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REVIEW OF FILLET WELD STRENGTH PARAMETERS FOR SHIPBUILDING.(U)
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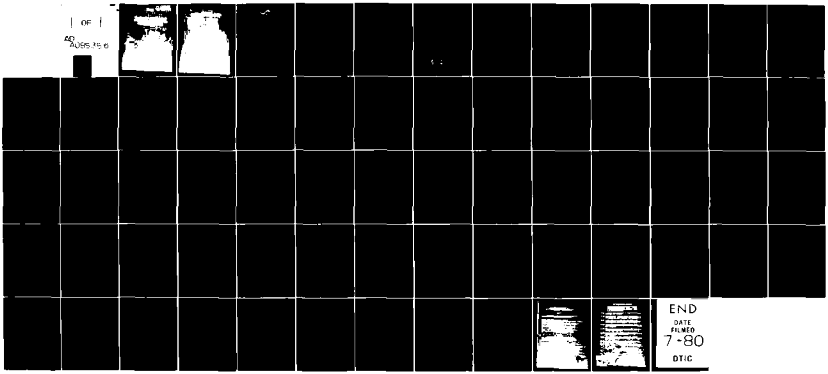

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Ship Structure Committee

An Interagency Advisory Committee
Dedicated to Improving the Structure of Ships

Address Correspondence to:

Secretary, Ship Structure Committee
U.S. Coast Guard Headquarters,(G-M/TP 13)
Washington, D.C. 20593

APRIL 1980

SR-1248

Fabrication methods are being closely examined by the shipbuilding industry in an attempt to hold down or reduce shipbuilding costs. An examination of the fabricating procedures disclosed that as much as 30 percent of the vessel construction man-hours are devoted to welding. A further analysis indicated that 75 percent of the welded joints were fillet welded.

Inasmuch as the requirements of fillet weld sizes have not been revised for many years, the Ship Structure Committee considered a review and analysis of current marine fillet weld requirements might provide an opportunity to reduce the sizes. This report reviews the fillet weld requirements of the various ship classification societies, presents a developmental procedure for a rational analysis of required weld strength and makes recommendations for further research.

Henry H. Bell
Rear Admiral, U.S. Coast Guard
Chairman, Ship Structure Committee

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16. Abstract

This report presents the results of a review of the current fillet weld specifications of the various classification societies and a developmental procedure for analyzing these rules by a rational method for estabilishing required weld size, and recommendations for further research.

The results indicated large deviations among rules which relate the fillet weld size to the thickness of the base plate. The required fillet weld size by the most conservative rule may be two times that required by the most liberal rule. There appears to be a need for reviewing these rules more closely by analytical means.

A computer program, named 'Automatic Dynamic Incremental Nonlinear Analysis (ADINA)', was used to determine the stress distributions in the welds of tee-joints under simple tension acting along the edges of the flange. This program could be used in determining the minimum weld sizes. A detailed explanation of the rationale of using 'ADINA' program or similar FEM programs is presented in this report.

17. Key Words

STATIC STRENGTH, FATIGUE STRENGTH, RESIDUAL STRESS, WELD DEFECT, INSPECTION, WELDING-CRACKING, WELDING - PROCESS

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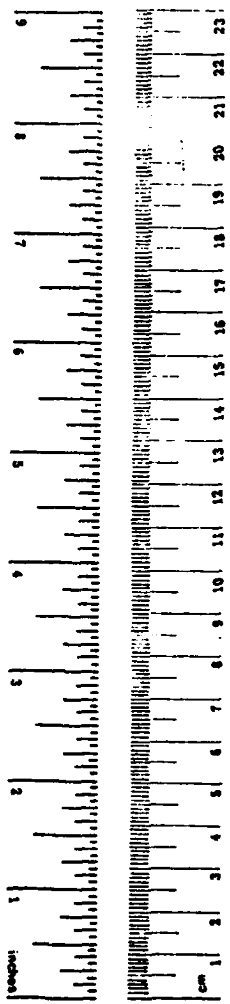
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

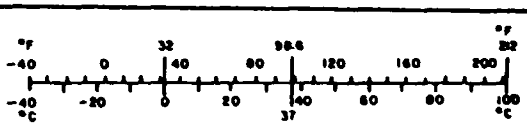
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

1. INTRODUCTION

1.1 Background

Fillet welds are extensively used in ship structures. In a typical ship hull construction, about 75% of the welds are fillet welds.(1) This is because a ship hull is essentially composed of a number of panel structures. A typical panel structure is composed of a plate and transverse and longitudinal stiffeners. These stiffeners are usually fillet welded to the panel. For example, a 50,000 deadweight ton cargo ship, of which the hull weight is approximately 15,000 tons, has approximately 7×10^5 feet of fillet welds, of which the weld metal weighs approximately 60 tons.

An overriding concern by ship designers and fabricators over the years has been to make sure these fillet welds are strong enough. Although many efforts have been made to reduce the weight of the ship structure by reducing thickness and dimensions of structural members, little attention has been placed on reducing the size of fillet welds, weight of which represents only a fraction of the structural weight. Rules on the size of fillet welds in ship structures have remained virtually unchanged for many years. It is quite possible that current specifications on fillet welds are too conservative.

The reduction of fillet sizes can have a significant impact on construction cost by reducing construction time, labor cost, the weight of welding consumables, etc. For example, 20% reduction in the fillet leg size will result in 36% reduction in the amount of the weld metal. The welding and assembly of ship hulls requires approximately the same number of manhours, and these two functions combined amount to about 60% of the total manhours for the completion of the hull structure.(2) This indicates that the welding operation accounts for about 30% of the labor cost in planning and constructing ship hulls. If we look at the total linear measure of the welded fillet joints employed in ship construction (75%), the labor cost in fillet welding is about a quarter of the total labor cost for constructing a ship's hull.

Reduction of the fillet size will also result in reduction of weld distortion. The reduction of out-of-plane distortion may result in an increase in buckling strength when the panel is subjected to compressive loading.(3)

This project was initiated with an ultimate goal of finding whether sizes of fillet welds could be reduced without affecting the structural integrity of a ship. More specifically, the original objective was to recommend updated fillet weld requirements for domestic ship application by reviewing the development of current marine fillet weld requirements and available test data.

1.2 Outline of the Study

The one-year study included the following tasks:

1. Literature survey,
2. Review of welding standards,
3. Contact with experts,
4. Analysis, and
5. Recommendations.

There have been many publications on various aspects of ship structural analysis,studies on the overall strength of a ship hull, and studies to determine stress distributions in various structural members. In fact, large-scale finite-element methods (FEM) have been developed by various research groups including ship classification societies in various countries for computing stress distributions in various structural members of a ship hull. However, no published articles specifically discuss stress distributions in fillet welds.

After searching for suitable techniques for analyzing the fillet weld strength, the finite-element method was found to be a reliable tool and probably one of few techniques which could fulfill the needs of this project. Therefore, efforts were made to develop a computer application of an existing program, named "ADINA" (Automatic Dynamic Incremental Nonlinear Analysis) which was developed by Professor K.J. Bathe in the Department of Mechanical Engineering at M.I.T.

2. LITERATURE SURVEY

A literature search used the following key words:

Static Strength

Fatigue Strength

Residual Stress

Weld Defect

Inspection

Welding Cracking

Welding Process

to generate the 81 papers that were surveyed in Appendix 1.

A review of assumptions and conclusions of the major past contributions (9 papers) in improving the understanding of fillet weld strength is summarized in Table 2.1

The survey showed:

1. The requirements for fillet weld size used in the codes of various classification societies were based on equivalent shear loads between a riveted and a welded structure.
2. The first attempt to compare experiment with theory was done by Vreedenburgh in 1954.[4]
3. The most recent attempt was by Kato in 1974,[11] using a finite element method (FEM), but again with some simplifications.
4. An accurate analysis has not yet been done.
5. Fillet welds are very strong when the current requirements are applied.
6. The statistics indicate no fillet failures and the weld size relates only weakly to cracking at the toe of the fillet.
7. More papers discuss fatigue strength than static strength.
8. Fatigue strength is more critical than static strength in fillet welds.
9. Contact angle between the base plate and the weld surface, welding defects such as undercut or cracks near the fillet toes in the base metal, and root gap are factors contributing to reduction of fatigue resistance and a fillet weld failure.

2.1 Statistics on Ship Hull Damage Related to Weld Defects

A study on hull damage related to weld defects has been carried out by Nippon Kaiji Kyokai[14] The study dealt with general structure damages of four types of ships: tankers, ore carriers, containers and general cargo ships. Out of 1200 surveyed ships, cracks in shell or strength deck plating were

TABLE 2.1 SUMMARY OF LITERATURE SURVEY

NAME	YEAR	SUBJECT	ASSUMPTIONS	CONCLUSIONS
Vreedenburgh (4)	1954	Static strength	(Experiments)	Design should be based on an experimentally derived envelope of weld strength. Reject theoretical approaches since they didn't agree with experiments. Introduce empirical coefficients to modify theoretical results.
Macfarlane Harrison (5)	1965	Fatigue of transverse fillet welds	(Experiments)	The fatigue strength of the transverse fillet welds is influenced by the relative sizes of the main and cover plates.
Swanell (6)	1968	Static strength of longitudinal fillet welds	Uniform shear	Effect of joint stiffness and load application on the shearing intensity - Toe displacement relationships.
Report of the Welding Inst. Research Laboratories (7)	1968	Fatigue	(Experiments)	Considerable increase in fatigue strength of fillet welded joints is reported when they have been either ground or hammer peened. For low cycle fatigue use grinding and for high cycle fatigue use peening.
Solumsmoen (8)	1969	Fatigue	(Experiments)	Welded specimens in mild and high tensile steel can be represented, approximately, by the same S-N curve.
Butler, Kulak (9)	1971	Static strength	(Experiments)	Transverse welds show about 44% strength increase over longitudinal welds but show a decrease in deformation capacity.
Clark (10)	1971	Static strength	(Experiments)	Strength of long joints and groups of fillet welds under eccentric loading is reported.
Kato (11)		Static strength of transverse fillet welds (F.E.M. analysis)	1) Direct stress on the tensile face of the weld is uniformly distributed. 2) Breaking will occur when the shear stress at a point of the fillet weld is: $\tau_{max} = \sigma_t/\sqrt{3}$ where σ_t = tensile strength of the welded metal.	From elastic solution, transverse fillet welds are 46% stronger than longitudinal fillet welds of the same size and length. Failure always occurred at the root of the fillet.
Maddox (12)	1975	Fatigue	Theory and experiments	Agreement between theory and experiments

found in 101 ships. Almost all of these were fatigue-crack initiated from the toe of fillet joint connecting internals to shell or deck plating, transverse members to shell plating and horizontal girders to bulkhead plating.

Other statistical studies made recently in the general area of the hull structural damages were reviewed and the following seven critical joints were identified:

1. Internals (longitudinal members) to shell plating.
2. Internals (longitudinal members) to strength-deck plating.
3. Primary transverse members to shell plating.
4. Horizontal girders to bulkhead plating.
5. Double bottom floor to inner bottom.
6. Double bottom girders to shell and inner bottom.
7. Face plates on deep web haunches.

These critical joints are also sensitive to fillet weld defects according to the statistical studies conducted by Nippon Kaiji Kyokai (Japan)[14], Newport News Shipyard (USA)[15] and Prof. Antoniou (Greece).[16]

2.2 Review of Static Strength of Fillet Welds

In order to study the effect of the direction of applied load on the strength of fillet welded joints, Butler and Kulak[9] conducted tests and analyzed resulting data.

The tests were conducted in four groups, each with the weld axis being inclined at angles of 0 (longitudinally loaded), 30, 60, and 90 (transversely loaded) degrees, respectively, to the direction of the applied load, (as shown in Figure 2.1) The material of the test specimens was CSA G40.12 which has a specified yield stress of 44 ksi and a minimum tensile strength of 62 ksi. AWS E60XX electrodes were used for welding the specimens.

Butler and Kulak chose to analyze their experimental data employing a load-deformation response for mechanical fasteners of the following form.

$$R = R_{ult} (1 - e^{-\mu\Delta})^{\lambda}$$

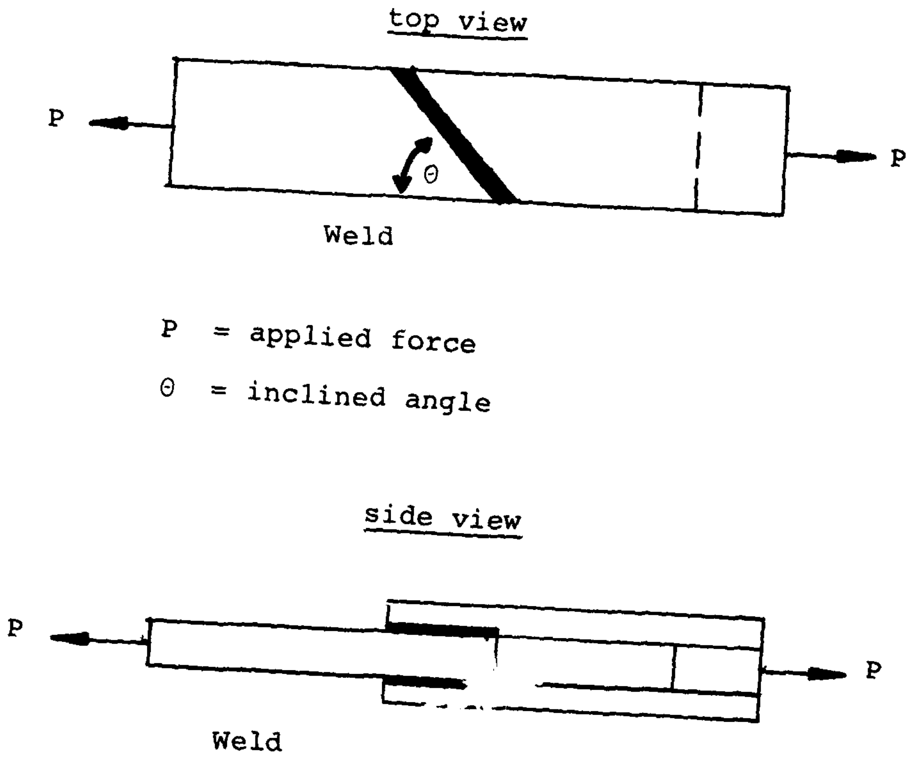


FIGURE 2.1 SCHEMATIC REPRESENTATION OF THE TEST SPECIMEN (9)

Where

R	=	fastener load at any given deformation
R_{ult}	=	ultimate load attainable by fastener
Δ	=	shearing, bending, and bearing deformation of fastener and local bearing deformation of the connected plates
μ, λ	=	regression coefficients
e	=	base of natural logarithms

Trial-and-error curvefitting of the experimental results was used to obtain the following expressions for the dependent variables in the equation. The inclined angle, θ, is the only independent variable to be given.

$$R_{ult} = \frac{10 + \theta}{0.92 + 0.0603\theta}$$

$$\Delta_{max} = 0.225\ (\theta + 5)^{-0.47}$$

$$\mu = 75\ e^{0.0114\theta}$$

$$\lambda = 0.4\ e^{0.0146\theta}$$

Where θ is the weld inclined angle to the direction of the applied load.

Readers are cautioned that these expressions were developed specifically for ¼ inch (leg size) fillet welds made with E60XX electrodes; and, therefore, care should be used before applying these to other size welds or welds using different electrodes.

Table 2.2 compares test results and predicted values for the ultimate load and the maximum deformation.

Figure 2.2 summarizes the results of load vs. deformation with respect to different inclined angles. The strength of the fillet welds tested increased approximately 44% as the angle of loads changed from zero degree (longitudinally loaded weld) to 90 degrees (transversly loaded weld); however, there was a substantial decrease in deformation capacity as the strength increased.

Kato and Morita(11) studied the strength of fillet welded joints theoretically by employing an approximate solution based

Group θ, deg	Ultimate load kips/in. Mean	Std. deviation	Maximum deformation, in. Mean	Std. deviation	Predicted values Ultimate load Kips/in.	Maximum deformation, in.
0	10.9	0.67	0.101	0.008	10.9	0.105
30	14.6	0.03	0.049	0.011	14.6	0.042
60	14.1	0.51	0.031	0.004	15.4	0.031
90	15.5	0.95	0.026	0.002	15.7	0.026

TABLE 2.2 TEST RESULTS AND PREDICTED VALUES (9)

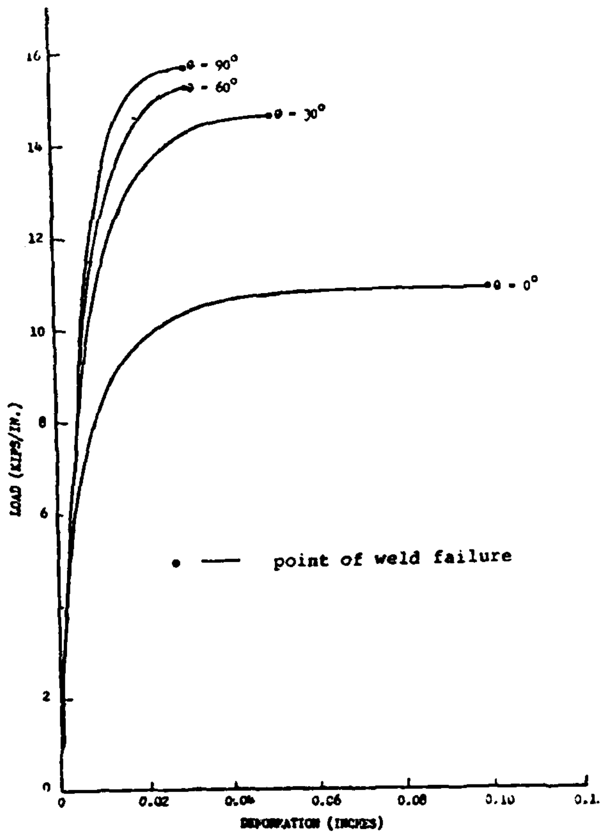


FIGURE 2.2 LOAD VS. DEFORMATION θ= 0° to 90° 1/4 in. FILLET WELDS (13)

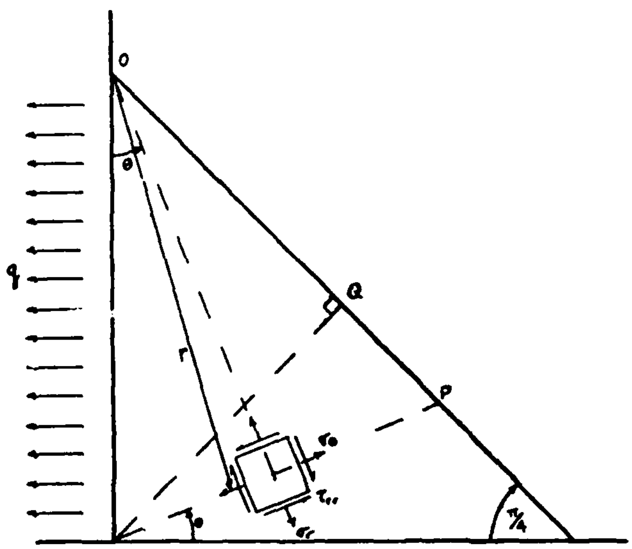


FIGURE 2.3 TRANSVERSE LV LOADED FILLET WELD (7)

on the theory of elasticity and supplemented this by an elastic-plastic strain-hardening analysis performed numerically using the finite-element technique. The approximate solution is based upon the following assumptions:

1. The direct stress (q) on the tensile face of the weld is uniformly distributed.

2. The pattern of the of the elastic stress distribution remains unchanged until the braking of the weld.

3. Breaking will occur when the shear stress at a point

of the fillet weld reaches

$$\tau_{max} = \frac{\sigma t}{\sqrt{3}}$$

where

σ_t = the tensile strength of the weld metal

4. The fillet weld has legs of equal size.

The model used for this study is shown in Figure 2.3. The maximum strength of a transversly loaded fillet weld was found to be:

$$T_{t,max} = 1.46\ A_W\ \tau_{max} = \frac{A_W\ \sigma_t}{\sqrt{3}}$$

The oblique plan RP ($\theta = \pi/8$) in Figure 2.3 is the fracture plane of a transversly loaded fillet weld and the throat RQ is the critical section of a longitudinally loaded fillet weld.

This indicates that transversly loaded fillet welds are 46% stronger than longitudinally loaded fillet welds of the same size and length.

2.3 Review of Fatigue Strength of Fillet Welds

It was reported (17) that the fatigue strength of a 5/16-inch fillet welded Tee-joint was reduced tremendously from plain-plate strength under certain types of loading and stress level. Table 2.3 shows the experimental data of such strength reduction.

Since fatigue strength is a major factor in fillet welds,

TABLE 2.3 FATIGUE STRENGTH OF FILLET WELDED TEE-JOINT UNDER CYCLIC LOADING (17)

	0 to Tension		Reversed	
	F100,000	F2,000,000	F100,000	F2,000,000
Plain Plate (A-7 steel)	47.8 ksi	31.7 ksi	26.8 ksi	17.5 ksi
Tee-Joint - 5/16" Fillet Welds, Failure in Welds	19.1 ksi	9.6 ksi	13.3 ksi	6.2 ksi

and it is difficult to alter the design to either avoid fillet welds or place fillet welds in areas of low stress, there is much interest in methods that may improve the fatigue strength of joints. The Welding Institute conducted experiments to determine the effect of peening and grinding on the fatigue strength of fillet welded joints.[18] The test pieces have non-load-carrying attachments fillet welded either parallel to or transverse to the direction of the applied stress. These specimens were fabricated in such a manner that the direction of stressing was parallel to the rolling direction of the material. Details of the test pieces appear in Figure 2.4.

To study the effect of peening, the samples were peened with a pneumatic hammer, fitted with a solid tool having a rounded end of approximately 1/2 inch diameter, that was moved along the toe of the weld at a speed of approximately 18 inches per minute. Usually, three runs of peening were required on each specimen to ensure that the whole length of the weld toe was subjected to the peening treatment.

Two types of local machining were also studied. The first consisted of grinding only at the weld toe. This grinding was carried out so as to ensure that the grinding marks were parallel to the direction of the stress. The second type of machining involved machining the whole weld to yield a concave profile and a smooth blend of the weld into the plate surface. The goal of this treatment was to obtain the maximum possible increase in strength that could result from machining.

During the testing, all specimens were axially loaded with one of the following stress cycles. Either the test piece was loaded under pulsating tension with a lower limit of zero or an alternating load causing minimum and maximum stresses equal in magnitude but opposite in sign. The criterion of failure was the complete rupture of the test piece.

Some of the samples were fabricated with welds around the ends of the gussets, while others were left with the ends unwelded. It was found that the fatigue strength of these two types of samples was the same for the non-load-carrying longitudinal fillet welds, and increased with both the peening treatment and local machining. The increase in strength grew larger as the life increased in the case of peening; whereas for the local machining operation, the increase was about the same for the whole range examined. The test results on the effects of grinding and peening for mild steel specimens with longitudinal and transverse gussets are shown in Figures 2.5 and 2.6, respectively.

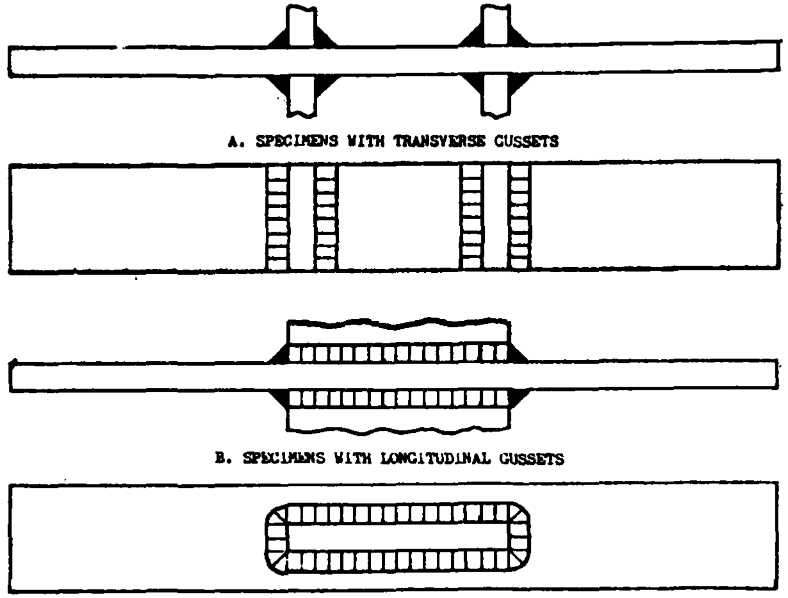


FIGURE 2.4 DETAILS FOR TEST SPECIMENS[18]

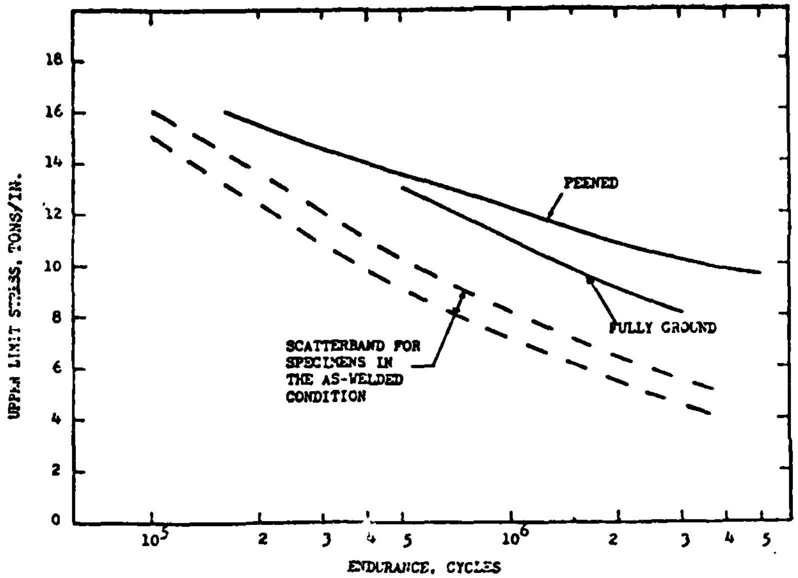


FIGURE 2.5 FATIGUE TEST RESULTS FOR MILD STEEL SPECIMENS WITH LONGITUDINAL GUSSETS SHOWING THE EFFECTS OF GRINDING AND PEENING.[18]

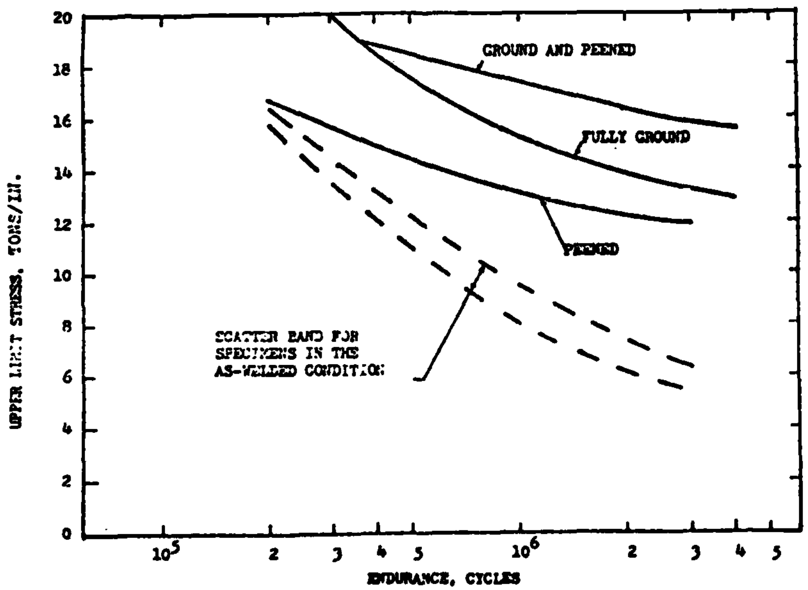


FIGURE 2.6 FATIGUE TEST RESULTS FOR MILD STEEL SPECIMENS WITH TRANSVERSE GUSSETS SHOWING THE EFFECTS OF GRINDING AND PEENING.[18]

In the tests employing pulsating tension, it was found that peening increased the fatigue strength by about 75%. With both pulsating tension and alternate loading, the full local grinding operation increased the fatigue strength by about 50% in all cases except that of mild steel specimens with transverse fillet welds which yielded nearly 100% improvement over the as-welded condition. Even though this is less of an increase than that obtained from peening, the difference in the slope of the S/N curves for peened and ground specimens accounts for the fact that grinding was found to be more effective than peening for tests in which the number of cycles was less than about 50,000. Full grinding of the test pieces with longitudinal fillet welds normally failed as a result of initiation at the root of the weld. In the case of light grinding at the weld toe, the improvement varied. This is assumed to be related to the fact that it is very difficult to control the degree of grinding. This technique, considered to be unreliable, is, therefore, not recommended. It is interesting to note that in tests performed on samples with transverse gussets, fully ground and also peened, fatigue strengths as high as the parent material could be obtained (Figure 2.6).

3. REVIEW OF STANDARDS

3.1 Review of Fillet Weld Specifications

For convenience, the following abbreviations have been used to represent various classification societies whose specifications are reviewed in this chapter:

L.R.	=	Lloyd Register
ABS	=	American Bureau of Shipping
GER.L.L.	=	Germanischer Lloyd
AWS	=	American Welding Society
AISC	=	American Institute of Steel Construction
D.N.V.	=	Det Norske Veritas
B.V.	=	Bureau Veritas
NKK	=	Nippon Kaiji Kyokai
USN	=	The United States Navy
USSR	=	Russian Classification Society

There are two measures of fillet weld strength extensively used in the various codes. One of them is based on the effective throat thickness (t), defined as the shortest distance from the root (A) to the face of the weld (Figure 3.1). Another one is based on the fillet leg (W) which, for an equal leg fillet weld, is equated to the throat thickness by

$$W = \sqrt{2} \cdot t$$

All the rules of the various classification societies give the minimum required weld size by fillet leg (W) or throat thickness (t).

The fillet leg or throat thickness is given as a function of the plate thickness of the attached members as well as its position in the ship structure. The latter reflects the different loading conditions to which the attached members are subject due to their position.

Some of the codes put limits on weld leg size as well as some allowances (for example, corrosion allowance) or restictions (for example, maximum permissible gap). As will be discussed later, ABS incorpoated a corrosion margin of 1.5 mm (0.059 inch) in throat thickness when they changed their requirements on fillet weld size from intermittent to continuous weld. ABS rules have also incorporated the corrosion margin in the base plate thickness requirements.

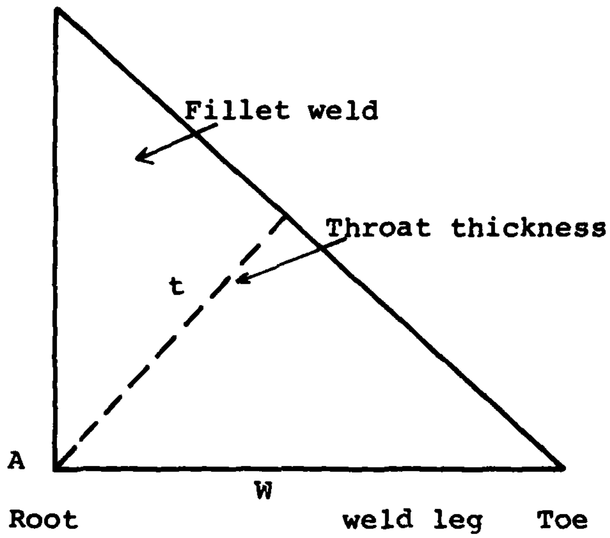


FIGURE 3.1 DEFINITION OF BASIC PARAMETERS IN FILLET WELDS

The fillet size requirements specified by ten major classification societies, the US Navy and the Structural Steel Designer's Handbook are summarize in Table 3.1. The 1977, or earlier editions, of the classification societies were used for these comparisons.

In order to compare the various rules, the required throat thickness for double continuous welds is plotted against the plate thickness (thinner of the two plates joined by the fillet) with respect to the location of the most common applications of structure members up to 24 mm thickness in Figures 3.2a through 3.2j. It is seen that the highest value is more than twice that of the lowest. The plots of fillet sizes also show dramatically the variation among the various classification society rules and suggest opportunity for rational improvement.

Investigation of the reasons for the differences in fillet sizes among the major ship classification societies was not too successful. Many of the welding specifications were developed many years ago and the history of their development was not well documented.

3.2 Corrosion Considerations

In designing welded joints of ships, for general corrosion, a method commonly used to ensure a proper design is the use of corrosion margin. The U.S. Navy specifications do not require a corrosion margin; however, ABS specifications have a corrosion margin built into the requirements for plate thickness and automatically provide one for the fillet welds because the sizes of fillet welds are based on plate thickness.

Special protective coatings have been used as an alternative for corrosion margin by some ship classification societies. However, this corrosion margin can not be taken as the allowable reduction in either plate thickness or fillet size.

Plate materials tend to corrode more than weld materials as far as usual combinations of plate materials and weld materials are concerned. The corrosion rate of ordinary ship hull steels in sea water is, according to Professors H.H. Uhlig and R.M. Latanission of M.I.T., roughly 0.005 inch per year. Since this rate decreases due to a build-up of oxides on the surface, normally a rate of 0.003 or 0.004 inch per year is used for a period of ten years. If a corrosion margin or 1.5 mm is imposed on a welded plate, a service life of approximately 20 years can be obtained. Since most surfaces on a ship that are exposed to sea water or bilge water are maintained so that some form of protective coating is kept intact most of the time, the corrosion margin of 1.5 mm is considered sufficient

TABLE 3.1 SUMMARY OF FILLET WELD SPECIFICATIONS

	WELD SIZE	W_{min} (mm)	gap_{max}	Increase due to gap	σ_{allow}	
ABS	$\left.\begin{matrix} w \\ t \end{matrix}\right\} = f\begin{pmatrix} t_{plate} \\ minimum \end{pmatrix}$	4.5	2_{mm} $\left(\frac{1''}{16}\right)$	IF $2 < gap < 5mm$ $\left(\frac{1''}{16}\right)$ $\left(\frac{3''}{16}\right)$ increase leg size by opening	No mention	ABS allows reduction in fillet size for deep penetration weld.
Det Norske Veritas	$t = f(t_{plate})$	5	No ment.	No ment.	No	In the cargo & ballast tanks some connections can be reduced by 5 mm in excess of the minimum required (3 + 1.t)mm or 6 mm which even is less if an effective corrosion protection is applied
Bureau Veritas	$t = f\begin{pmatrix} t_{plate} \\ minimum \end{pmatrix}$	5	No	No	No	Where deep penetration is used, reduce throat depth up to 15%
German Lloyd	$t = f\begin{pmatrix} t_{plate} \\ minimum \end{pmatrix}$ $t_{min} > .4\,t_{max}$	No	No	No	No	
Lloyd Register	$t = f\begin{pmatrix} t_{plate} \\ minimum \\ 3\ 5mm \end{pmatrix}$ t>.21tor<hand 3mm autom. deep penetr.	No	No	No	No	With automatic, deep penetration welds may be reduced by 15%
Taiwan Register	$w = f\begin{pmatrix} t_{plate} \\ minimum \end{pmatrix}$	No	No	No	No	Not excessive deposit of weld is permitted (oversize)
N.K.K.	$w = f\begin{pmatrix} t_{plate} \\ minimum \end{pmatrix}$	No	No	No	No	Undersized fillet welds can be considered if weld length is less than 10%
Registro Italiano	$w = f(t_{plate})$	4 ÷ 4.5mm for $t \leq 6mm$ 5mm for $t \geq 6mm$	No	No	No	
A.W.S.	$w = f\begin{pmatrix} t_{plate} \\ maximum \end{pmatrix}$	No	No	No	No	Fillet welds in any single continuous weld should be permitted to be undersized by 1/16" without correction provided that the undersized weld doesn't exceed 10% of the length of the weld.

TABLE 3.1 SUMMARY OF FILLET WELD SPECIFICATIONS (CONTINUED)

	WELD SIZE	MINIMUM LEG LENGTH, w	gap max	INCREASE DUE TO GAP	c_{allow}
USSR Register of Shipping	$w = \alpha\ \beta\ T_1$ α: weld strength factor (depends on structural item) β: factor determined from the type of weld	3 mm	no	no	no
U.S. Navy	$w = \frac{e\ T_1\ R_1}{1.414\ R_2}$ e : weld efficiency T_1: thickness of weaker member R_1: UTS of weaker member R_2: shear strength of weld deposit	no	no	no	no
Structural Steel Designer's Handbook	$w = \frac{1.411\ R_1\ T_1}{R_2}$ for tension $w = \frac{1.414\ R_3\ T_1}{R_2}$ R_3: shear strength of base metal	1/8 inch for building, 3/16 inch for bridge	no	no	no

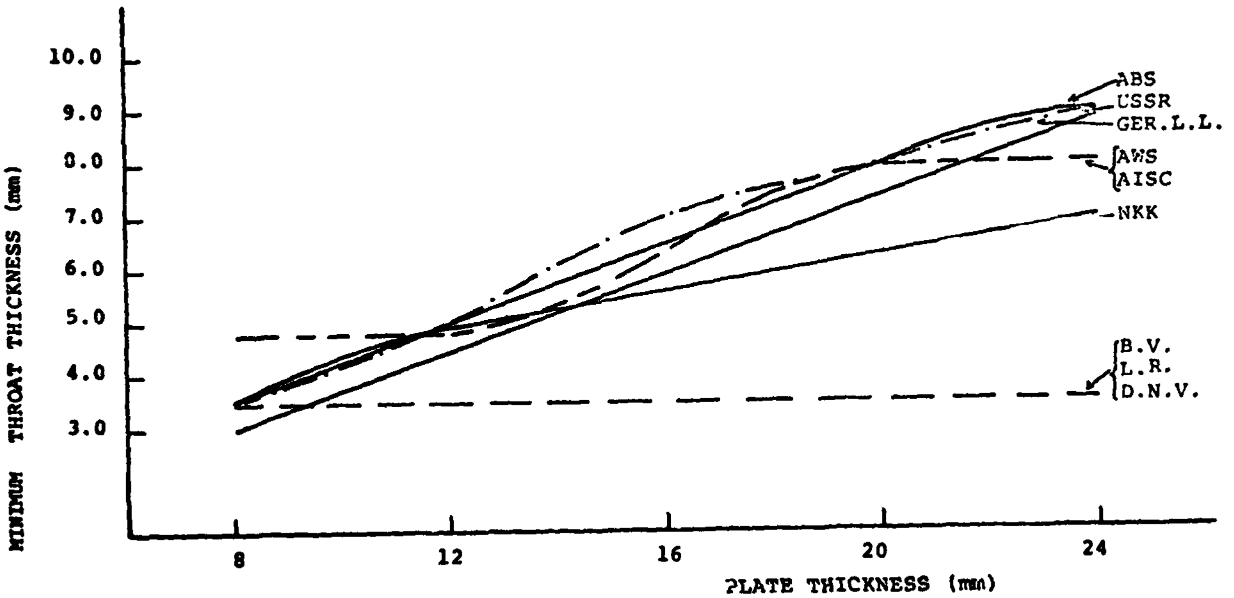


FIGURE 3.2a CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN DOUBLE BOTTOM FLOOR AND SHELL PLATING (LONG'L FRAMING)

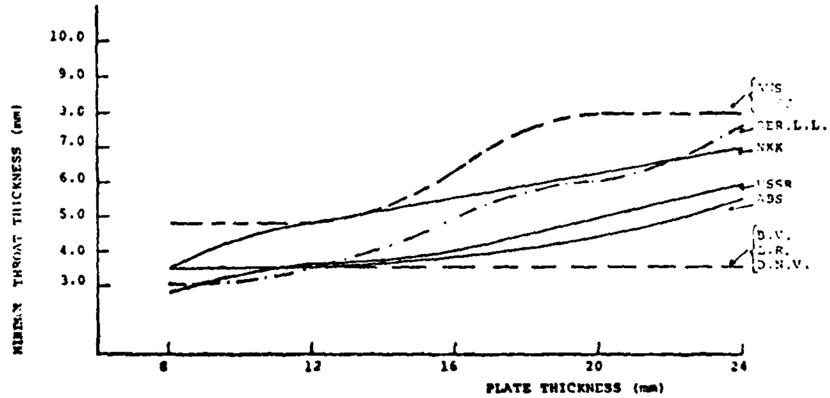


FIGURE 3.2b CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN DOUBLE BOTTOM SIDE GIRDERS AND INNER BOTTOM

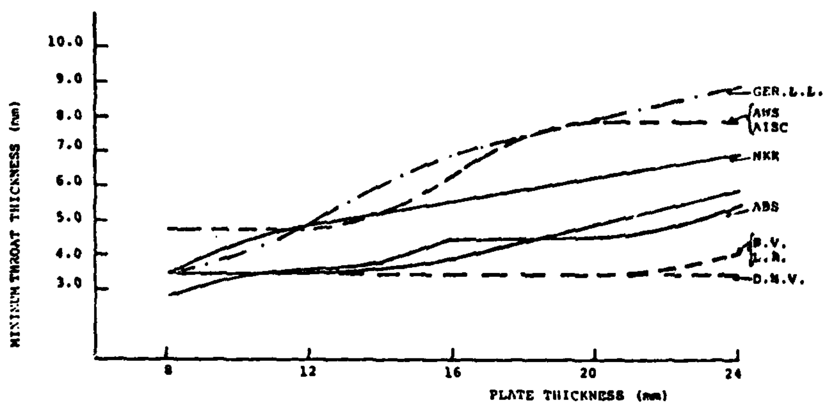


FIGURE 3.2c CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN WEB FRAMES AND SHELL PLATING

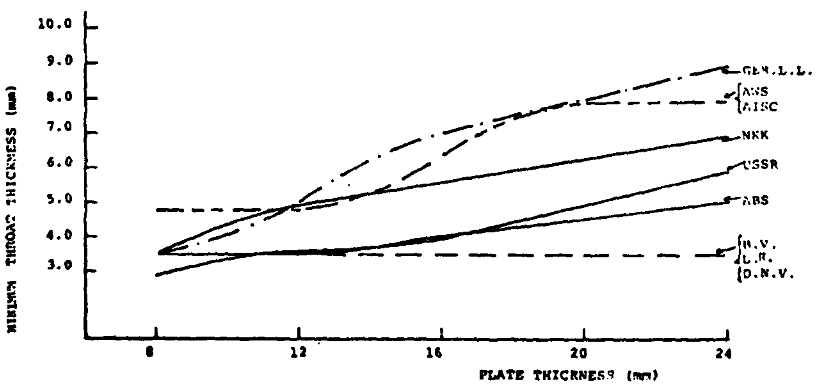


FIGURE 3.2d CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN STIFFENERS AND NON-TIGHT STRUCTURAL BULKHEADS

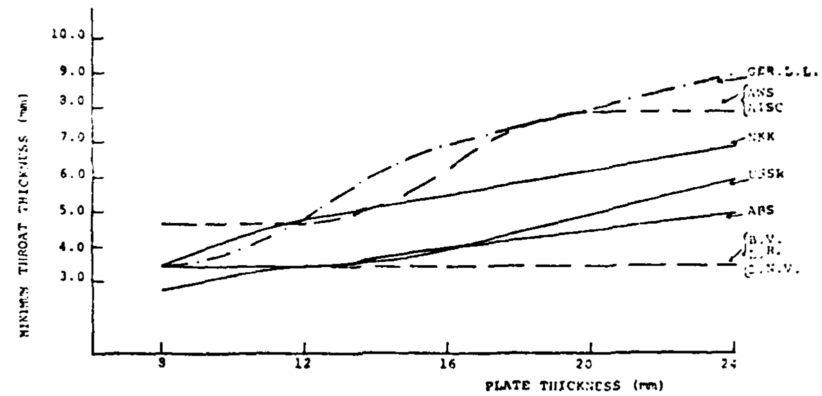


FIGURE 3.2e CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN BEAMS AND DECK

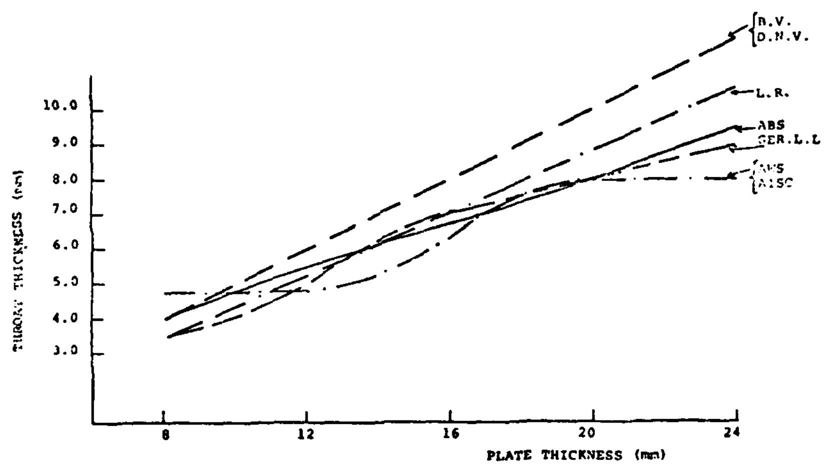


FIGURE 3.2f CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN HATCH COVER STIFFENERS AND WEBS, END ATTACHMENT

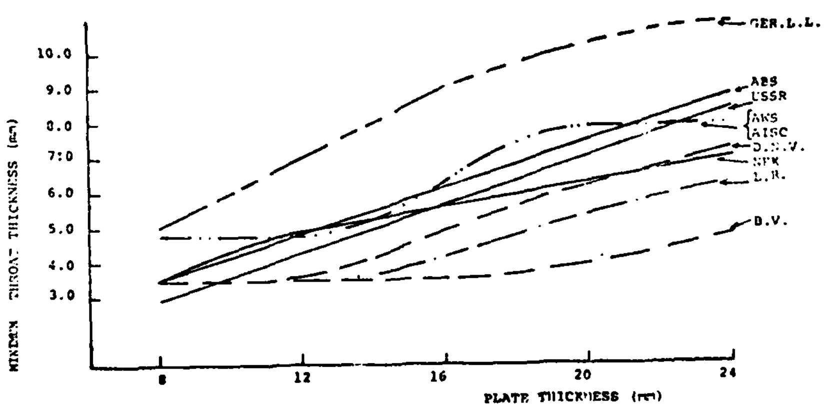


FIGURE 3.2g CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN CENTER GIRDER AND KEEL

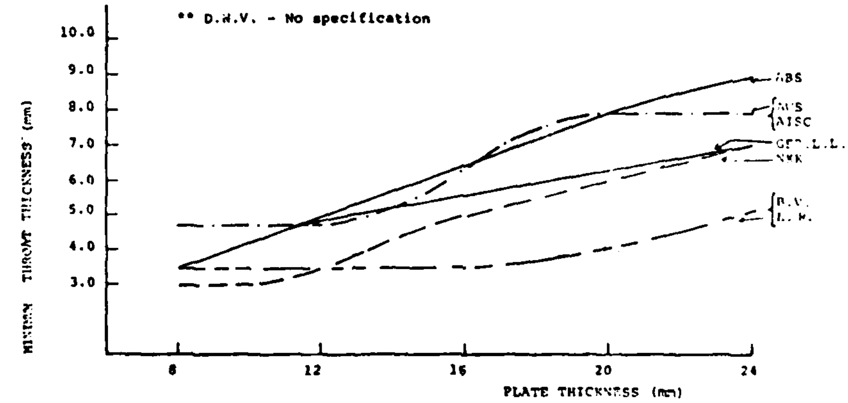


FIGURE 3.2h CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN DECK AND SHELL PLATING

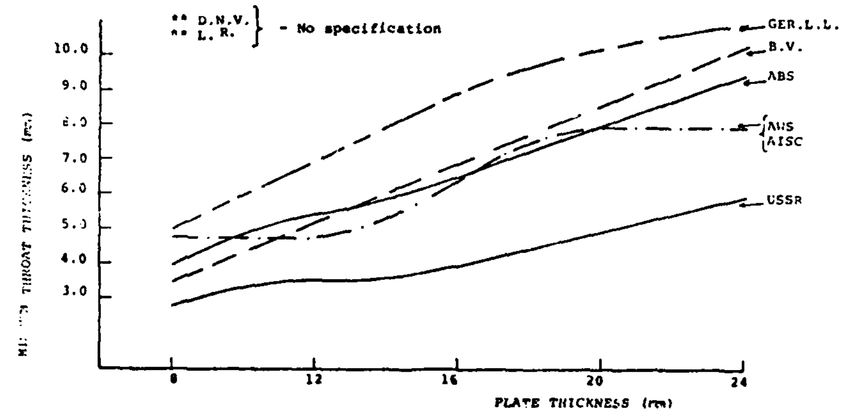


FIGURE 3.2i CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN FOUNDATIONS OF MAIN ENGINE AND SHELL, TOP PLATE OR INNER BOTTOM

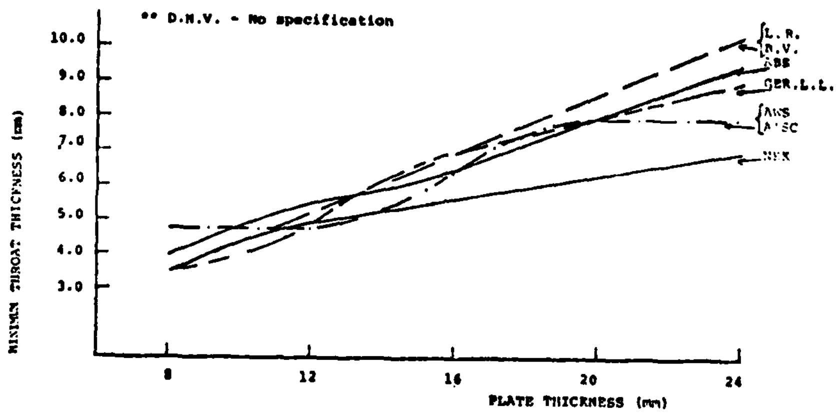


FIGURE 3.2j CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN RUDDER JOINTS ON THE MAINSTOCK

for steel weld joints in a sea water environment.

3.3 Fabrication Limits

Metallurgical restraints impose a minimum size of fillet welds. To decrease a weld specification below 3/16 inch (leg size) would be unrealistic because it is too small for welding practice.

There are occasions in which fillet welds made under optimum welding conditions tend to be slightly undersized, as shown in Figure 3.3. It is a common attitude for an inspector to reject these slightly undersized fillet welds. In many cases, two or more passes of weld metal must be added to satisfy the requirements. It is usually, in this case, impractical (if not impossible) to add only a small amount of weld deposit. The weld is always overwelded, as shown in Figure 3.3b. This not only wastes time, labor, and material, but also creates more distortion which causes more fabrication errors in other joints. This kind of waste can be reduced by allowing some undersized welds, if the structural integrity of a ship is not impaired. Distortion can also be reduced by not adding more weld material to the joints.

The maximum gap requirements and the allowable convexity for fillet welds specified by the U.S. Navy is discussed in Section 3.4. ABS rules have the same maximum gap requirement but do not require the maximum allowable convexity. Other classification societies do not mention requirements for either gap or convexity.

3.4 Review of U.S. Navy Welding Specifications

The U.S. Navy welding specifications are presented in a different format than the other standards discussed in the previous section. The required weld sizes are presented in graphical form of a plot of plate thickness versus joint efficiency.* Different plots are presented for each different combination of construction materials and electrodes used, and types of welded joints. Rather than use a different graph for various joint locations in the ship, the Navy specifications for joint efficiency include the factor of joint locations. A partial listing of the required joint efficiency is given in Table 3.2. For a complete listing, see reference 19.

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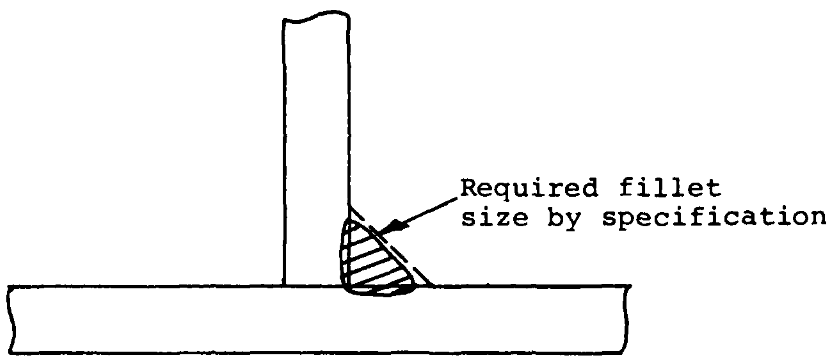
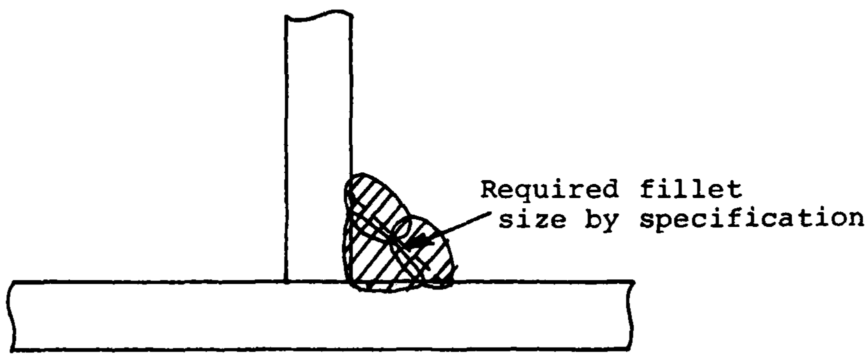
* Joint efficiency is defined as the ratio of ultimate strength of weld deposit to ultimate strength of base material.



a. Slightly Undersized Fillet Weld



b. Overwelded Fillet Joint as a Result of Additional Welding Two Passes

FIGURE 3.3 UNDERSIZED AND OVERWELDED FILLET JOINT

TABLE 3.2 REQUIRED USN JOINT EFFICIENCIES FOR VARIOUS FILLET WELDED JOINTS[19]

Item	Connection	Joint Efficiency (Per Cent)
Bilge Keels	Connections to shell	75
Bulkheads, Longitudinal and Transverse	Main subdivision bulkheads	100
Decks and Platforms	Longitudinal	75
	Transverse	
	With deck on only one side	75
	With deck on both sides	100
	Shell and interbottom	75
Foundations	Gun Foundations	100
Framing, Longitudinal and Transverse	Connections to flanges or faceplates around lightening holes End connections to intersecting members	75
	Ordinary frames (less than 24-inches in depth)	100
Masts and Booms	All joints	100
Piping Penetrations	Shell plating and supports	100
Vertical Keel	Connections to flat keel and rider plate	75

One example of the Navy welding specifications is shown in Figure 3.4. The graph is plotted for a continuous, double-fillet welded tee-joint made of medium steel (U.T.S. 60,000 PSI) using MIL-6011 electrodes.

Comparisons of the U.S. Navy specifications to other welding standards for required weld size versus plate thickness for joints between double bottom floors and shell plating, between web frames and shell plating, and between decks and shell plating can be seen in Figures 3.5, 3.6, and 3.7, respectively. While Germanischer Lloyd is the most conservative, followed by the American Bureau of Shipping and the U.S. Navy, Bureau Veritas, Lloyd Register and Det Norske Veritas are the most liberal. Also, it is very apparent that there is a wide range between the most conservative rules and the most liberal rules. In fact, there is over a factor of two difference in some cases. This difference may not be as large as it seems because the specifications may be based upon slightly different models or include or exclude different considerations. For instance, one may include a corrosion allowance and another may tell the designer to add on a margin in addition to what is required by the chart.

The U.S. Navy specifications have the same maximum gap requirements as that required by ABS specifications. The maximum gap that is allowed without increasing the weld size is 1/16 inch. If the gap is greater than 1/16 inch, the required weld size is equal to the normal required size plus the gap. The maximum permitted gap even with increasing the weld size is 3/16 inch.

The U.S. Navy specifications also limit the maximum allowable convexity for fillet welds which varies with the weld size as shown in Figure 3.8.

The tolerance on fillet weld size is as follows[19]: "Fillet welds up to and including 3/8-inch size shall not vary below the specified size by more than 1/16 inch, and any such variance shall not extend for a total distance greater than 1/4 of the joint length nor for more than 6 inches at any one location. Fillet welds, 7/16-inch size and larger, shall not be less than the gage limits for their respective sizes."

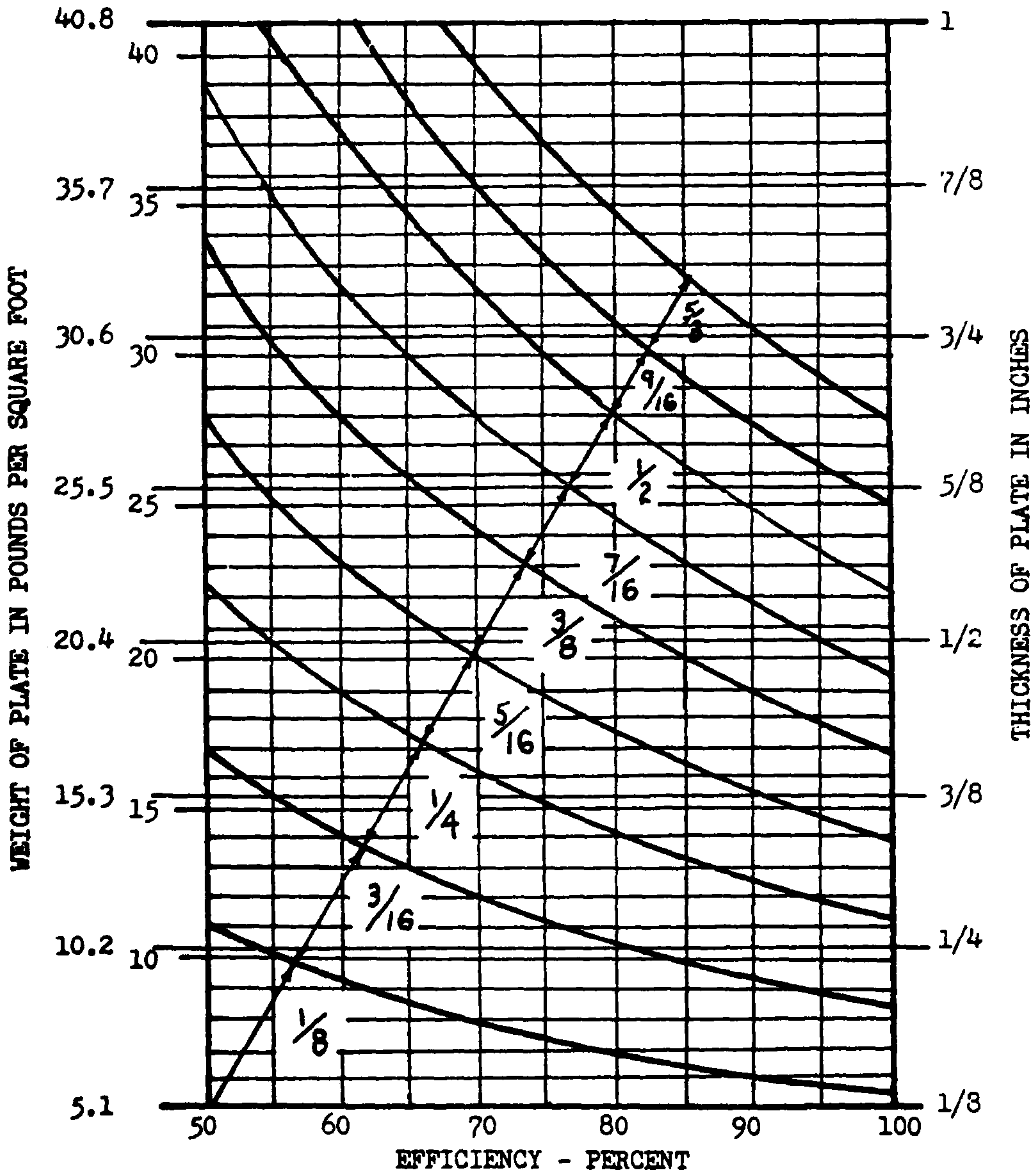


FIGURE 3.4 EFFICIENCY CHART FOR CONTINUOUS DOUBLE-FILLET WELDED TEE JOINTS MADE BETWEEN MEDIUM STEEL WITH MIL-6011 ELECTRODES[19] BASED ON THE THINNEST OF THE TWO PLATES JOINED

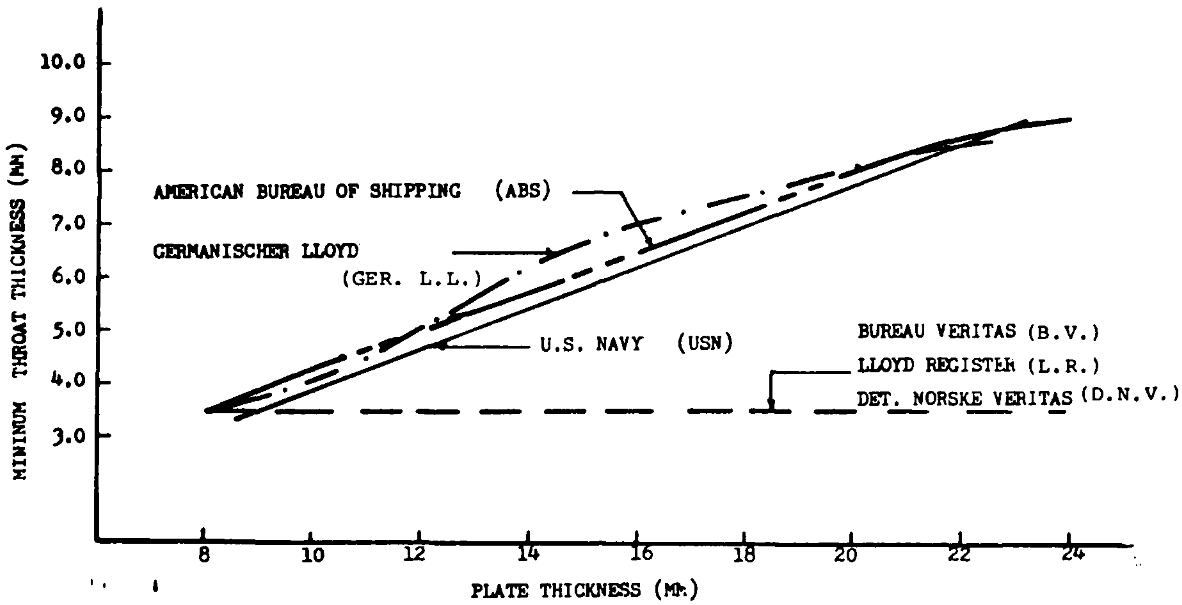


FIGURE 3.5 CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN DOUBLE BOTTOM FLOORS AND SHELL PLATING

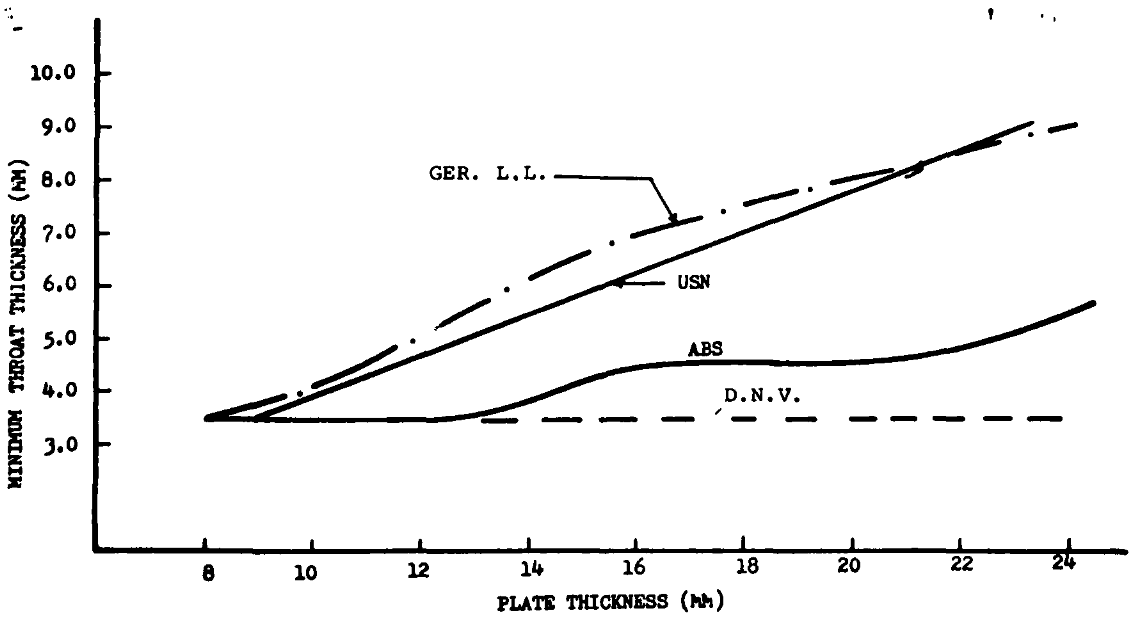


FIGURE 3.6 CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN WEB FRAMES AND SHELL PLATING

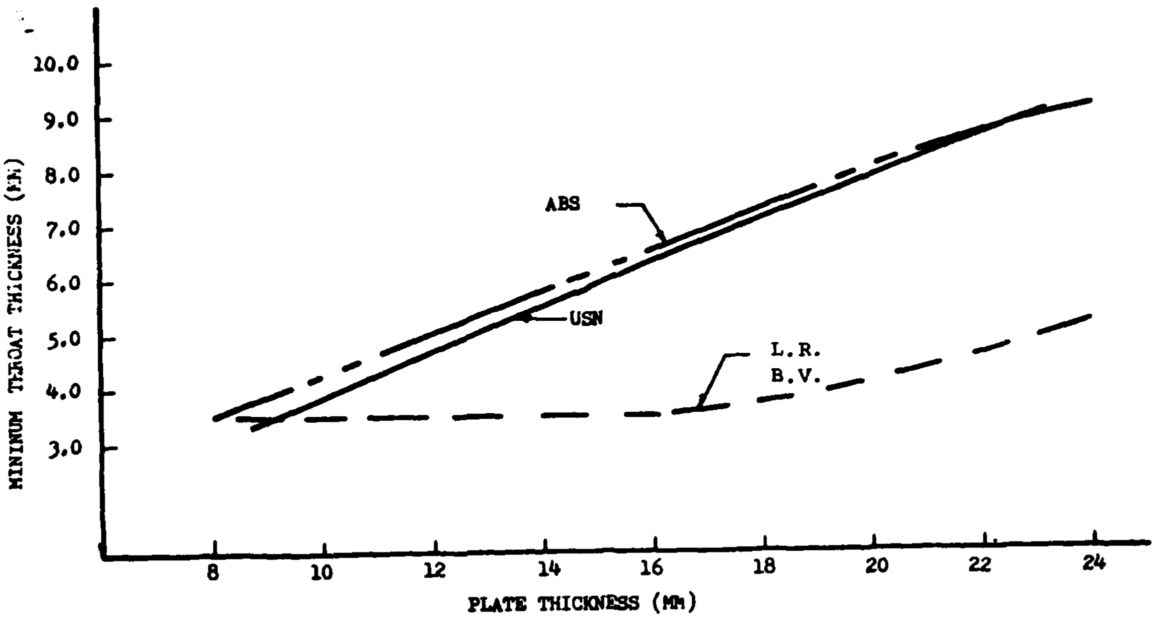


FIGURE 3.7 CURRENT WELDING REQUIREMENTS FOR JOINTS BETWEEN DECKS AND SHELL PLATING

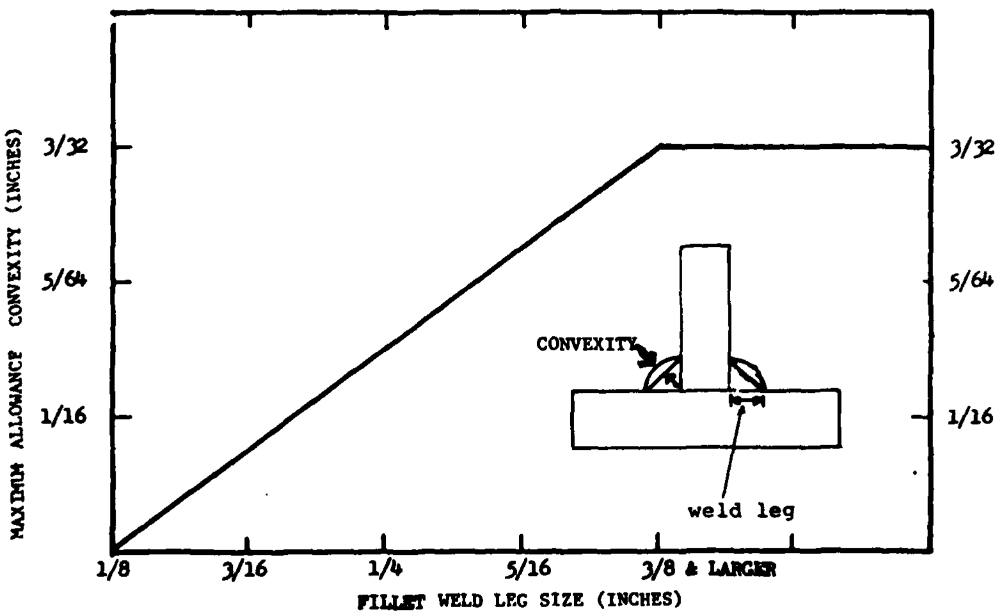


FIGURE 3.8 MAXIMUM ALLOWABLE CONVEXITY FOR FILLET WELD SIZES (19)

4. DEVELOPMENT OF ANALYTICAL METHOD

To study the stress details in the welds of a fillet joint, either a photoelastic analysis or mathematical stress-strain analysis, can be used. With complex structures such as ships, thousands of combinations of different types of joints and their applied loads may exist. The photoelastic analysis is not practical to apply to all joint-load combinations in a ship. For this reason, mathematical stress-strain analysis is considered a more useful and effective means for calculating stresses in fillet welds.

4.1 Analytical Method

A finite-element computer program, named "Automatic Dynamic Incremental Nonlinear Analysis (ADINA)", was used to develop the tool for reviewing the currently existing fillet weld specifications.

Program ADINA, a general purpose finite-element computer program for linear and non-linear, static and dynamic, three dimensional analysis, is an out-of-core solver, i.e., the equilibrium equations are processed in blocks, and very large finite-element systems can be considered. Also, all structure matrices are stored in compact form, i.e., only non-zero elements are processed, resulting in maximum system capacity and solution efficiency.

Inputs in the program are the joint dimensions and geometries, coordinates of each node, applied loads, boundary restraints and material properties, such as Young's modulus E, tangent modulus E_t (for the case of strain hardening), yield stress σ_t and Poisson's ratio υ, of the base material and weld deposit.

The outputs from the computer analysis are the stress distribution over the fillet weld, displacements in every nodal point and strain conditions (elastic or plastic) of the stressed areas under certain external loads.

Figure 4.1 shows the general solution procedure of the ADINA program.

4.2 Method for Determining Minimum Fillet Weld Sizes

To determine the minimum fillet weld sizes, either allowable design stress intensities or the strain conditions in weld have to be integrated in the analytical steps of ADINA programming. The fillet joint dimensions and geometry can be obtained from actual drawings of ships. Figure 4.2 shows the working process of how the computer program determines the minimum fillet weld sizes if all required information is known.

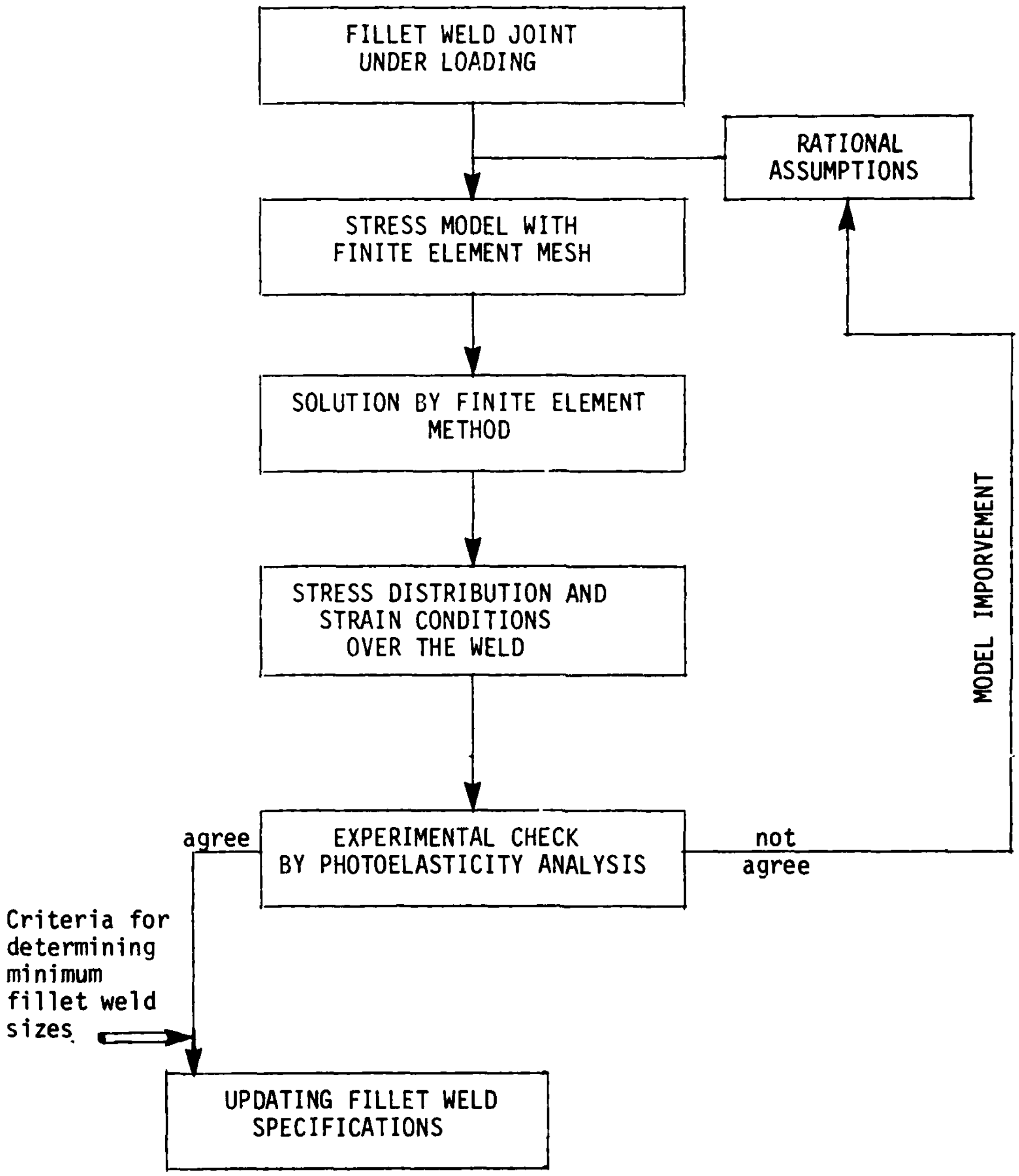


FIGURE 4.1 GENERAL SOLUTION PROCEDURE OF THE ADINA PROGRAM

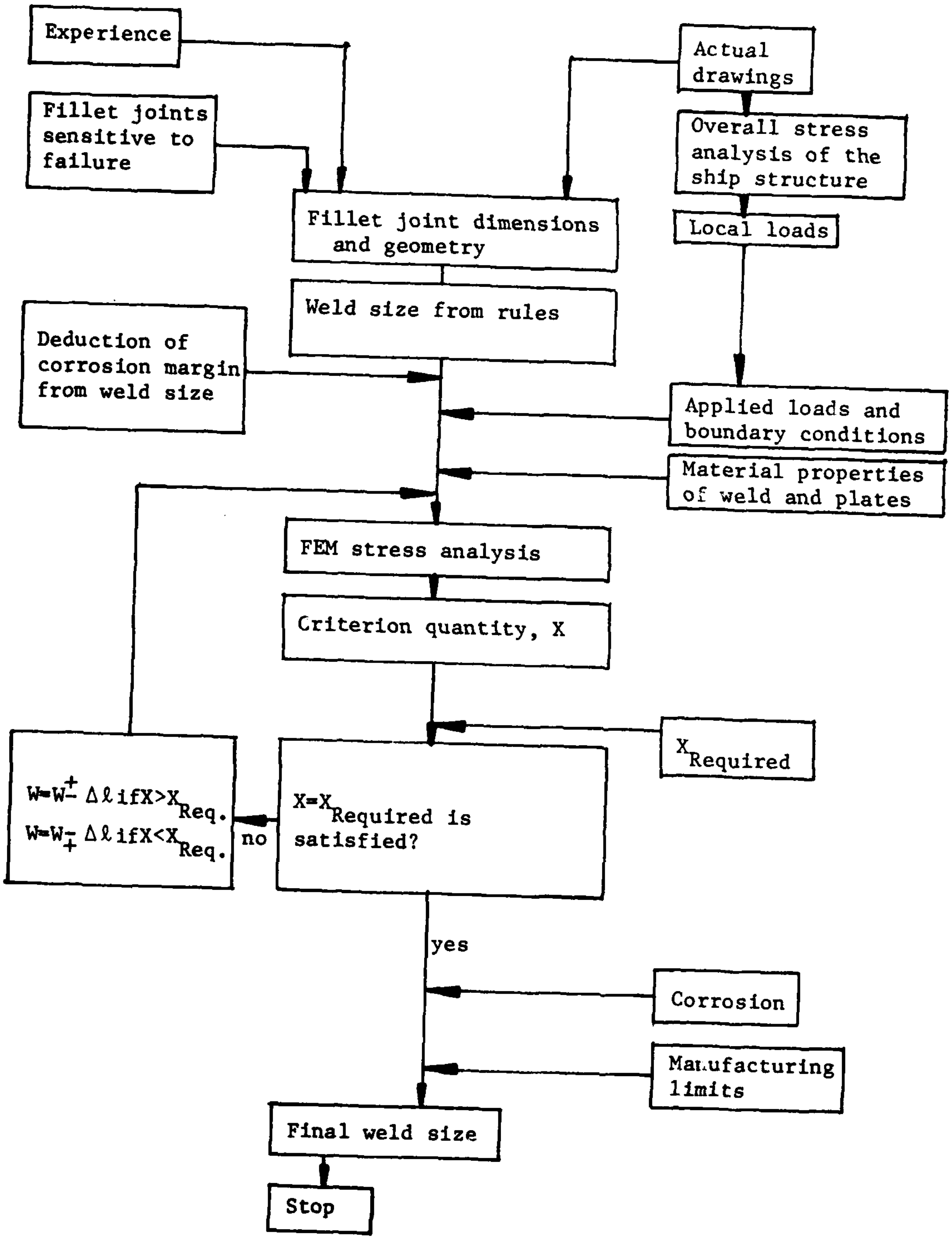


FIGURE 4.2 PROCESS FOR DETERMINING MINIMUM FILLET WELD SIZE

Overall stress analysis of the ship structure using either theory of structures or finite-element stress analysis must be performed to obtain the local loads acting on the joint. The boundary conditions supporting the edges of the cut-off joints are also essential factors in the analysis and have to be rationally assumed.

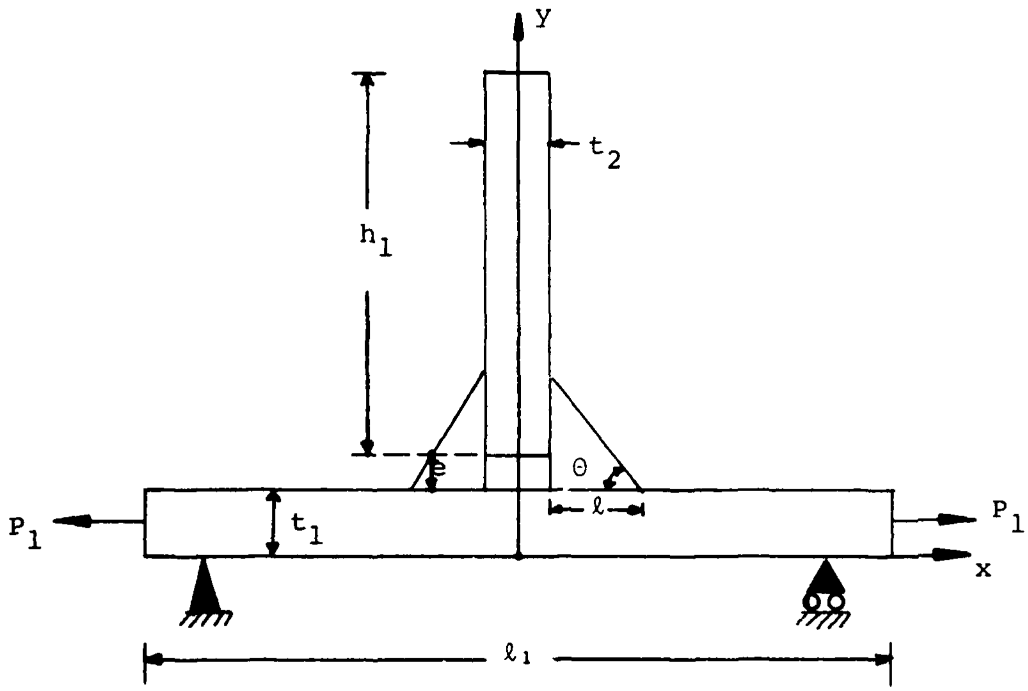
A criterion is required in the analysis for determining the minimum weld sizes. Let X be designated as a criterion quantity such as yielding, and $X_{required}$ as the critical quantity. If X is not equal to $X_{required}$, the fillet weld size may be reduced or increased by an amount of $\Delta \ell$ and a new weld dimension is formed. The iterative process then begins until the situation of $X=X_{required}$ is reached. The size of fillet welds resulting from this iterative process is the theoretical minimum size required under certain applied loading conditions. Corrosion margin may be added to this theoretical weld size. The final fillet weld size is then checked by the manufacturing limits caused by metallurgical or operational considerations. For example, the smallest welds that can be made by the available welding process or the minimum required weld sizes for preventing cracking due to rapid cooling.

4.3 Mathematical Modeling and General Yielding Criterion

Due to the overall geometry of ships, the local details of a tee-joint may be analyzed in accordance with the types of loading which are either longitudinally effective or transversely effective. In some cases the longitudinal and transverse structures interact, such as the corner welds of a panel structure, so that a three-dimensional model must be used. In other cases it is possible to isolate the longitudinal effects from a transverse structure, treating them as boundary conditions, and deal only with the transverse joints. In such a case, a two-dimensional analysis may be applied.

A two-dimensional analysis for a tee-joint under simple tension acting on the flange was used to check the validity of the ADINA program and to modify the program for general applications of the fillet weld strength analysis. Figure 4.3 shows the mathematical model of a tee-joint under simplified loading condition.

The joint with tension on the flange shown in Figure 4.3 may represent a tee-joint in the floor of midship section, midway between the stiffeners but with only ship hull girder stress which is uniformly distributed (approximately) across the flange thickness.



e = gap between the web and the flange

Θ = angle of fillet weld with x axis

ℓ = fillet leg size

h_1 = web height

ℓ_1 = length of flange

t_1 = flange thickness

t_2 = web thickness

FIGURE 4.3 MATHEMATICAL MODEL OF A FILLET WELDED TEE-JOINT UNDER TENSILE LOAD ACTING ON THE FLANGE

A criterion $X_{required}$ is needed for determining the minimum weld sizes in ADINA analysis. In this research, a general yielding concept was developed. This is to use the general yielding condition along the weld leg as a determining factor.

The criterion of general yielding is defined by

$$X = X_{required}$$

where

$$X = \frac{\text{Length of yield plastic zone along the weld leg}}{\text{Weld leg size}} = \frac{\ell_\rho}{\ell}$$

The required yielding criterion is assumed to be 1.

To illustrate the concept of general yielding criterion numerically, a calculation was conducted for a tee-joint shown in Figure 4.3 with rough mesh sizes.* Since the joint is symmetrical, only half of the joint was analyzed.

Figure 4.4 shows half of the tee-joint with finite-element meshes. The dimensions of the joint are assumed as follows:

Length (ℓ /2)	= 800 mm
Plate 1 thickness (t_1)	= 18 mm
Plate 2 thickness (t_2)	= 10.5 mm
Web height (h_1)	= 300 mm
Fillet weld leg (ℓ)	= 5 mm
Root gap (e)	= 1.59 mm

The applied boundary conditions are as follows:

(i) Clamped, across face A

(ii) Simply supported, at point B

Since the stress-strain relationship above the yield point depends on the history of loading, the loading function of applied tension on the joint flange is assumed to have 36 step increments. The load increases from 0 to 50 Kgr/mm^2, as shown in Figure 4.5.

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* Rough mesh size was used in this test run because the accuracy of results was not important and the purpose of this run was merely to demonstrate the concept of general yielding.

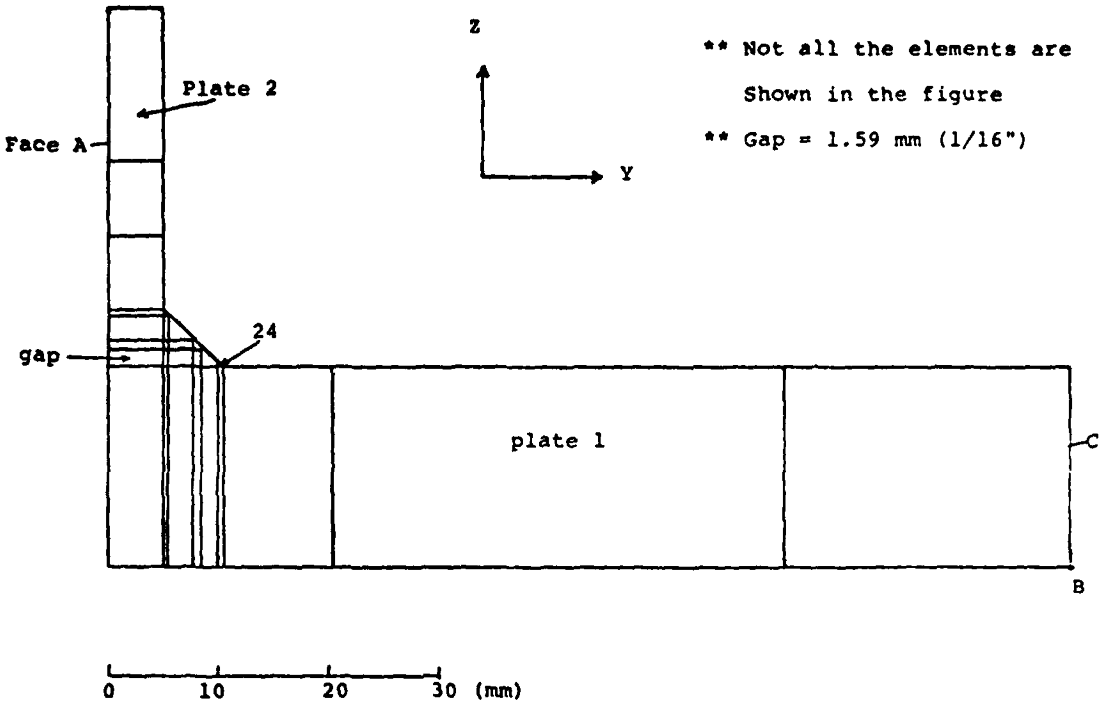

FIGURE 4.4 FINITE ELEMENT MESH FOR TEST RUN

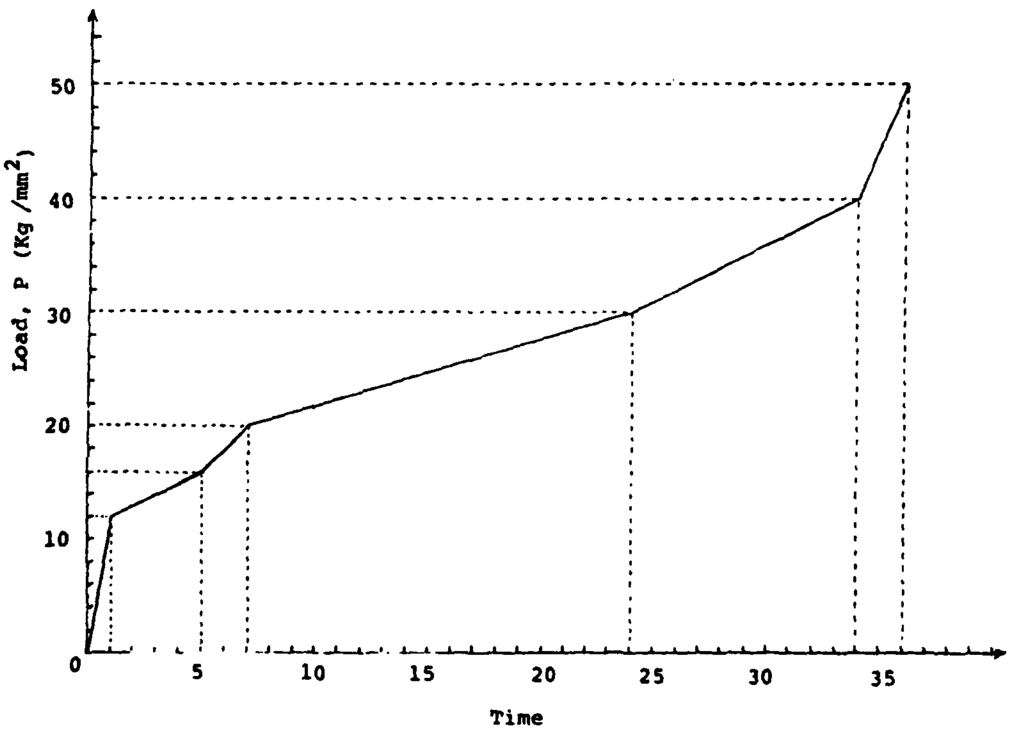

FIGURE 4.5 LOADING FUNCTION FOR TEST RUN

The variable finite-element mesh consists of 33 elements and 48 nodes. The mesh is finer near the root and toe due to possible stress concentrations in these areas.

Assume that the material properties of base plates and weld metal are the same. They are:

$$E = 21{,}000 \text{ Kgr/mm}^2$$

$$\sigma_y = 21 \text{ Kgr/mm}^2$$

$$\nu = 0.3$$

$$E_t = \frac{1}{40} E$$

The analysis is an elastic-plastic, 2-D, plain-strain analysis, using the Von-Mises yield criterion, with a linear strain hardening. As the load starts to increase, all elements are in the elastic region. At some load level, some elements go into the plastic region. The results of the analysis are shown in Figure 4.6. The shaded lines give the elements that become plastic at a given time step.

Hence, at time step 2 (corresponding to a load of 15 Kgr/mm^2), the small element n$^{\underline{o}}$ 24 at the toe of the fillet is plastic (given by vertical lines). Then at time step 5, the next element becomes plastic and so on.

So, for each time step (corresponding to a given applied load), the portion of the fillet weld leg which is in the plastic region can be found. At time step 2, for example, 10% of the fillet weld leg is plastic, or using the definition of X, X=10%. Similarly, at time step 5, X = 20%, at time step 9, X = 40%, and so on, For a given load, as long as X is less than $X_{required}$ the fillet size can be reduced and the iteration process continues until the condition of X = 1 is reached.

In the above example, the state of X = 1 happened at time step 14, with an applied load of approximately 25 kgr/mm^2.

It is interesting, physically, to examine how the plastic zone progresses. First, plasticity appears in the toe element due to high stress concentration (of the order of 1.5). The next element which goes to plastic region is the one next to the toe element. Then, plasticity appears in the root of the fillet. This observation may be a good explanation of the statistical results which indicated that the fatigue crack always initiated from a fillet toe.

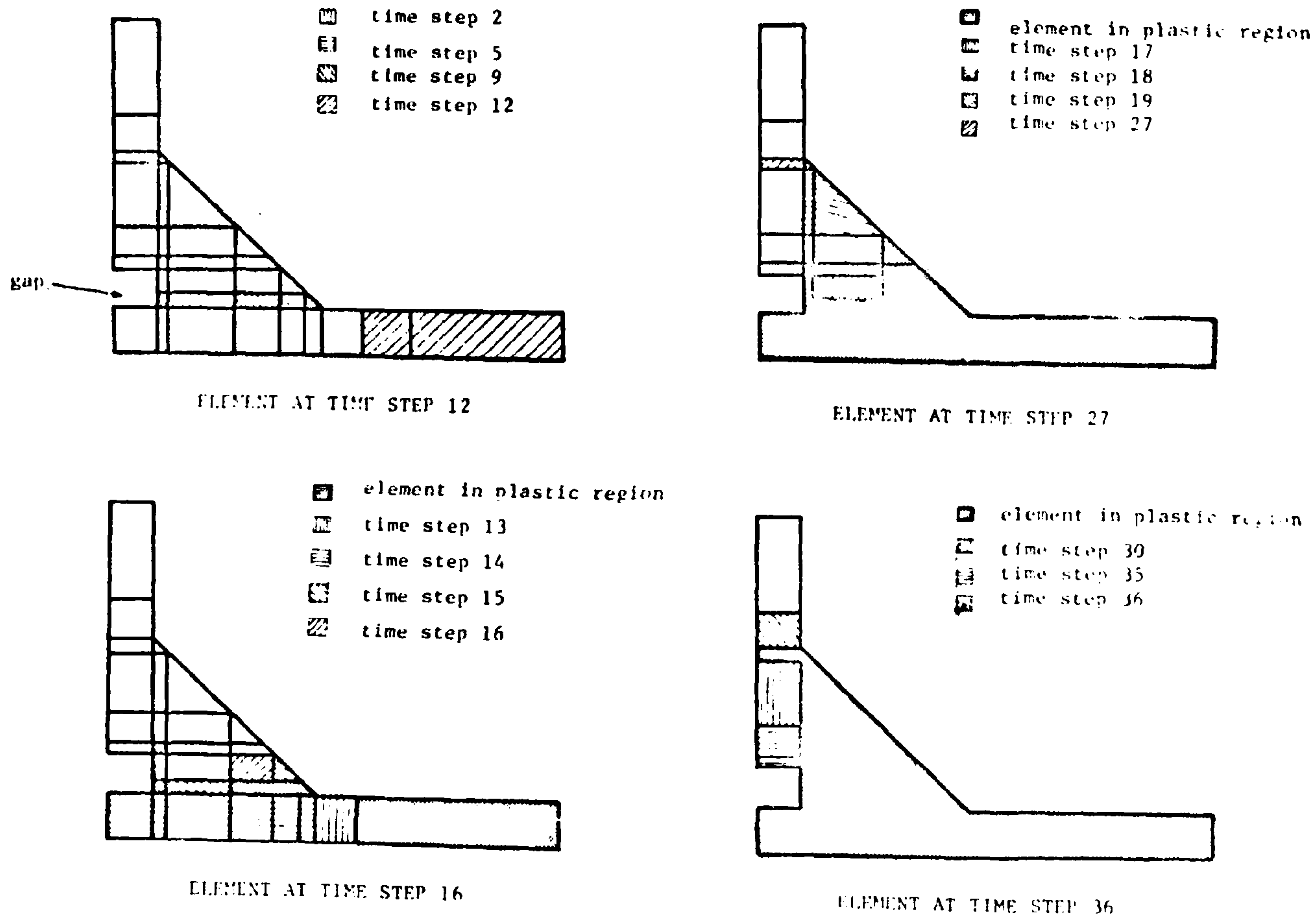

FIGURE 4.6 SPREAD OF PLASTIC REGION IN THE TEST ELEMENT

4.4 Numerical Example of the Effect of In-Plane Tensile Stress in Bottom Shell Plating on Fillet Weld Strength

The example shown in this section is simply to demonstrate how the fillet weld sizes can be reduced using the ADINA program. The effect of root gap on the stress concentration at the toe of a fillet weld under in-plane tensile load applied on the flange was also analyzed.

The joint analyzed is shown in Figure 4.3. The finite-element model consists of 72 plain-strain elements* and 219 nodes, as can be seen from Figure 4.7. Dimensions of the joint shown in the Figure are the same as that between a transverse floor and the shell plating of an AD-37 class ship.

Assuming that the uniform tensile load is caused by ship hull girder bending on the bottom shell plate in the midship section of an AD-37 class ship, this load may be determined by simple beam theory and the load is[20]:

$$\sigma_T = 34{,}538 \text{ psi}$$
$$= 24.29 \frac{\text{Kgr}}{\text{mm}^2}$$

This load is applied in the line connecting the nodes 1, 2, and 3, and in a negative Y direction.

The analysis performed was an elastic-plastic analysis using the Von-Mises yield criterion, with a linear strain hardening. The tangent modulus was assumed to be

$$E_t = mE = \frac{1}{40} E$$

The joint was assumed to be made of mild steel, with the following material properties:

$$E = 21{,}000 \text{ Kgr/mm}^2$$
$$\sigma_y = 24.5 \text{ Kgr/mm}^2$$
$$\nu = 0.3$$

Since an elastic-plastic analysis is performed, it is important to make small load step increments in the plastic region. If the step increments are large, no equilibrium stiffness matrix can be reformed in the program. So, the total load was applied in three static steps of 50%, 70% and 100% (Figure 4.8)

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* Since the joint is long in the direction of welding compared to other two directions, a plain-strain condition is assumed on the weld cross sections.

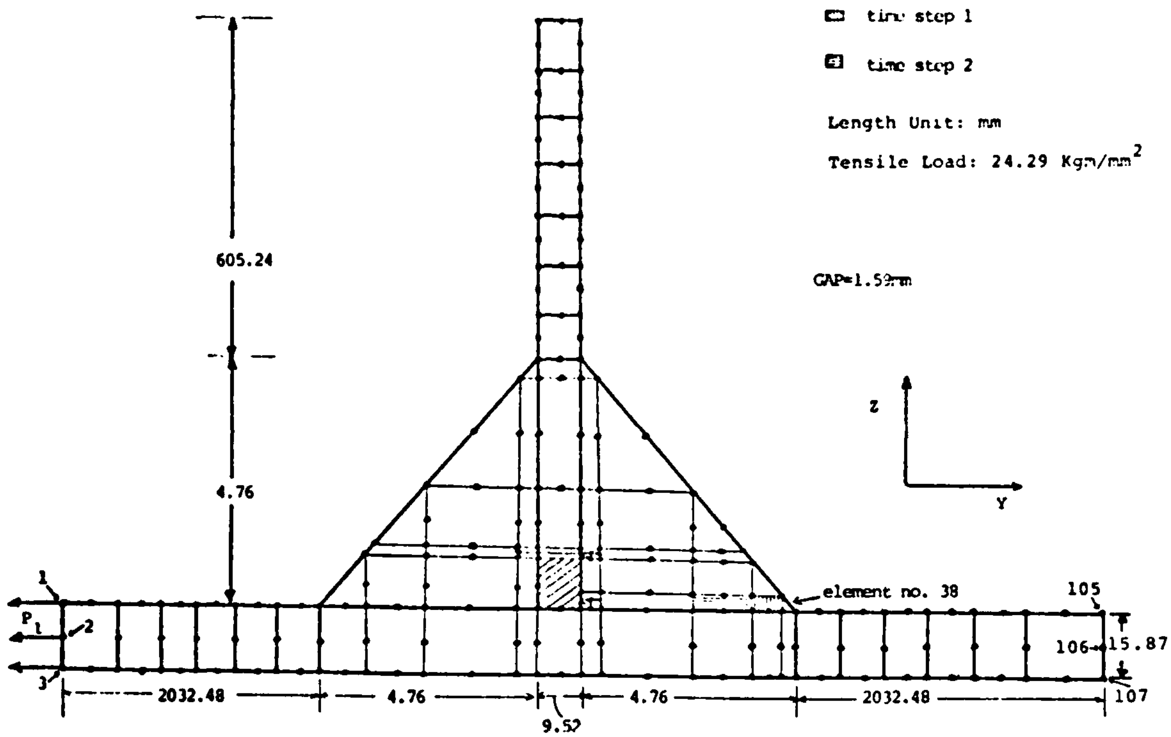

FIGURE 4.7 TWO DIMENSIONAL FINITE ELEMENT MESH

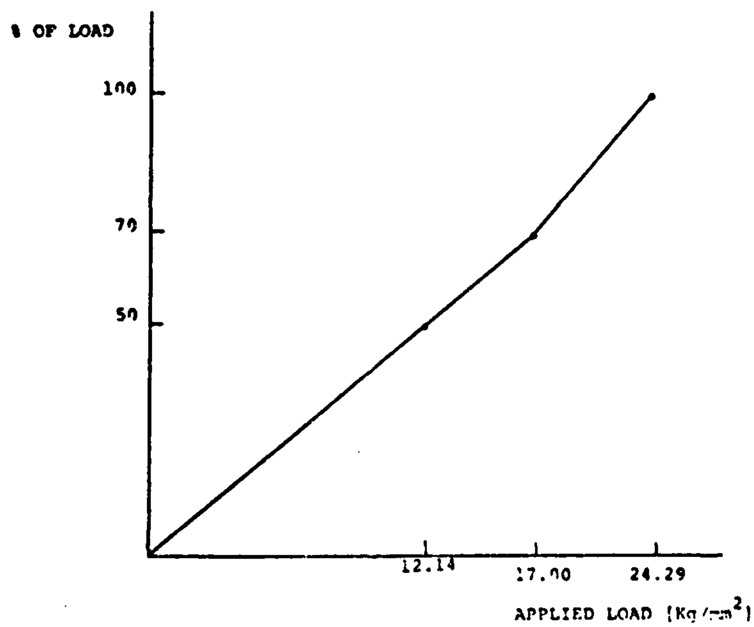

FIGURE 4.8 THE STATIC STEPS OF APPLIED LOAD ON A T-JOINT

This computer model is suitable to perform various kinds of parametric analysis, provided that only one parameter varies per time holding all the others constant.

The first calculation was performed by varying the weld size of the joint under simple tension (Figure 4.3). The iterative process started with an arbitrary value, ℓ, = 4.76 mm* and gradually reduced the fillet sizes by 10%, (4.284 mm) 20% (3.808 mm) and 30% (3.332 mm). The results are shown in Figure 4.9. This figure shows that since the slope of the curve X vs. % of reduction is still far from zero at the point of 30% reduction, a 30% reduction is, therefore, feasible in this case.

Ship structures, like any other structures, are never completely free of imperfections and defects due to design or fabrication limitations. These imperfections may cause the real structure to depart from the ideal model which is used in the strength calculations. Knowledge of the extent of the departure may provide reasonable insight into the safety considerations which can be integrated into the structural design procedures.

There are several ways in which a gap can be formed between the web of the joint and the base plate. The most common way is due to the fact that plates are never straight. They always have some initial deflections, so that in a micro scale, the plate shape is like the one shown in Figure 4.10. At point A of the figure, the maximum gap occurs. The cross section of the joint at point A is the one shown in Figure 4.7.

The second calculation was performed by varying the root gap of the fillet weld from the maximum allowable value of 1.59 mm, allowed by ABS rules, to as much as 30% more.

The computer calculations were conducted for the following cases:

Case #1: Maximum allowable gap (1.59 mm)

Case #2: Gap increase of 10% (1.749 mm)

Case #3: Gap increase of 20% (1.908 mm)

Case #4: Gap increase of 30% (2.067 mm)

---

* This value according to ABS rule, is a required fillet weld size for a joint in the transverse floor of midship section in the double bottom.

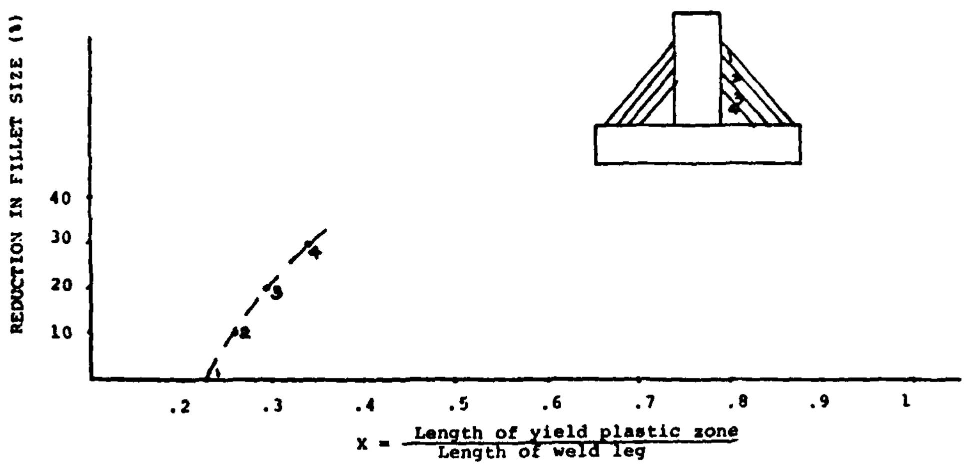

FIGURE 4.9 REDUCTION IN FILLET WELD SIZE VS. QUANTITY X, FOR A TRANSVERSELY LOADED TEE-JOINT UNDER SIMPLE TENSION ON ITS FLANGE

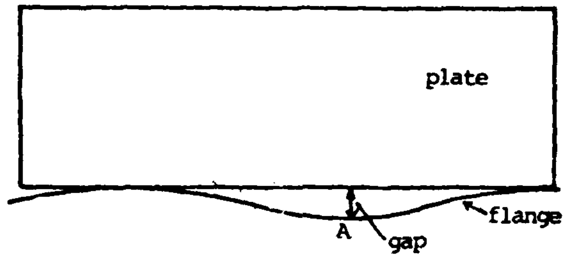

FIGURE 4.10 GAP FORMATION IN A FILLET WELD

During all these calculations, the weld leg, the applied load, the geometery of the joint and the material properties were held constant. Figure 4.11 presents the results of the computer calculations. This figure shows how the stress concentration varies with the percent of increase in root gap, for the element number 38. The conclusion, for the loading condition tested, is that the stress concentration near the toe of a fillet weld decreases slightly ~~as the gap~~ increases.

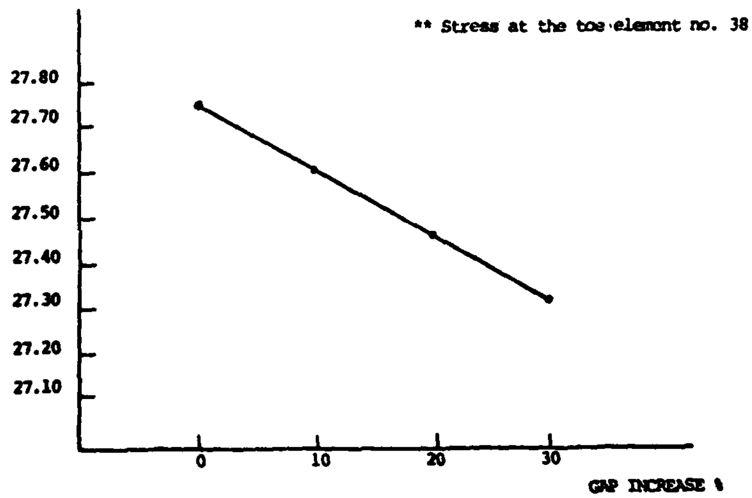

FIGURE 4.11 STRESS CONCENTRATION AT THE TOE ELEMENT

5. CONCLUSION AND RECOMMENDATIONS FOR FURTHER RESEARCH

5.1 Conclusions

1. Some experimental and simple mathematical studies on fillet weld strength (mostly fatigue strength) have been conducted by various researchers, but very little analytical work on detailed stress analysis in welds has been done.

2. Comparisons of fillet weld requirements of various classification societies indicate that the most conservative rule may require twice the size than that required by the most liberal rule.

3. Many failures in ship structures were fatigue cracks initiated from the toe of fillet welds.

4. Slightly undersized welds are sometimes inevitable due to the welding process limitations in actual practice. Overwelding may arise if corrections are made to satisfy the requirements by specifications. More distortions as well as waste of time, labor, and materials may cause many other adverse effects. Updated rules should then be determined through analysis to accept such slightly undersized welds.

5. A general yielding criterion which requires a full plastic zone along the weld legs as the indication of failure is proposed to determine minimum fillet weld sizes.

6. The "ADINA" program or a similar FEM program with modifications, can be used for analyzing fillet weld joints under complicated loading conditions.

5.2 Recommended Further Research

It is recommended that further research be made on the following tasks:

Task 1. Determination of Stress Distributions in Ship Structures to Assist the Analysis in Welds. To analyze the stress and strain conditions in welds of various fillet joints of ship structures using "ADINA" computer program, it is first necessary to determine the stress distributions in the ship structures. The stress found in the cross-sections beside a particular joint are used as the stress boundary condition (local loads) acting on the cut-off edges of that joint in the computer analysis. Many analyses and measurements have been conducted to determine the stresses in the ship structures caused by various combinations of loads to which the ship is subjected in the open sea. Theories of structures are usually used for determining the stresses caused by simple loads such as hull girder bending and plate bending due to lateral water pressure and stiffener restraints. Stresses caused by some special type of loads, such as liquid sloshing loads, and stresses in the areas with more complicated combination of joint geometries are often studied using numerical techiques. Recently, a finite-element method has been used to determine the stress distributions over the entire ship structure of an oil tanker by ABS. Although the efforts have been made for determining the stresses in the ship structures, these stresses have not yet been characterized for reviewing the rules. It is therefore recommended that stresses in the ship structures under various combinations of loads be characterized in terms of joint geometry and joint location for a particular ship.

Task 2. Review of Fillet Weld Strength of Various Joints in Ships by Computer Analysis. Ship Structure Committee sponsored research has developed a computer method, using the "ADINA" computer program, for analyzing the strength of fillet welded tee-joints. A simple tensile load acting on the two edges of the flange was analyed in a numerical example to demonstrate the program. It is recommended that analysis of weld strength of various joints in ships using "ADINA" or similar computer programs be conducted. The expected results will relate the minimum allowable fillet weld sizes (where the critical yield criterion is just met) to the plate thickness of the joints at a particular location in ships. Photoelastic, or similar stress analysis, experiments for determining the fillet weld strength of several tee-joints under simple loading should also be conducted to check the validity of the mathematical modeling and the computer results. Any modifications in the mathematical modeling or in the computer programs should then be made before going on to the analysis of the joints under more complicated loading conditions.

Task 3. Development of a Rational Procedure for Updating the Fillet Weld Specifications. A ship structure Committee sponsored study has indicated the possibility of reducing fillet weld size requirements. One way to achieve a solution is to develop an algorithm approach. In this approach, the required weld sizes would be the sum of the increments in weld size which are required for each of the factors that might affect the strength of a welded joint. Within each category, the value of the increments could vary from zero to some maximum value depending on the conditions of the particular joint in question.
The joints would be classified by type to take into account

the required joint efficiency, possible different requirements of different classes of ships and the location of the joint in a given ship. A matrix would be set up to give the value of each increment for different joint classifications.

Table 5.1 represents the elements of the algorithm system. With information previously developed, along with some experiments, a simple computer program can be developed to take account all the factors in the algorithm chart and to perform the optimization through the iterative procedures in the computer. The algorithm charts can then be reviewed and incorporated in the specifications.

Task 4. <u>Study of the Significant Benefits from the Reduction of Fillet Weld Sizes.</u> The reduction of fillet weld size requirements can benefit ship construction by allowing smaller welds, reducing the cost of construction, accepting slightly undersized welds if the itegrity of the joint is not impaired, and reducing weld distortion by depositing less weld metal to the joint. Among the anticipated benefits, the cost saving may be the most important concern by the shipbuilders.
A preliminary study on the cost saving due to the reduction of fillet weld size has been conducted by Malliris[21]. Based on a possible 30% reduction of fillet weld size the total cost saving including welding consumables, welding time and labor cost in the construction of a 50,000 DWT tanker can reach $102,900 and 22 tons of welding consumables.
It is, therefore, recommended that an economic study be undertaken that would include the reduction of welding consumables, welding time and labor cost.
It is also recommended that the beneficial effect of reduction of fillet weld size requirements on the weld distortion be studied as it may be one of many important considerations in determining the acceptable undersized weld in actual welding practice. Either experimental approach or computer analysis, such as using the computer programs developed at M.I.T., may be used for this study.[3]

TABLE 5.1 FILLET WELD ANALYSIS SYSTEM ELEMENTS

Category	d_i	Method of Determination
Static strength	d_1	Computer FEM
Fatigue margin	d_2	Experimental results
Fabrication or workmanship	d_3	FEM
Welding Method	d_4	Experimental results
Conditions of welding	d_5	Industrial data
Environmental:		
Corrosion (general)	d_6	Calculation-experimental results
Corrosion (local)	d_7	Experimental results
Quality control:		
Ability to detect defects	d_8	Industrial data
Test procedure required	d_9	Specifications
Design method	d_{10}	Judgement
Strengths of the weld metal	d_{11}	Experimental results
Metallurgical restraints	d_{12}	Experimental results

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7. Report of the Welding Institute Research Laboratories, "Effect of Peening and Grinding on the Fatigue Strength of Fillet Welded Joints", British Welding Journal, Vol. 15, No. 12, December 1968, p. 601-609.

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11. Kato, B., Morita, K., "Strength of Transverse Fillet Welded Joint", Welding Journal, Vol. 53, No. 2, February 1974, p. 59-s-64-s.

12. Maddox, S.J.,"An Analysis of Fatigue Cracks in Fillet Welded Joints,", International Journal of Fracture, Vol. 11, No. 2, April 1975, p. 221-243.

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15. Cochran, C.S., and Jordan, C.R., "In Service Performance of Structural Details," SSC-272, Ship Structure Committee, 1978.

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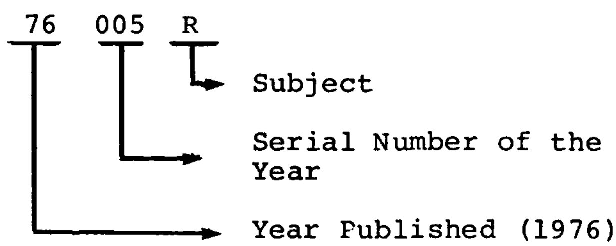
21. Malliris, A.P., "Static Strength of Fillet Welds Using the Finite Element Method," MIT M.S. Thesis, Dept. of Ocean Engineering, Sept. 1978.

APPENDIX I

LIST OF LITERATURE ON FILLET WELDS, 1943 - 1977

Appendix I is a list of literature on fillet welds from Northeast Acaemic Science Information Center (NASIC) which is available at M.I.T.

Example



Subjects are classified as follows:

- S: Static Strength
- F: Fatigue Strength
- R: Residual Stress
- D: Weld Defect
- I: Inspection
- C: Welding Cracking
- P: Welding Process

77001D	Antoniou, A.C.	A Survey on Cracks in Tankers Under Repairs	Proceeding of the PRADS-International Symposium, Tokyo, Japan, Oct. 1977	
77002D	Kaku, S.	Recent Tendency of Hull Structural Damages and Their Countermeasures	Proceeding of the PRADS-International Symposium, Tokyo, Japan, Oct. 1977	
76001S	Gurney, T.R.	Finite-Element Analyses of Some Joints with the Welds Transverse to the Direction of Stress	Weld. Res. Int.	Vol. 6, No. 4
76002F	Maddox, S.J.	Fracture-Mechanics Analysis of the Fatigue Behavior of Fillet Welded Joints	Weld Res. Int.	Vol. 6, No. 5
76003S		Design of Welded Joints, Part 2	Can. Mach. Metal-Work	Vol. 83, No. 3
76004FD	Japan Ship-Building Research Institute	The Research on the Brittle-Fracture and Fatigue Strength of Thick Welded-Plate with High Heat-Input Welding Processes (in Japanese)	Jap. Ship-building Res. Inst.	SR-153
76005R	Malisius, R.	Shrinkage and Residual Stresses in Welded T and Cruciform Joints (in German)	Schweisstechnik	Vol. 30, No. 2
76006I	Webber, D. Maddox, S.J.	Problems in the Detection and Monitoring of Fatigue Cracks in Al-Zn-Mg Alloy Fillet Welds	Welding Institute Conf. on the Detection and Measurement of Cracks, Abington, Cambridge	
76007D	Lamba, H.S. Cox, E.P.	The Effects of Clustered Porosity on the Shear Strength of a 514F Transverse Fillet Welds	Construction Engineering Research Lab. (Army)	CERL-TR-M-196

76008DI	Antoniou, A. et al.	Fabrication Factors Affecting Structural Capability of Ships and Other Marine Structures	Report of Committee III.3 ISSC, 1976	
75001F	Maddox, S.J.	Analysis of Fatigue Cracks in Fillet-Welded Joints	Internat. J. Fracture	Vol. 11, No. 2
75002F	Mathers, E.	Fatigue of Stainless Steel Fillet Welds at Low Temperatures	Conf. on Welding Low Temperature Containment Plant, Welding Institute, Abington, Cambridge	
75003F		Fatigue Strength of Transverse Fillet and Cruciform Butt Welds in Steels	Engineering Sciences Data Unit Ltd., London	ESDU-75016
75004C	Chew, B.	Diffusion of H in Fillet Welds	Metals Technology	Vol. 2, No. 2
75005C	Araki, M Nagae, T.	Cracking in Multipass Fillet Welds	Nippon Kokan Tech. Rep. (oversea)	No. 18
75006P	Brayton, W.C. Evance, R.M. Naister, R.P.	Shipyard Welding--Applicability of Firecracker Welding to Ship Production	Maritime Administration, Washington, DC	MA-RD-920-77040
75007S	Burner, W.K.	Accurately Specified and Controlled Fillet Weld Size in Ship Hull Construction	Coast Guard Engineer's Digest	Jan-Feb-Mar, 1975
74001S	Vidmir, M.	Static and Dynamic Load-Bearing Capacity of Al Welds	Varina Technica	Vol. 23, No. 3
74002S		Hot Tap Connection on Gas Pipelines Operating at High Pressure	Gas Engineering Management	Vol. 14, No. 10

74003S	Kato, B. Morita, K.	Strength of Transverse Fillet Welded Joints	Welding Journal	Vol. 53, No. 2
74004F	Heins, C.P. Yamada, K.	Design Procedure for Fatigue Due to Daily Traffic	Federal Highway Admin., Maryland Div.	FHWA/MD/R-76/12
74005F	Nunn, D.E.	An Investigation into the Fatigue of Welds in an Experimental Orthotropic Bridge Deck Panel	Transport and Road Research Lab., Crowthorn, England	TRRL-LR-629
74006D	Sato, K. Ueda, Y. Tanaka, T. Seo, K. Tunenari, T.	Study on Treatment of Fillet Weld with Root Gap (in Japanese)	J. Soc. Naval Arch. of Japan	Vol. 136
73001S	Belchuck, G.A. Naletov, V.S. Orekhov, V.P.	Influence of Depositing Fillet Welds on the Shape, Microstructure and Fatigue Strength of Welded Joints	Welding Production	Vol. 20, No. 2
73002S	Sager, R.J.	Designing for Welding	Aluminum Welding Seminar Technical Papers, The Aluminum Assoc., New York	
73003C	Fukui, T. Sugiyama, Y.	Lap Joint Fillet-Weld Cracking Tests of Al Alloys (in Jap.)	Sumitomo Light Metal Tech. Rep.	Vol. 14, No. 4
73004C	Araki, M. Magano, T. Harasawa, H.	Cracking in Multi-Run Welds (in Japanese)	Nippon Kokan Tech. Rep.	No. 61
73005C	Sherman, D.R. Fisher, J.M.	Flange-to-Web Connection Requirement on Beams with Corrugated Webs	Weld. J.	Vol. 52, No. 3

73006I		Method for the Radiography of Fillet Welds in Welded-in and Welded-on (Pipework) Connections	Schweissen Schneiden	Vol. 25, No. 5
73007I	Dubreson, J. Evrard, M. Lepenven, Y.	Non-Destructive Testing of Fillet Welds	Sound. Tech. Connexes	Vol. 27, No. 1 and 2
72001F	Mori, M. Matoba, M. Kawasaki, T. Nakajima, M. Hirose, M	Application of Program Fatigue Test to Member Joints of Hulls	Mitsubishi Tech. Bulletin	Jul., 1972
72002C	Clark. P.J.	Basis of Design for Fillet-Welded Joints Under Static Loading	Improving Welded Product Design Conf., Welding Institute	
72003I	Francois, C. Nouvet, A. Tanaka, T.	Detection of Cracks Using Acoustic Techniques in Fillet-Welded Steel Sheets During Strain Tests	Sci. Tech. Armement	Vol. 46, No. 4
71001S	Nishida, Y.	Strength of Fillet Welds in V-Shapes	Sumitomo Search	May, 1971
71002S	Butler, L.J.	Strength of Fillet Welds as a Function of Direction of Load	Weld. J.	Vol. 50, No. 5
71003F		How Explosive Peening Affects Fatigue Properties in Maraging Steel, Fortiweld and an Al-Zn-Mg Alloy. Pt. 1, Experimental Details and Results	Metal Construction and British Weld. J.	Vol. 3, No. 10
71004C	Boniszewski, T.	Association Between Service Failure and Fillet Profiles of Tube Stub-Header Weldments	Metal Construction and British Weld. J.	Vol. 3, No. 12

71005I	Krakovyak, M.F. Grebennik, I.L.	Ultrasonic Inspection Technique for Fillet Welds in Small-Diameter Tubes	Weld. Prod.	Vol. 18, No. 9
71006D	Ishiyama, K. Nakamura, Y.	Blowholes of Fillet Weld Joint (in Japanese)	J. Mech. Eng. Lab.	Vol. 25, No. 5
71007D	Fujita, Y. Hagiwara, K. Fujino, H. Hashimoto, H.	The Strength of Fillet Welded Structures with Misaligned Members	J. Soc. Naval Architects of Japan	Vol. 130
70001S		Strength of Welded Joints of Wrought Mg Alloys	Schweisstech-nik	Vol. 20, No. 12
70002S		Investigations of the Geometrical Shape of Butt and Fillet Welds	Schweissen Schneiden	Vol. 22, No. 5
70003S		What Designers Should Know About Welding Aluminum	Weld. Des. Fabr.	Vol. 43, No. 4
70004F	Archer, G.L.	Fatigue Strength of Mild Steel Fillet Welded Tube to Plate Joints	Metal Constr. Brit. Weld J.	Vol. 2, No. 5
70005S	Kassov, D.S. Reiderman, Y.I. Luvshits, M.G. Kutepov, Y.N.	Selecting Safe Limiting Stresses in the Calculation of Fillet Welds	Weld. Prod.	Vol. 17, No. 2
70006P	Dikum, V.N. Chernov, Y.A. Pelevin, Y.P. Duben, L.V.	Automatic HV Fillet Welding With Powder-Filled Wire	Weld. Proc.	Vol. 17, No. 3
70007P	Persson, H.A. Gredborn, K.E.	Utilization of the Penetration for Fillet Welds	Acta Polytechnica Scandinavia, Stockholm, Sweden	APS-ME-51

70008P	Persson, S.A.	Vertically Welded Fillet Welds	Acta Polytechnica Scandinavia, Stockholm, Sweden	APS-ME-51
70009S	Blodgett, O.W.	New AISI-AWS Allowables	Weld. J.	Vol. 49, No. 8
69001S		Influence of Joint Thickness on the Static Strength of --Steel-- Fillet Welds	ZIS MITT	Vol. 11, No. 9
69002F		Fatigue Tests on Specimens with Holes, Butt and Fillet Welds in Mild and High-Tensile Structural Steels	Metal Constr. Brit. Weld. J.	Vol. 1, No. 3
69003C		Lamellar Tearing in Multi-Pass Fillet Joints	Weld. J.	Vol. 48, No. 9
69004C		A Fractographical Examination of Lamellar Tearing in Multirun Fillet Welds	Metal Constr. Brit. Weld. J.	Vol. 1, No. 2
69005P	Archer, G.L.	Fatigue Strength of Mild Steel Fillet Welded Tube to Plate Joints	Metal Constr. Brit. Weld. J.	Vol. 2, No. 5
69006P		Recommendations for Arc-Welded Joints in Clad Steel Construction (in French)	Soud. Tech. Connexes	Vol. 23, Nos. 9 and 10
68001F		Effects of Peening and Grinding on the Fatigue Strength of Fillet Welded Joint	Brit. Weld. J.	Vol. 15, No. 12
68002R	S. Wanell	Deformation of Longitudinal Fillet-Welds Subjected to a Uniform Shearing Intensity	Brit. Weld. J.	Vol. 15, No. 3

68003S	Higgins, T.R. Preece, F.R.	Proposed Working Stresses for Fillet Welds in Building Construction	Weld. J.	Vol. 47, No. 10
67001S	Feder, D.	Influence of Weld Thickness on the Static Strength of Side Fillet Welds	Schneiden	Vol. 19, No. 7
67002I		Ultrasonic Inspection of Fillet Welds in Lap Joints	Prezegl Spawalnictwa	Vol. 19, No. 9
66001S	Naka, T.	Deformation and Strength of End Fillet Welds	Tokyo Univ. Fac. Engineering	Vol. 28, No. 7
66002S	Bornscheuer, F.W.	The Load Testing of Double Strap Joints Made from Grade ST 37 Steel Having Flank and Frontal Fillet Welds	Schweissen Schneiden	Vol. 18, No. 7
66003S	Abolitz, A.L.	Plastic Design of Eccentrically Loaded Fasteners	Eng. J. of AISC	Vol. 3, No. 3
66004I	Berger, D.S. Herrala, J. Paasche, O.G.	An Investigation of the Reliability of Prequalified Fillet Welding Procedures for Welded Steel Bridges	Oregon State Highway Dept.	Sept., 1966
66005S	Van Douwen, A.A. Witteveen, J.	Proposed Modification of the ISO Formula for the Calculation of Welded Joints	Lastechniek	Vol. 32, No. 6
65001F	MacFarlane, D.S.	Some Fatigue Tests of Load Carrying Transverse Fillet Welds	Brit. Weld. J.	Vol. 12, No. 12
65002FR	Cordiano, H.V. Werchniak, W. Silverman, B.S.	Fatigue of Structural Elements Development of Theory and Measurement of Residual Stresses at the Fillet Welds in 1-1/2 Inch HY-80 Steel	Naval Applied Science Lab., Brooklyn, NY	13 Sept., 1965

65003F	Reemsnyder, H.S.	Fatigue Strength of Longitudinal Fillet Weldments in Constructional Alloy Steel	Weld. J.	Vol. 44, No. 10
64001S		Partial Projections Caused by Fillet Welding on the Surface of Hull Plating	Nippon Kokan Tech. Rep.	No. 31
63001S	Lord, O.S. Schutz, Jr., F.W.	Tensile Strength of Steel Connections Having Transverse and Longitudinal Fillet Welds	Georgia Inst. of Tech. Atlanta Engineering Experiment Station, 22 Jan., 1963	
63002P		Development of Techniques for Manual Fillet Welding on Thick Plate Titanium Alloy	Naval Applied Science Lab., Brooklyn, NY, Tech. Memo 1924H2 USGRDR6516	
60001S	Blank, G.F.	Ultimate Strength of Butt and Fillet Welds of ASTM 203-D and USS T-1 Structural Steels	General Dynamics, Astronautics, San Diego, CA	GDA-7E-2367
56001S	Lois, H. Campus, F.	Stiffeners in Welded Plate Girders	Weld. J.	Vol. 35, No. 1
54001S	Vreedenburgh, C.G.J.	New Principles for the Calculation of Welded Joints	Weld. J.	Vol. 33, No. 8
53001S	Koenigsbeger, F. Green, H.W.	Load-Carrying Capacity of Fillet Welded Connections	Weld. J.	Vol. 39, No. 9
49001S	MacCutcheon, E.M.	Rivetted vs. Welded Ship Structure	Weld. J.	Vol. 28, No. 2
46001S	Leavitt, C.M.	Proportioning of Weld Sizes	Weld. J.	Vol. 35, No. 2
45001S	Boardman, H.C.	Stresses in Welded Structures	Weld J.	Vol. 24, No. 1

44001S	Spotts, M.F.	Stresses in Fillet Welds with Eccentric Loads	Weld. J.	Vol. 23, No. 8
43001S	Fergusson, H.B.	Strength of Welded T-Joint for Ships' Bulkhead Plates	Weld. J.	Vol. 22, No. 2
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