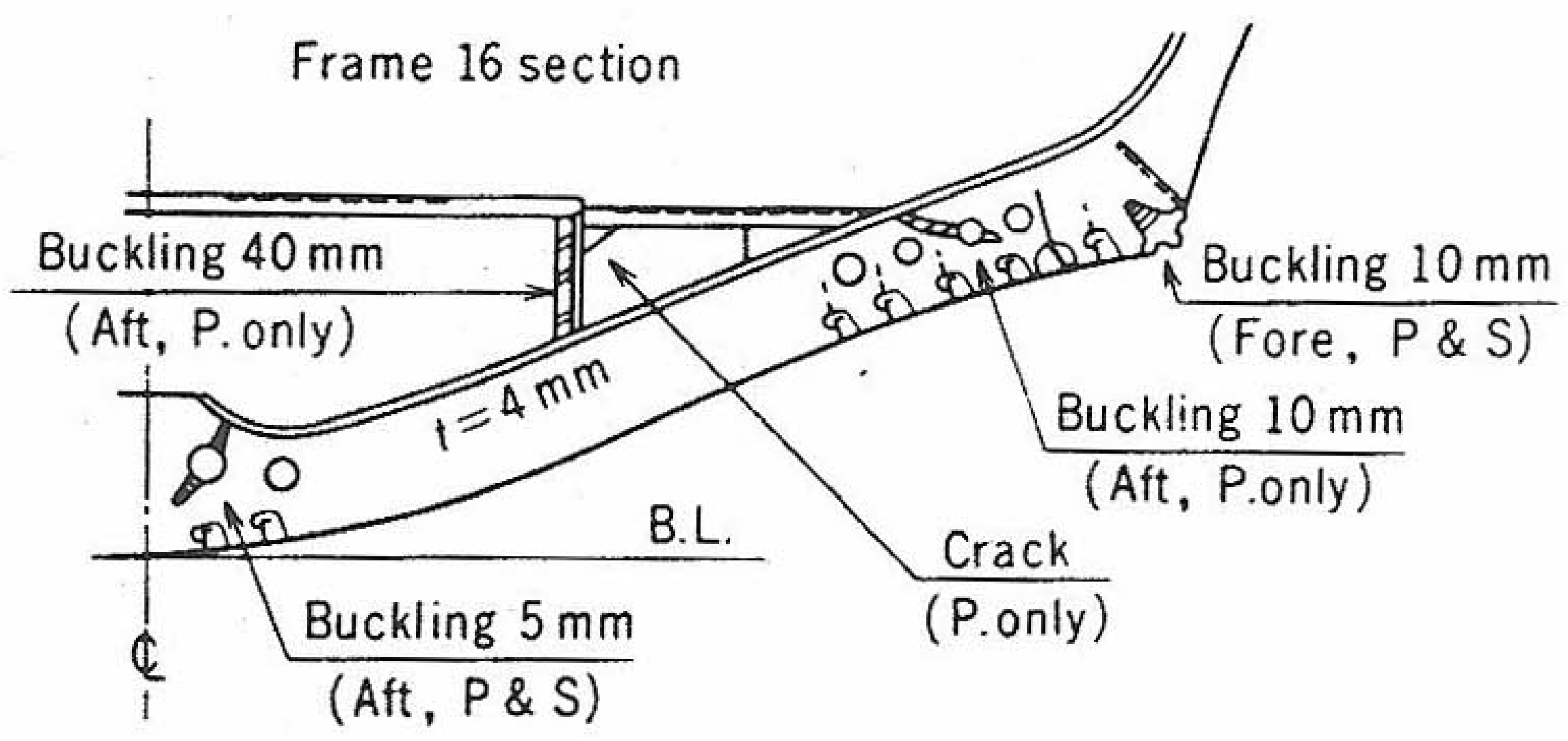

Fig. 7 Bottom damage on 32 m torpedo boat

panel was tested to examine the fatigue strength under periodic high water pressure.

Fig. 6 shows the midship section of this torpedo boat. The thickness of bottom plating and side shell was 4.5 mm and deck plating 4.0 mm.

At the time of propeller tests in winter seas at a speed of 48 knots, the forward bottom suffered from a number of dents and buckling of the bottom transverse webs. It transpired that this damage was a result of an underestimation of the external forces and lack of strength against shearing forces and local buckling. **Fig. 7** shows the sketch of the damage to this craft(4).

Investigation into the damage thus experienced has contributed to the refinement of design standards. Extensive studies on the panel design were pursued. In the study, full scale partial models of three different types of stiffener, i.e. riveted, fillet welded and integrated stiffened panel (stiffener and skin extruded together) were investigated under the maximum water pressure of 343 kN/m^2 and 10^5 repeated cycles of pressure load. **Fig. 8** shows a comparison of the fatigue strength of the three types of panel structure from which the superiority of the integrated stiffened panel to the other types is apparent. In addition to these tests, the strength of a steel panel was also examined for comparison with the light alloy material.

From these tests the design of panels based on elastic and plastic characteristics of materials was established. This design method was adopted in the Tentative Standards for

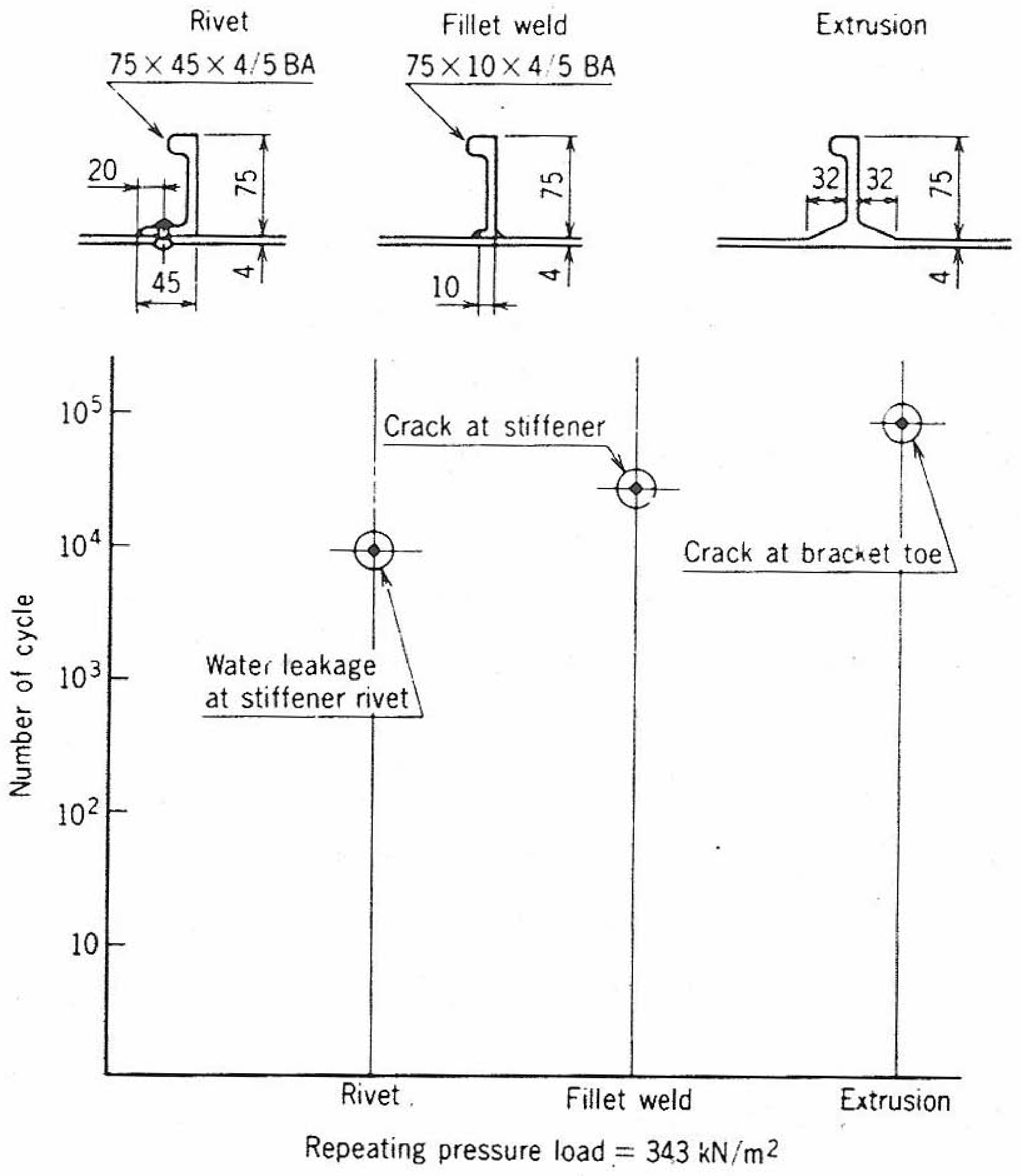

Fig. 8 Comparison of fatigue strength of three different types of panel

Light Structure Craft issued by the Marine Department, Ministry of Transportation of Japan on 13 April 1972. An abstract of the standards is given in the Appendix. The integrated stiffener panel has been used for high-speed craft built since that time, as explained in a later section.

3.4 Framing system

The longitudinal framing system was adopted in most of the high-speed craft constructed by Mitsubishi. This system has advantages when considering the local strength of bottom panels. Further, the structural weight of the longitudinal in connection with the longitudinal strength of hull girder. Further, the structural weight of the longitudinal framing system is about 20% less than that of the transverse framing system. However, in general the longitudinal system uses larger numbers of connecting members compared to the transverse system and consequently the construction costs are greater. Therefore we may say that the choice of the framing system depends on the required performance and the construction cost. The transverse system has been used for carft of speed length ratio $V/\sqrt{L} \lesssim 4$ (V is in knots and L in metres) where slam accelerations at the bow are not severe, **Fig. 9** shows the comparison of hull weight in defferent framing system.

It is possible to use welding for all structural members as in steel ships. However, thinner plating is favourable from the viewpoint of weight saving and accordingly riveting has been used in the longitudinal frames. Recently, however, larger sized extrusions became available; for instance, a panel extruded with two stiffeners has been developed where two stiffeners are integrated on to a plate with 600 mm pitch. This arrangement is called a π-section and is shown in **Fig. 10. Fig. 11** shows a midship section of the 31 m high-speed patrol boat as an example of the extensive use of such π-sections.

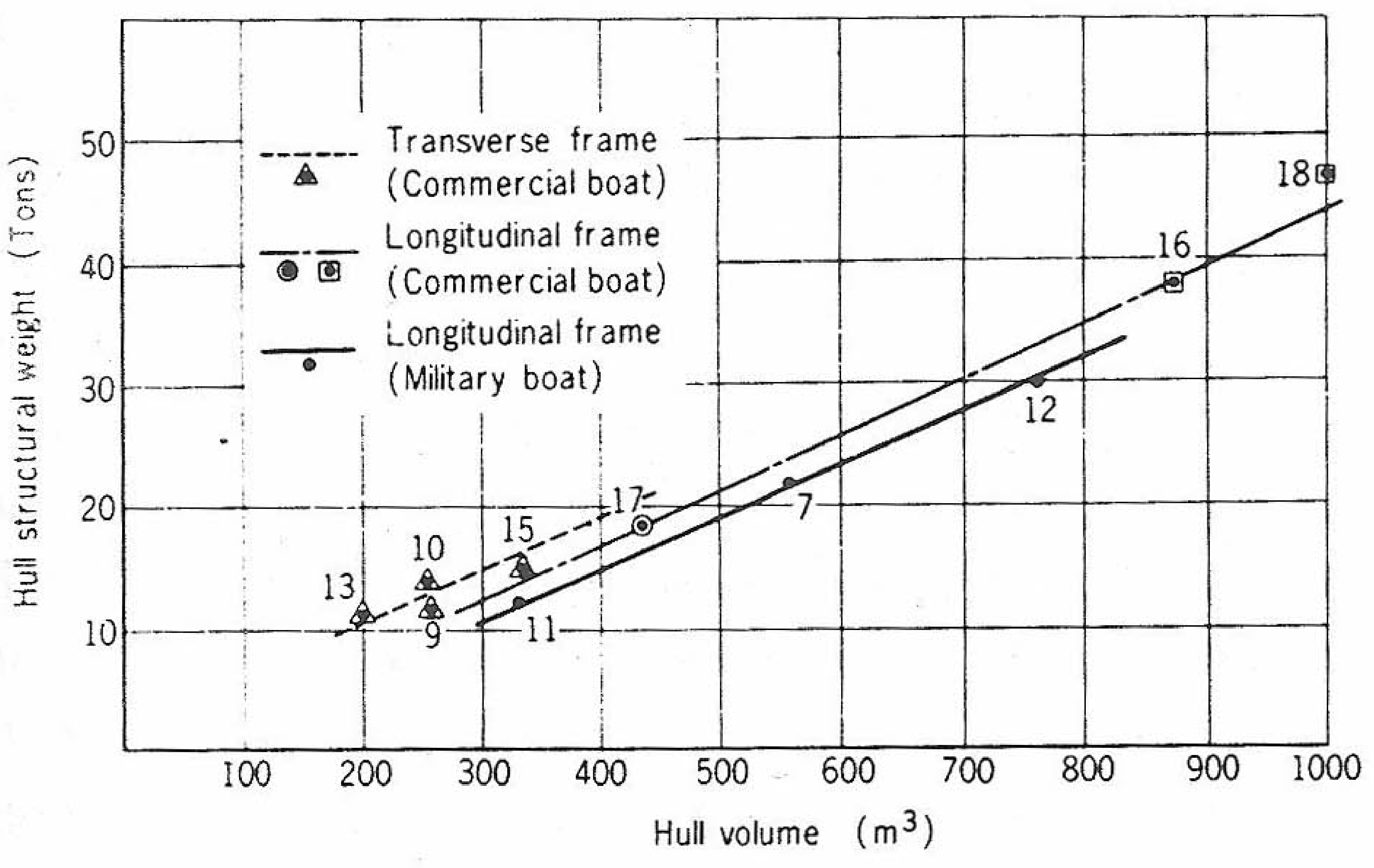

Fig. 9 Hull structural weight fraction

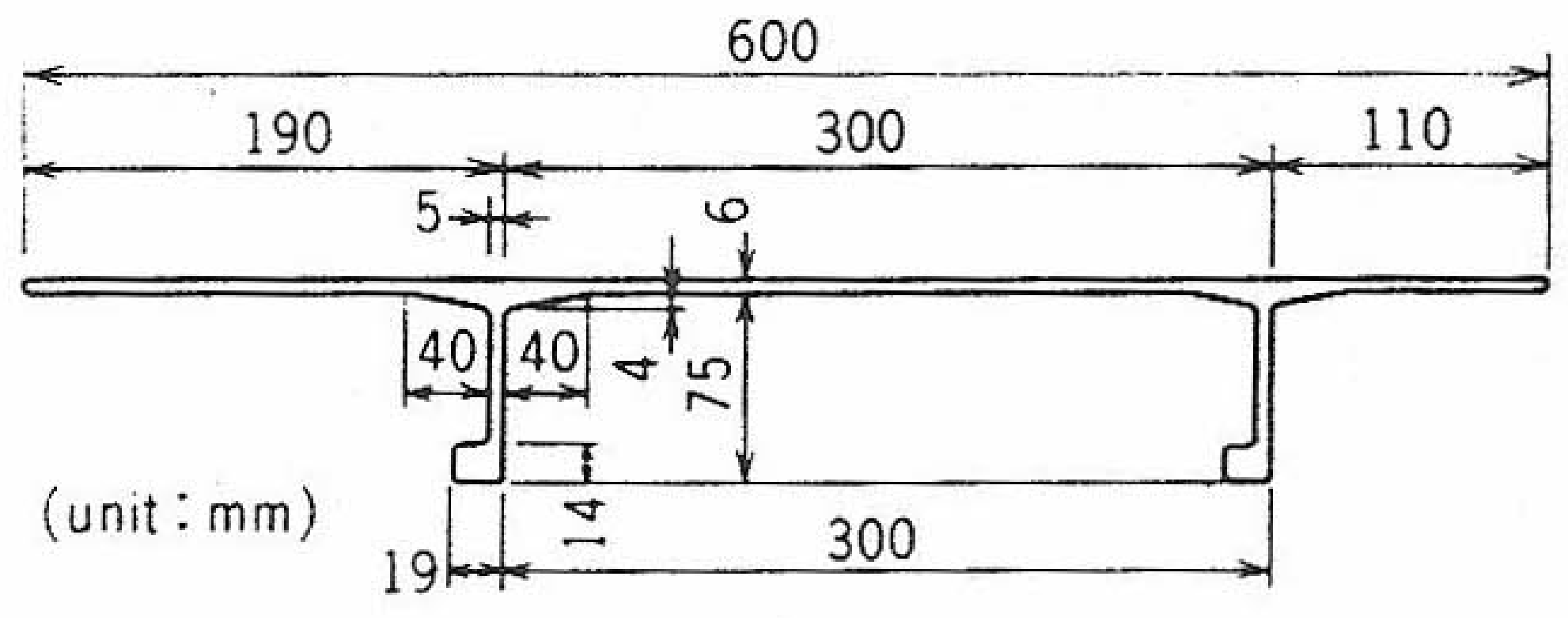

Fig. 10 Extruded panel with two stiffeners, π-section

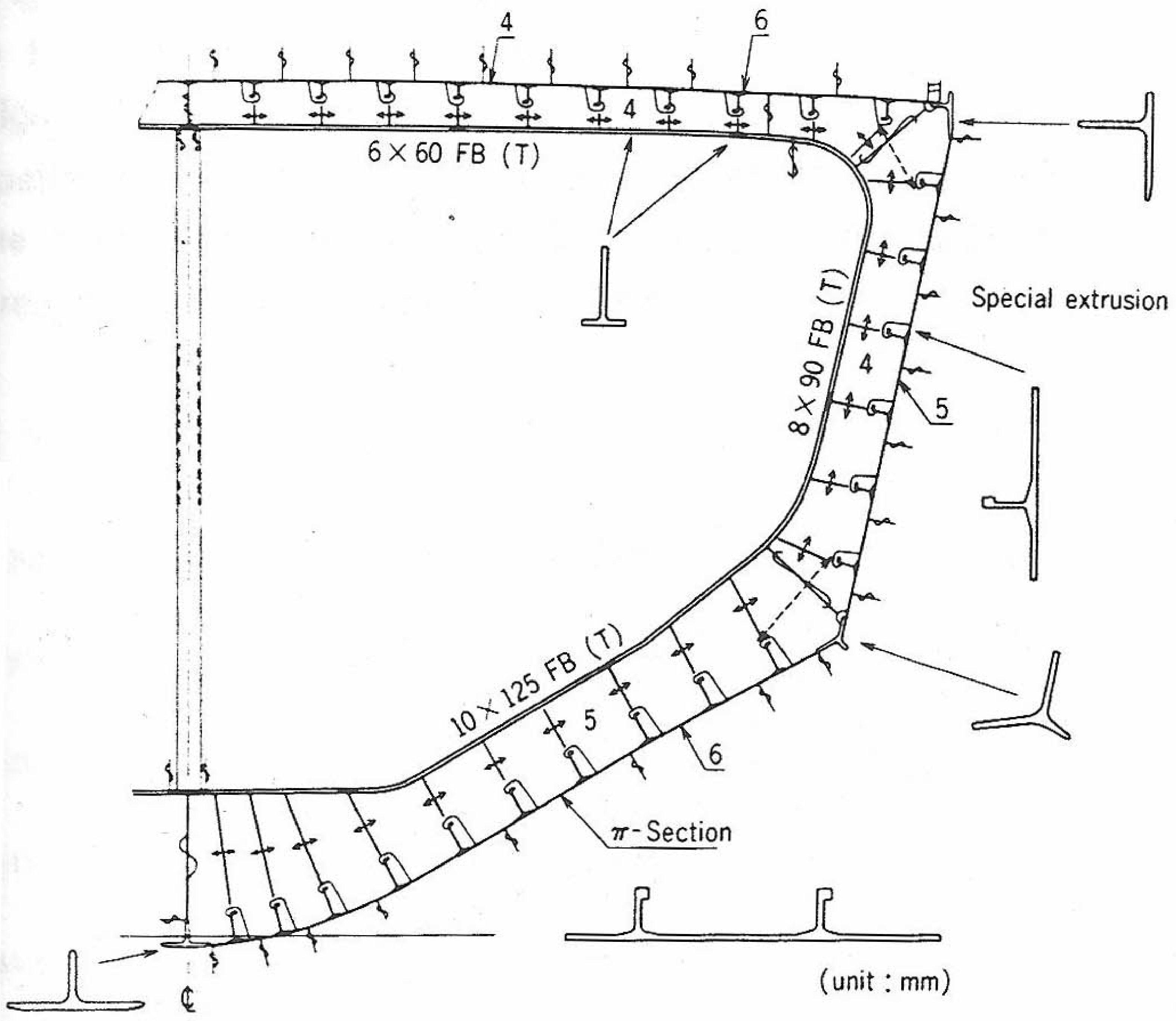

Fig. 11 Midship section of 31 m patrol boat

3.5 π-section panel

Superiorities of stiffener integrated panel compared with conventional riveted and fillet weld types are as follows:

(1) Stress concentrations at the joint of stiffener and plate can be eliminated by properly shaping the fillet; the low fatigue strength, one of the weak points of light alloy material can then be recovered.

(2) It is possible to avoid fillet welds where stresses concentrate. Fillet welds can not be examined by means of non-destructive surveys and welding defects often occur. For the connection of π-section panels, butt welds are applied at the line where working stresses are small. Usually such parts can be examined easily by means of non-destructive surveys.

(3) Distortion due to welding can be reduced, and in particular, irregular distortion due to fillet welding can be avoided, resulting in a good external appearance of the hull surface. Further, welding labour costs can be reduced by use of large stiffened panels.

(4) Automatic one-side welding developed in the Shimonoseki Shipyard has contributed towards reliability and a good external appearance of welded joints. Effective use of π-sections has been brought about by this welding system.

(5) It has been proved from panel experiments that the fatigue strength is doubled when compared with riveted structure of the same scantlings.

However, there are disadvantages of stiffener integrated panels as follows:

(1) High strength is not to be expected because hardening of the material is not practical for extruded panels.

(2) For A 5083 light alloy, extrusion of plates thinner than 5 mm is not possible, since material of higher strength has inferior properties with respect to extrudability.

In determining the shape of the fillet part, stress analyses of panels by the finite element method were carried out for two cases, i.e. one for a tapered straight line and the other for a parabolic line. It was found that the difference in principal stresses at the centre of the panel and at toe of the fillet part were smaller for the tapered straight line than for the parabolic line. Based on this study and from the point of view of convenience of fabrication, the tapered straight line type has been chosen for π-sections, the scantling of the π-section were determined by the method shown at the appendix B.

Table 3 shows a comparison of the structural weight of a 31 m patrol boat of conventional hull structure making use of π-sections from which it may be seen that a weight saving of about 3% was obtained.

3.6 Local strength

One of the most important areas of high-speed craft with respect to local strength is the bow bottom panels on which

Table 3 Weight of main hull structure of 31 m patrol boat

	Existing Structure (kg)	Structure by use of π-section (kg)
Shell plate	7097	7097
Transverse floor plate	2623	2623
Longitudinal stiffener & stringer	5065	4707
Deck beams	384	384
Deck plate	2215	2215
Pillar & stanchion	86	86
Bulkhead & wall	1606	1606
Gun support	28	28
Machinery foundation	576	576
Floor beam	393	393
Rudder & shaft brackets	539	539
Rivet & weld	438	226
Paint & coating	—	—
Total	21050	20480

severe slam forces act. As mentioned previously the 45 knots torpedo boat experienced a number of severe dents in this region. To withstand such damage, strengthening material was added and as a result of this experience a new type of panel structure, such as the π-section explained in the previous section, has been developed.

In the following, other local damage experienced by high-speed craft constructed at Mitsubishi are explained.

3.6.1 Bottom panel immediately above propeller

The fatigue strength of aluminium alloy material is low, and therefore the structural design of stern bottom panels including shell plating directly above the propeller must be carried out carefully. Due to the periodic surface forces excited by the propeller, certain of the early light alloy craft experienced crack damage on the panel above the propeller which sometimes occurred during shipbuilders sea trials.

To avoid such damage the tip clearance must be sufficiently large to reduce surface forces below a certain level, and at the same time the natural frequencies of panels in contact with the water should be much higher than the propeller blade frequency.

Fig. 12 is a plot of the double amplitude propeller surface force pressure fluctuations P determined by use of Taniguchi's experiment(5) versus tip clearance g_t/D and propeller loading factor defined by BHP/ND^3, where BHP is the horse power, N the rpm, D the propeller diameter in metres, and g_t is the tip clearance in metres.

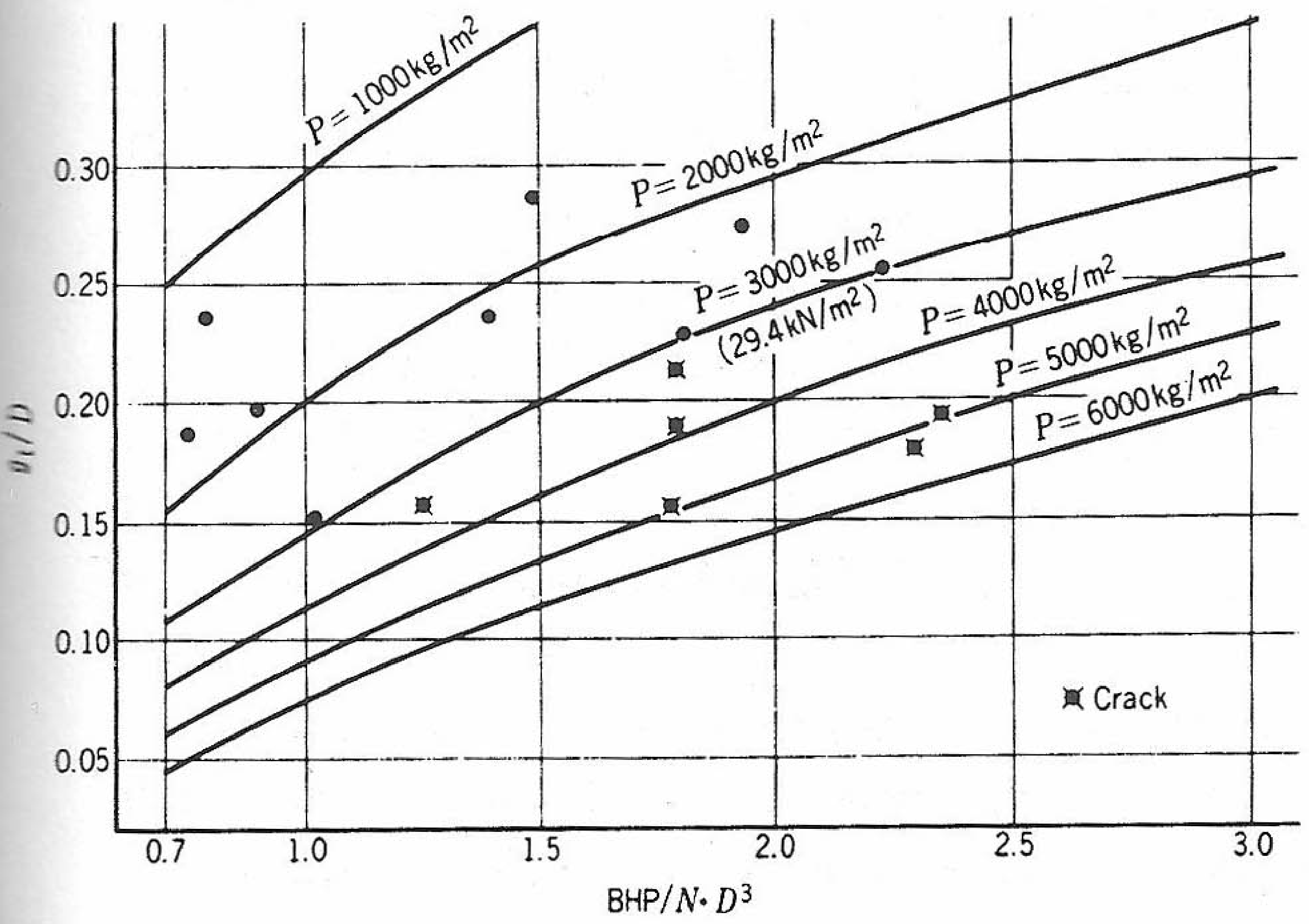

Fig. 12 Criterion for propeller tip clearance

Judging from the damage experienced, the propeller tip clearance should be larger than the value of the bold line in Fig. 8, which corresponds to a pressure fluctuation of 3 ton/m² (29·4 kN/m²).

Our experience indicates that it is not necessary for the natural frequency of the panel to be greater than twice the blade frequency for both twin-screw and triple-screw arrangements.

3.6.2 Appendages

In the early stage of construction of aluminium alloy craft, stainless steel or aluminium fabrications for shaft brackets and rudders had been used from the point of view of galvanic corrosion. However, it became clear over a period of time that, except for special purposes, mild steel can be used without any galvanic corrosion.

Shaft brackets are either of the V-type or I-type. The latter is to be preferred from the viewpoint of appendage resistance. The strength of the shaft bracket is determined in such a way that the unbalanced force due to the absence of one propeller blade can be withstood by a cross supported beam system which is composed of the shaft and the arm of shaft bracket. At Mitsubishi the I-type shaft bracket has been used without any trouble. Since the material is different from that of shell plating, an insulating sheet is inserted between the bottom plate and the shaft bracket which is fixed by means of riveting. Some craft have experienced damage due to grounding. However, this was not vital for the main hull structure.

3.6.3 Deck and floor panel

Deflections of upper deck and floor panels due to the weight of a walking human body should be minimal so as not to give any feeling of lack of strength. 1/150th deflection of the shorter span of the panel has been considered to be the upper limit of deflection.

4. Construction of all-aluminium light alloy high-speed passenger craft

4.1 Background of the construction

From 1977 to 1980, three large all-aluminium alloy high-speed passenger craft were constructed in the Shimonoseki Shipyard of Mitsubishi Heavy Industries. They were two 45 m and one 48 m craft, all of which demonstrated good performance in service.

This was the first occasion that large all-light alloy passenger craft of such size had entered service in Japan. For usual commercial purposes so-called high performance vessels such as hydrofoil craft and hovercraft have been used as passenger carriers. Our semi-displacement, high-speed passenger craft were designed so as to achieve highly economical performance including considerations of low cost of operation and maintenance. The so-called high performance craft are based on highly sophisticated technology.

They are therefore delicate and reliable service is not guaranteed without well prepared supporting systems. On the other hand the sales features of our craft were low operational and maintenance costs, high reliability and availability. Their particulars are shown in Table 1 for craft numbers 16, 18 and 19.

4.2 Propulsive performance

The first craft of this series was designed to meet the requirement of one hour operation over 42 km distance between Atami and Oshima island in the Sagami Sea out of Tokyo Bay. On this route a 1200 gross ton passenger ship had been carrying 758 passengers at 12 knots with a crew

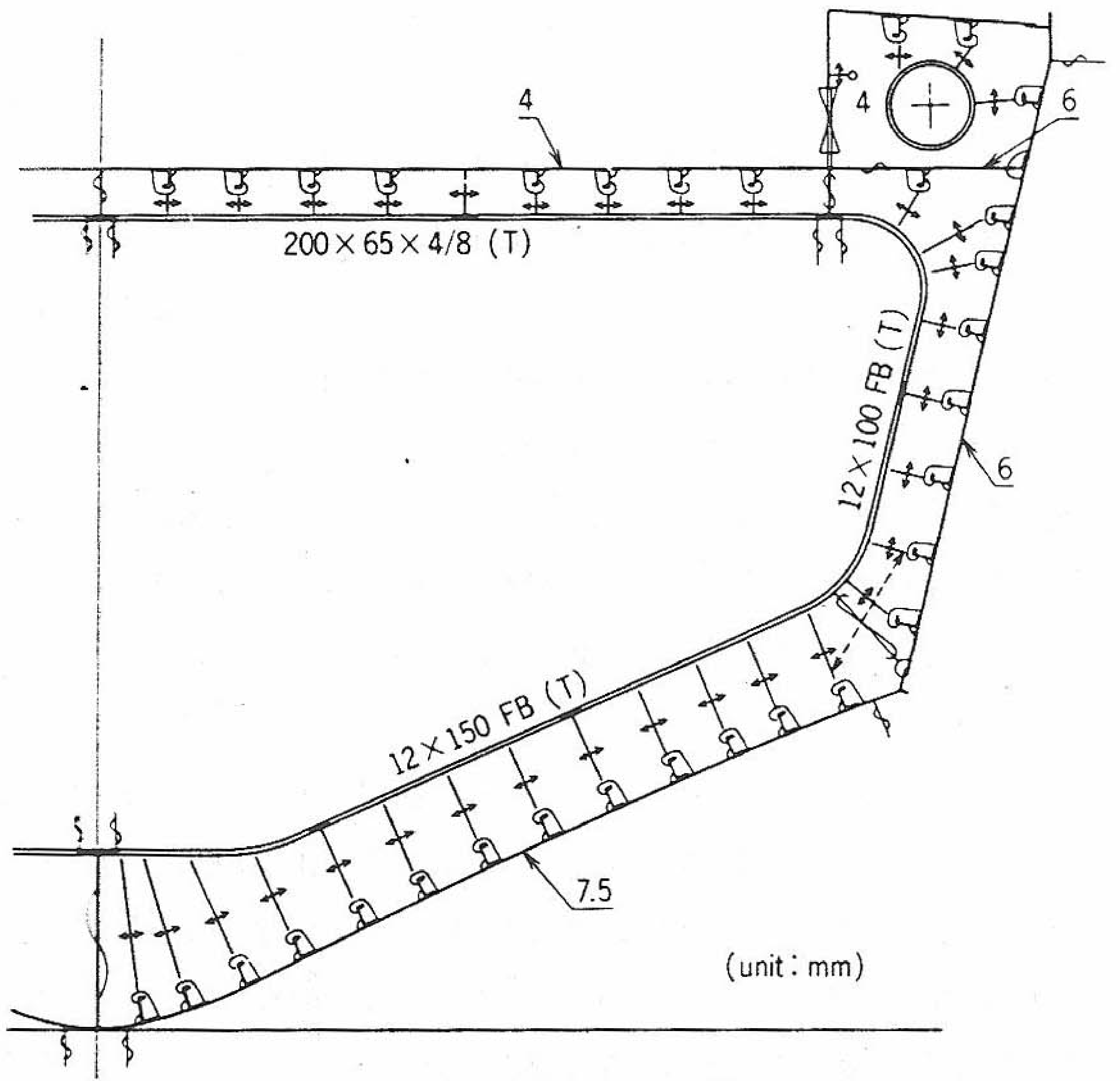

Fig. 13 Midship section of SEAHAWK

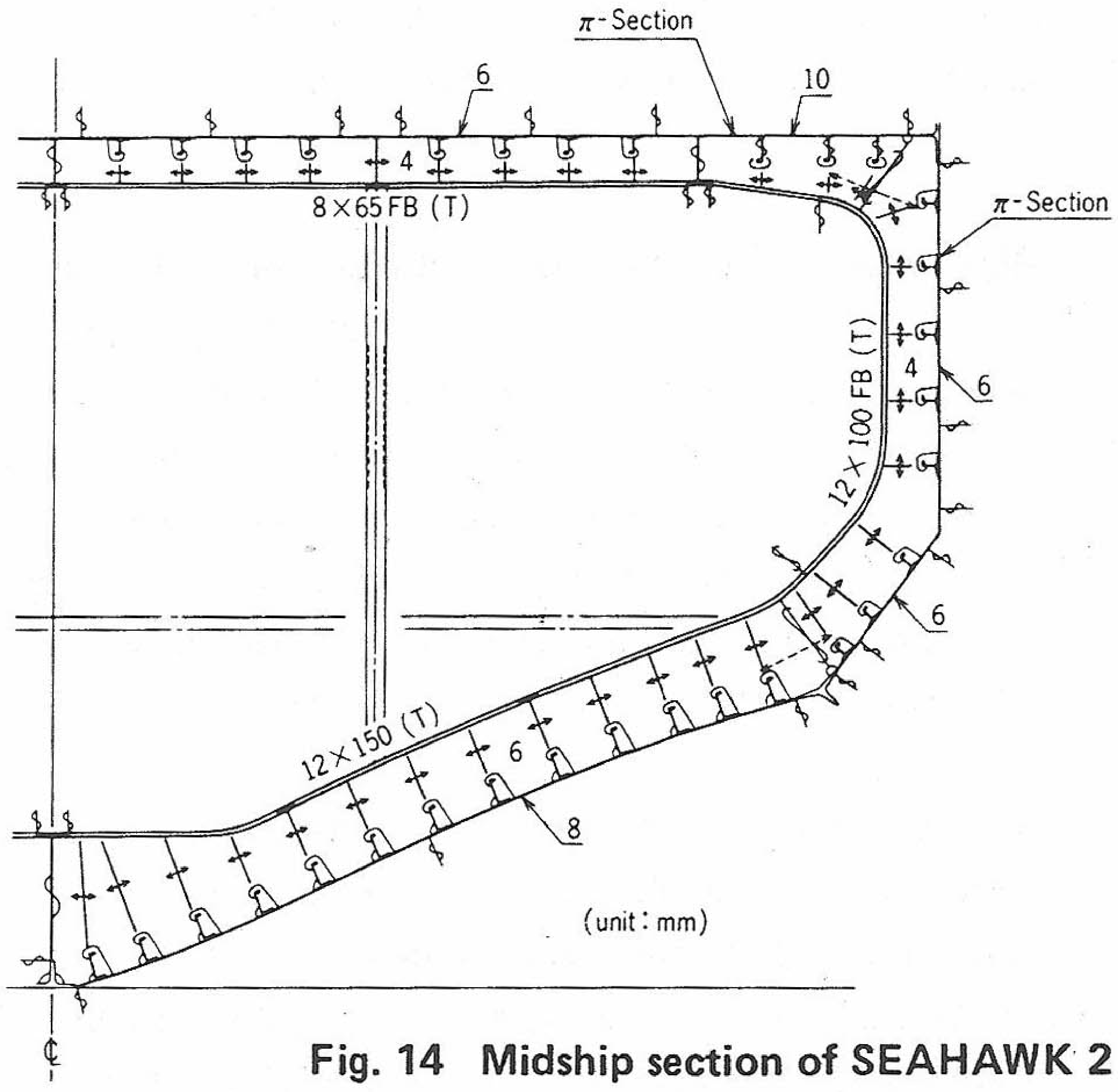

Fig. 14 Midship section of SEAHAWK 2

of 39. In order to increase the service speed from 12 knots to 25 knots and to reduce operational costs, a light alloy craft was introduced.

Though this route is along the coast, the sea is open to the Pacific Ocean and therefore good seakeeping qualities were required. A ship length of 45 m was chosen as the minimum to maintain service availability, although a figure of over 90% was achieved in practice. The owner was satisfied with the service performance of this craft and ordered another slightly larger vessel of 48 m to cope with the increase of passengers. In 1980, a 48 m all-aluminium alloy passenger craft, SEAHAWK 2, was constructed and a further 45 m craft was built for another customer.

4.3 Hull structure and economics

The Tentative Standards for Light Structure Craft issued by the Japanese Government mentioned previously are applied to craft of less than 24 m in length and speed-length ratio $V/\sqrt{L} > 4$. For the construction of craft larger than 24 m, the external forces have to be estimated individually.

For the structural design of the 45 m craft, the accelerations due to slamming were estimated from the experimental data of a 3.6 m model in the Nagasaki Experimental Tank of Mitsubishi Heavy Industries. Then assuming that the total weight and wave loading act at a point 30% of craft length from the bow, and the craft can be regarded as a rigid body, the maximum longitudinal bending moment was estimated. Cross checks were carried out on the external forces estimated by use of available standards such as the Tentative Standards of the Japanese Government, the method of Heller and Jasper(6), Rules of the Classification Societies such as American Bureau of Shipping, Det Norske Veritas, etc.

The first 45 m craft SEAHAWK has passenger spaces of the sunken type. Therefore, box girders were inserted at the corner of deck to increase the longitudinal strength. **Fig. 13** shows the midship section of SEAHAWK. For SEAHAWK 2, on the other hand, flush-type passenger rooms were chosen, and therefore such special structure was not used. **Fig. 14** shows the midship section of SEAHAWK 2. For the improvement of the hull structure, π-section panels were used as shown in Fig. 14.

In the design stage of SEAHAWK 2 a comparative study of structural materials was carried out which indicated that under the specified number of passengers and service speed, the increase in the material cost of aluminium alloy was almost compensated by the increase in cost due to the larger machinery for a steel hulled structure. The steel hulled structure required one more set of main engines, shafting propeller and the related structure because of the size of the craft. Therefore it was found that the operational and maintenance costs for the steel hulled structure were 1.5 times greater than those for the aluminium hulled structure which has a twin-screw installation. From these studies, the economical superiority of the aluminium-hulled structure was recognized by the customer. Hadler et al drew similar conclusions for high-speed naval craft(1).

4.4 Full-scale measurements in rough seas

To confirm the strength of the craft and to accumulate design data, stresses and accelerations under slamming conditions were measured for SEAHAWK and SEAHAWK 2 off Oshima Island. Usually it is difficult to carry out full-scale measurements in service, especially for passenger ships, but fortunately, full-scale measurements on SEAHAWK were carried out continuously for three months(7).

The measured results were compared with the Tentative Standards for Light Structure Craft issued by the Japanese Government. The longitudinal bending moment was determined from stresses measured on shell plates, using the modulus of the section. The equivalent static pressure was determined from measured stresses under the following assumptions:

(1) Bottom panels can be regarded as rectangular plates whose boundaries are fixed and on which a uniform pressure is applied.

(2) Longitudinal frames on bottom panels can be regarded as beams whose ends are fixed and which are subject to a uniform pressure.

(3) Web frames on bottom plates can be regarded as beams with uniform pressure distribution one end of which is fixed at the keel and the other end is supported at the chine, the effective width of shell plating when regarded as a part of a longitudinal member being based on Schade's theory(8).

Fig. 15 shows comparisons of longitudinal bending moment thus determined and equivalent static pressure with the values determined by using the Tentative Standards. From these comparisons it has been confirmed that the strength based on our practice agrees quite well with the Standards. Therefore it may be said that from our full scale measurements, the reliability of the Standards has been confirmed even when they are applied to high-speed craft larger than the 24 m which is specified in the Standards.

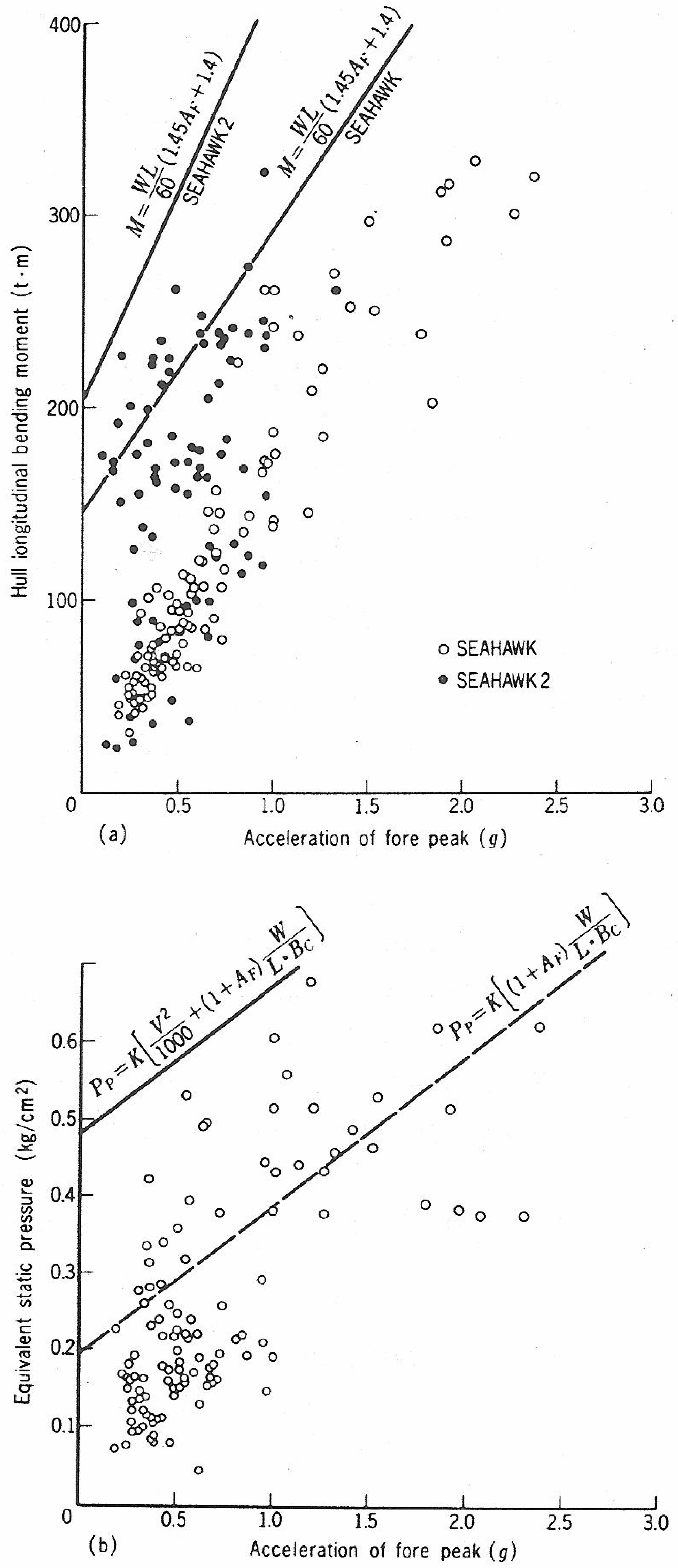

Fig. 15 Full-scale measurements on SEAHAWKS

5. Economical comparison of various aluminium alloy high-speed passenger boats

For the economical comparison between various type of passenger boats, it is essential to estimate all running cost including purchasing price based on the available time schedule, time distribution of expected number of passengers in every season for intended courses by taking consideration of route conditions such as weather, sea condition, etc.

In case of passenger boats, the income depends on the number of passenger, and the expenditure increases proportionally to the fuel consumption, that is to the output of main engines. Then it is considered that the economy of the passenger boat depends on the factor, $(n\cdot V/\mathrm{PS})$ where n is number of passengers, V is service speed, PS is output of main engines corresponding to the service speed. The bigger is this factor, the bigger is the income, and the smaller expenses. However, n depends largely on the design of ship and varies according to the amount of fuel oil or endurance, etc. Then the deadweight $(\mathrm{DW}=n+\mathrm{F.O.}+\mathrm{etc.})$ is considered to be a proper instead of n. Therefore $\mathrm{DW}\cdot V/\mathrm{PS}$ may be called transportation efficiency. **Fig. 16** shows this transportation efficiency plotted against ship's maximum speed V of various type passenger boats with speeds of 20–30 knots. The reason why the author adopted ship's maximum speed instead of service speed is due to the fact that it is difficult to get reliable data for service speeds and corresponding engine output. In this figure, SEAHAWK 2 can be seen as the most economical ship at maximum speed 30 knots or service speed 26–28 knots. However there are some items to be remarked:

(1) In case of gas turbine as main engine, the value of PS should be about 1.5 times larger when compared with diesel engine, e.g. for Jet Foil and ACV.

(2) Seakindness must be taken into consideration. For instance, small catamaran such as Jet Cat, and small SES such as HM-2 show poor seaworthiness in rough sea. On the other hand, Jet Foil has excellent seaworthiness

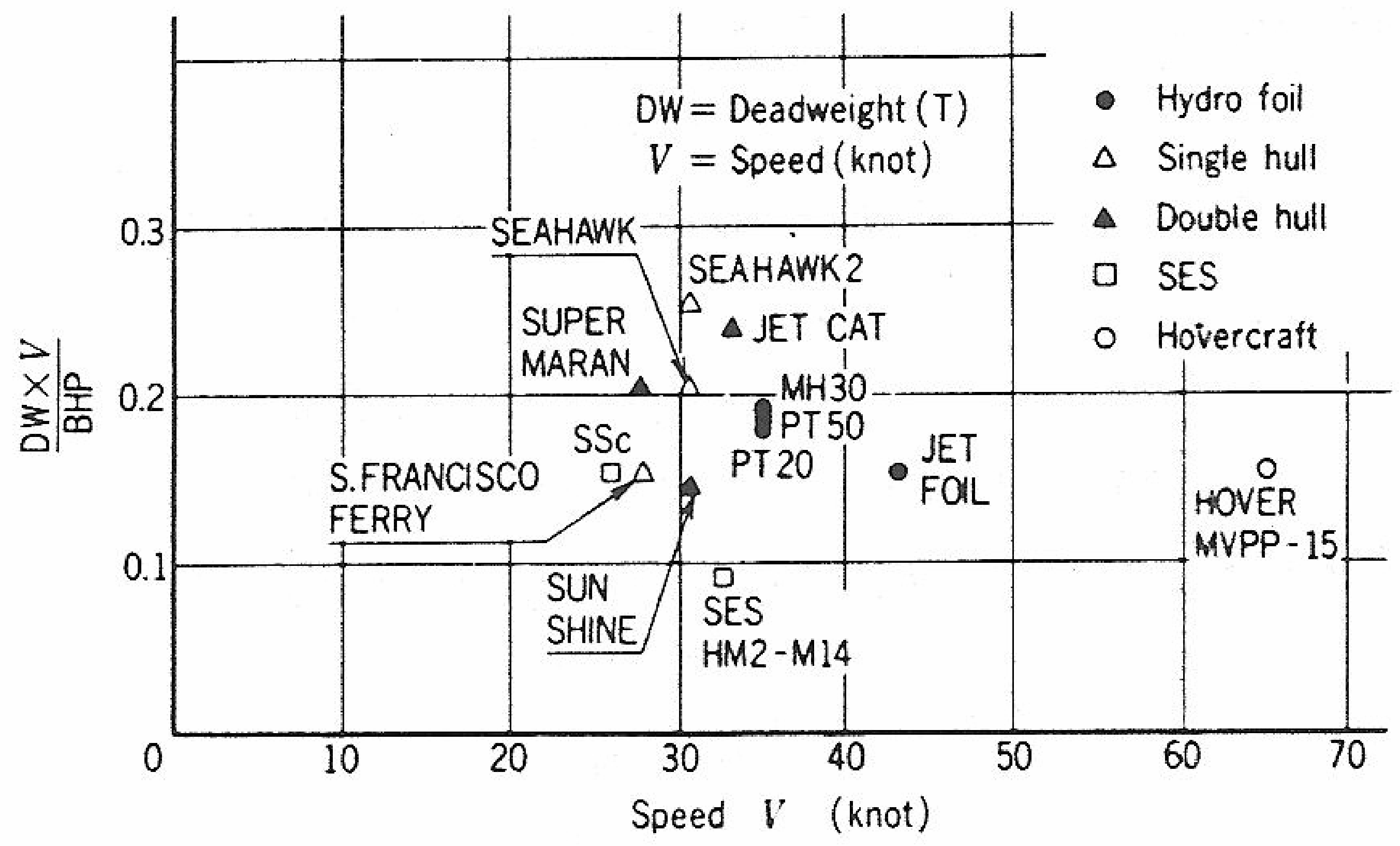

Fig. 16 Transportation efficiency

within a limited seastates. Further, the passenger comfortability for single hull of semi-planing type such as SEAHAWK is reduced in rough seas.

(3) Ship's purchasing price is not included in such a simple expression of transportation efficiency.

6. Concluding remarks

In the early stages aluminium alloy was regarded as simply replacing steel for hull structure. The favourable character of light alloy, i.e. easy extrudability, was not effectively used and rivets were used in most connections of strength members.

In accordance with the development of welding techniques and the refinement of fabrication techniques, the extent of welding has been gradually expanded together with progress in the extrusion of stiffened panels and a variety of sections. All-welded structure has become possible for smaller boats, as in steel hulled vessels. In this way the applicability of light alloy to hull structure has increased.

In Japan, 35 m torpedo boats were the early examples of the effective use of the advantageous characteristics of light alloy for military use, and SEAHAWK 2 and the 31 m patrol boats mentioned previously are the latest examples of full use of these characteristics.

The authors consider that there is still room for improvement with respect to extrudability of 5083 material which has been widely used in Japan. Though efforts have been devoted in the past 30 years to developing light alloy material superior to 5083, satisfactory results have not yet been obtained. This emphasises the difficulties of developing a new material in which higher strength and easier extrusion are compatible. However, it is clear that the development of such material will widen the applications of light alloy to high-speed craft of improved performance with low operational and maintenance costs.

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Appendix A

Abstract from Tentative Standards for Light Structure Craft issued by the Marine Department, Ministry of Transportation, Japan on 13 April 1972.

These standards are applied to ships built of steel or anti-corrosion aluminium alloy with registered length less than 24 metres.

(1) Bending moment amidships, M in ton·m

$M = C \cdot W \cdot L$

W : displacement in tons

L : ship's length in metres

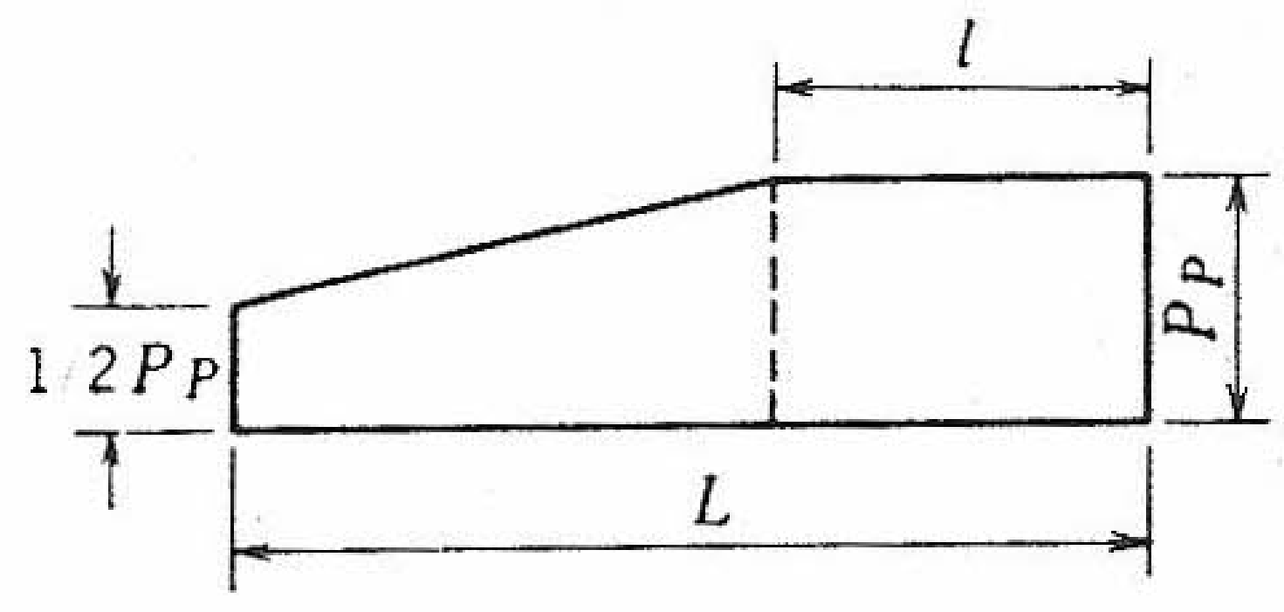
C : 0·120 for coastal area service

0·096 for restricted area coastal service

0·072 for smooth water, river and harbour service

(2) Design pressure for bottom plate : P_p

$$P_p = K\left(\frac{V^2}{1000} + k\frac{W}{LB_c}\right)$$



P_p : impact pressure on bottom plate in kgf/cm^2

V : ship's speed in knots

B_C : ship's width at chine in metres

k : 5.0 for coastal area service

4.0 for restricted area coastal service

3.0 for smooth water area service

K : correction for ship's bottom shape based on deadrise angle β

1.0 for $\beta < 10°$

$K = \left(\frac{5}{\beta - 5}\right)^{2/3}$ for $\beta > 10°$

Pressure distribution along ship's length to be as follows:

$$l = \frac{L}{10}\left(4 + \frac{1}{10} \cdot \frac{V}{W^{1/6}}\right)$$

Values of C and k may be related to vertical acceleration at the bow A_F (in g) as follows:

$$C = \frac{1}{60}\,(1.45A_F + 1.4)$$

Service area	C in bend. moment	k in pressure	Vertical acc. A_F (g)
Coastal area	0.120	5	4
Restricted coastal area	0.096	4	3
Smooth water area	0.072	3	2

Appendix B

The scanting of the π section

In case of plate thickness which varies linearly, the plate can be regarded as a variable section beam and their scantling will be determined based on the bending stress at each section to be optimum, that is the stress to be equal at the centre of span and both ends.

The bending stress at each section can be obtained as follows:

(1) at the root of stiffeners with tapered beam,

$$\sigma(x) = \frac{wl^2}{(t_0)} \cdot \frac{\left(\frac{k}{12} - \frac{x}{2l} - \frac{x^2}{2l^2}\right)}{\frac{1}{6}\left(1 + \alpha - \frac{\alpha}{\beta} \cdot \frac{x}{l}\right)^2} \quad \text{for} \quad 0 \leqq x \leqq f \qquad (1)$$

(2) at the middle of the span,

$$\sigma(x) = \frac{wl^2}{(t_0)} \cdot 6 \cdot \left(\frac{k}{12} - \frac{x}{2l} + \frac{x^2}{2l^2}\right) \quad \text{for} \quad f \leqq x \leqq \frac{l}{2} \qquad (2)$$

where

$$\alpha = \frac{t_1}{t_0}, \quad \beta = \frac{f}{l}, \quad \text{and}$$

$$k = \frac{\frac{1}{2} + \beta^2(2\beta - 3) + 6\left(\frac{\beta}{\alpha}\right)^2 \left[-\frac{\beta}{\alpha}\log(1+\alpha) - \frac{\alpha}{1+\alpha}\left\{1 - 2(1+\alpha)\frac{\beta}{\alpha}\right\} - \frac{(\alpha\beta + \beta - \alpha)(2+\alpha)}{2(1+\alpha)}\right]}{\left(\frac{1}{2} + \beta\right) + \frac{\beta(\alpha+2)}{2(1+\alpha)^2}}$$

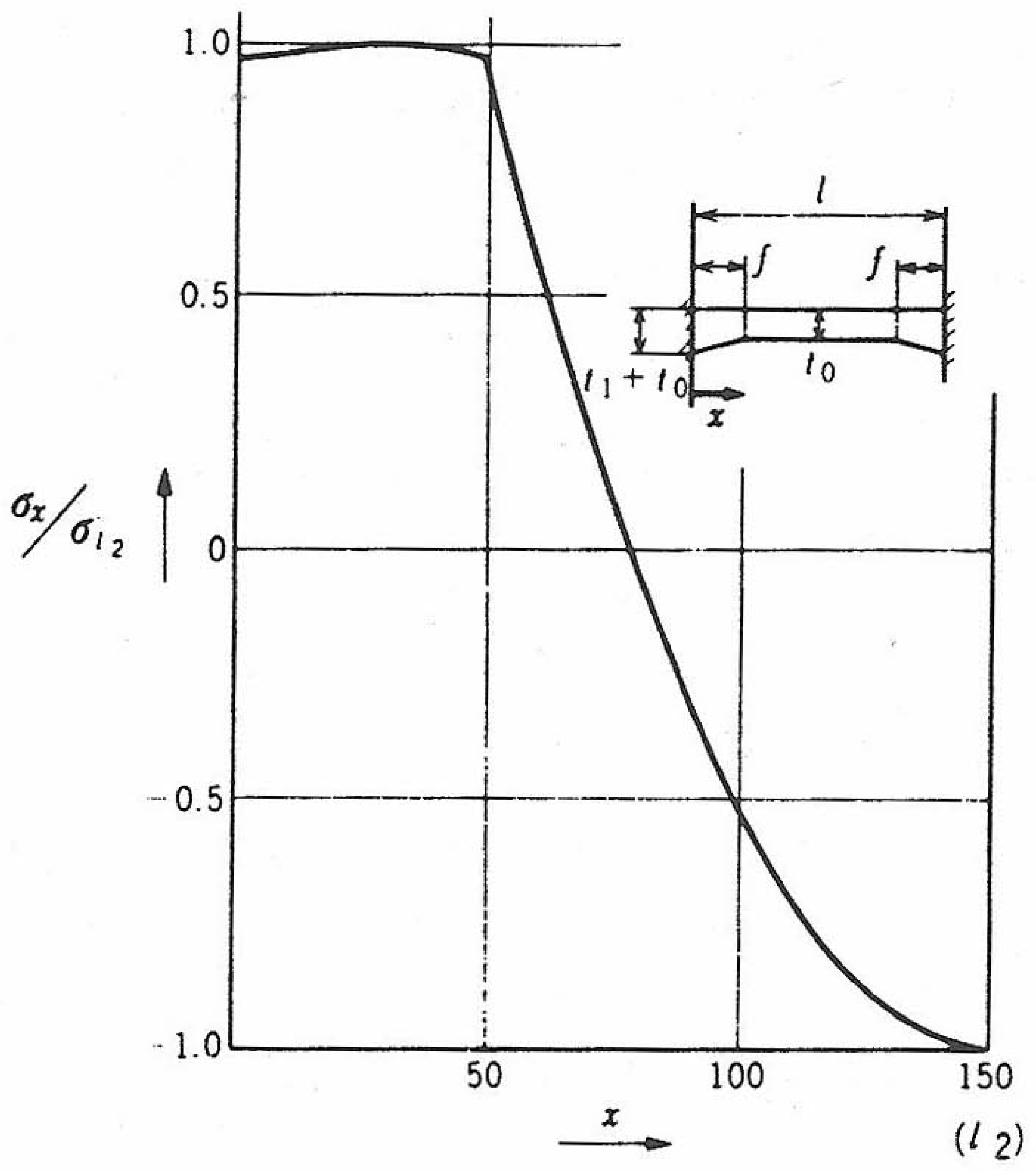


Fig. 17 Stress diagram of π-section

For the π-section of span l = 300 mm shown in Fig. 10 the stress can be calculated as shown in Fig. 17 and the relation of thickness and the length of tapered part f will be

$$\frac{t_0}{t_0 + t_1} = \frac{5.7}{10} \qquad (3)$$

$$\frac{f}{l} = \frac{49}{300}$$

Thus we can get the scantling of π-section as shown in Fig. 10.