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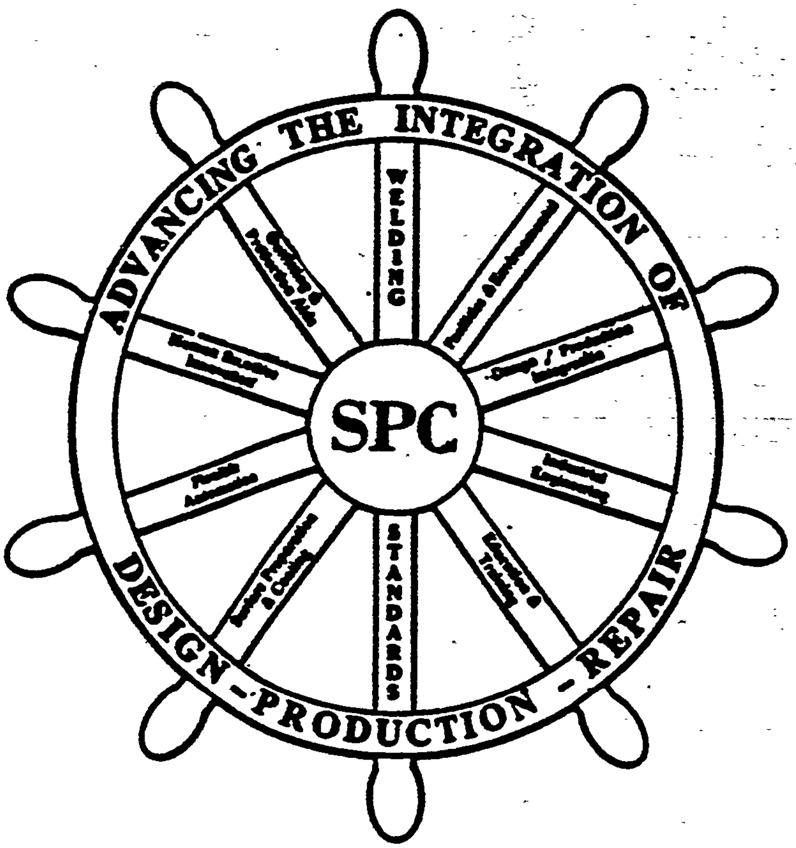

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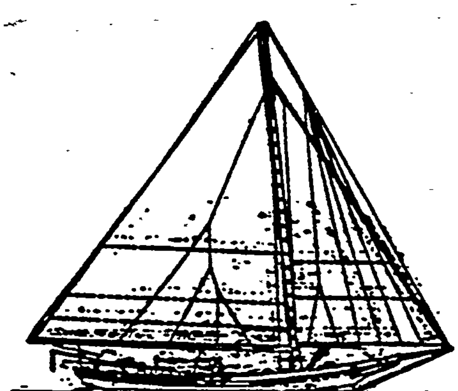

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Designing Partial Penetration Tee Joints for Naval Ships

No. 12A

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ABSTRACT

This paper reviews development of weld design equations which can be used to analyze beveled partial penetration tee Joints. The method developed herein follows closely the development of equations for design of square edge partial penetration tee Joints which was presented at the 1936 Ship Production Symposium. for U. S. Navy ship design, technical authority is vested in the Naval Sea Systems Command (NAVSEA). The published NAVSEA design criteria for partial penetration tee joints is so conservative that it is mathematically impossible to design a conventional 100 percent efficient partial penetration beveled tee Joint. The alternate method for beveled Joints outlined in this paper might be an acceptable replacement for the simple, though unduly, conservative existing design criteria with a more rigorous engineering analysis.

The alternate method for bevelled joints is similar to the alternate square edge Joint design criteria presented in reference (1). Again, six probable conditions for failure are investigated. These are derived, from three probable locations (the weld throat or the intercostal or the continuous neat affected Zone Boundaries) under two possible load directions (longitudinal or transverse to the weld). The corresponding equations used to design conventional square Joint fillets are modified to account for the neat affected zone boundary changes due to the bevel geometry as well as for the fillet size.

The modified design equations developed in this paper are applicable to Joints with balanced or unbalanced bevels. A sample implemention of the design equations using an electronic spreadsheet program on a Personal Computer are included. The proposed design equations are compared to the existing U. S. Navy criteria.

Partial penetration welds are preferred to full penetration welds because they do not require backgouging. A backgouge is typicallv required for full penetration tee joints. This operation removes some of the weld root deposited on the first side, and generally cuts away a large amount of the base material on the second side. The base material removed must, of course, be put pack by welding. This raises the cost to achieve a full penetration Weld not only for the backgouge operation, but also by the cost of adding back the solid material which was removed during backgouge.

NOMENCLATURE

The terminology is in accordance with American Welding Society and applicable military standards. The important terms and abbreviations are explained below. See figure 1 for further clarification.

CONTINUOUS MEMBER- The member which continues through the tee joint.

INTERCOSTAL MEMBER- The member which ends at the tee joint.

AB- Angle of bevel

AH- Angle of HAZB. AH=AB for geometry

B- bevel depth

E- weld joint Efficiency: weld strength as a percentage of the strength of the intercostal member.

HAZB- Heat Affected Zone Boundary

S- Size of fillet leg

SNC- Ultimate Shear strength of the Continuous member.

SUI- Ultimate Shear strength of the Intercostal member.

SWL- Shear strength of the Weld, Longitudinal airection.

SWT- Shear strength of the Weld, Transverse direction,

TC- Thickness of Continuous member

TI- Thickness of Intercostal member

TUC- Ultimate Tensile strength of the Continuous member.

TUI- Ultimate Tensile strength of the lntercostal member.

Z- land width; TI minus the right and left Devel depths

ALTERNATE FILLET SIZING

There are two methods approved by the U.S. navy for designing square edge fillet welds for surface ships, The original method is documented in reference 4. The alternate square edge fillet design method was developed by Charles Jordan anti Bob Krumpen of Newport News Shipbuilding (references 2 & 3) during the 1970's and 80's. NAVSEA autnorized use of the alternate method for surface ship construction and repair.

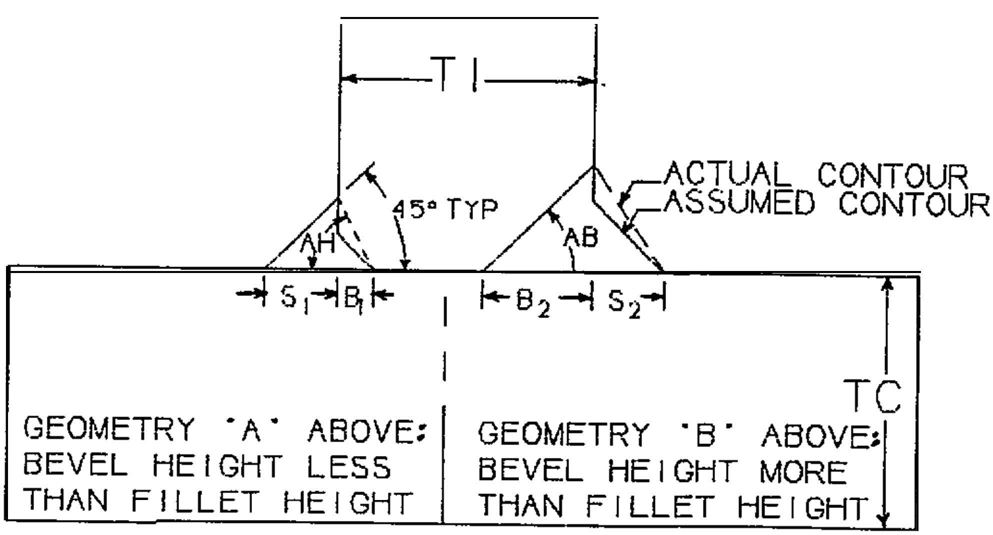
The proposed design method for bevel edged tee joints is an extension of the NAVSEA approved alternate method for determining minimum fillet sires for square edge tee Joints reported in reference 1. At the time of this writing, use of the Partial penetration beveled tee Joint design method presented in this paper is under review by the Naval Sea Systems Command, U. S. Navy, and has not implemented at lngalls.

DERIVATION OF METHOD

The derivation of the purposed beveled edge tee Joint design equations exactly paraliels development of the approved alternate square edge fillet sizing method. Two possible conditions of loading are considered; longitudinal (shear along the weld and transverse (tensile) to the weld. Shear across the weld (in the plane of the continuous member) is not considered in either method. The longitudinal shear loading would be typical of a beam and plate combination in pure bending. The transverse tensile loading would be typical of a stancnion or foundation.

Under each condition of loading, three possible failure locations (simplified fracture surfaces) are considered. Please see figure 2 for a pictoral representation of the three surfaces. The strength of each of the three planes is related to the strength of the intercostal member by a design equation. The weld joint design is adequate when the weld strength equals the weaker member strength. A correctly designed 100%

FIGURE 1 : NOMENCLATURE



efficient weld must satisfy ail six proposed design equations and will provide 100% of the strength of the weaker member under both loading directions. Throughout this paper, the intercostal member is assumed to be the weaker.

LOGITUDINAL SHEAR LOADING

Condition 1- Relates load capacity of weld throat to intercostal member loaa capacity under longitudinal shear loading. In this case the lengths of the right and left throats are calculated assuming a 45 degree angle of the failure plane. This angle was chosen to permit the proposed equation to remain compatible with the existing method. The 45 degree angle gives the shortest length of the throat ignoring convexity and production reinforcement. The weld capacity (weld longitudinal shear strength times the total throat failure plane length) is related by the required efficiency to the intercostal member shear strength using the following equation:

$$(1)\ TI < \frac{(SWl)\ (\text{total throat Length})}{(Sul) * E}$$

For geometry "A", where the bevel height is Smaller than the fillet size (B < S / TAN(AB)),

(1A) throat length = .707 * (S+B)

When ML this equation is identical to equation (1) of reference (1). When B=O, only geometry "A" is applicable.

The close parallel relationship of equations between the Proposed bevelled joint design method and the approved alternate Square edge joint design method shows that the proposed equations are an extension of the alternate square edge equations rather than a departure into radical new design theory. This factor should simplify and speed aporoval of the proposed equations based on Past approval of the alternate square edge fillet design equations.

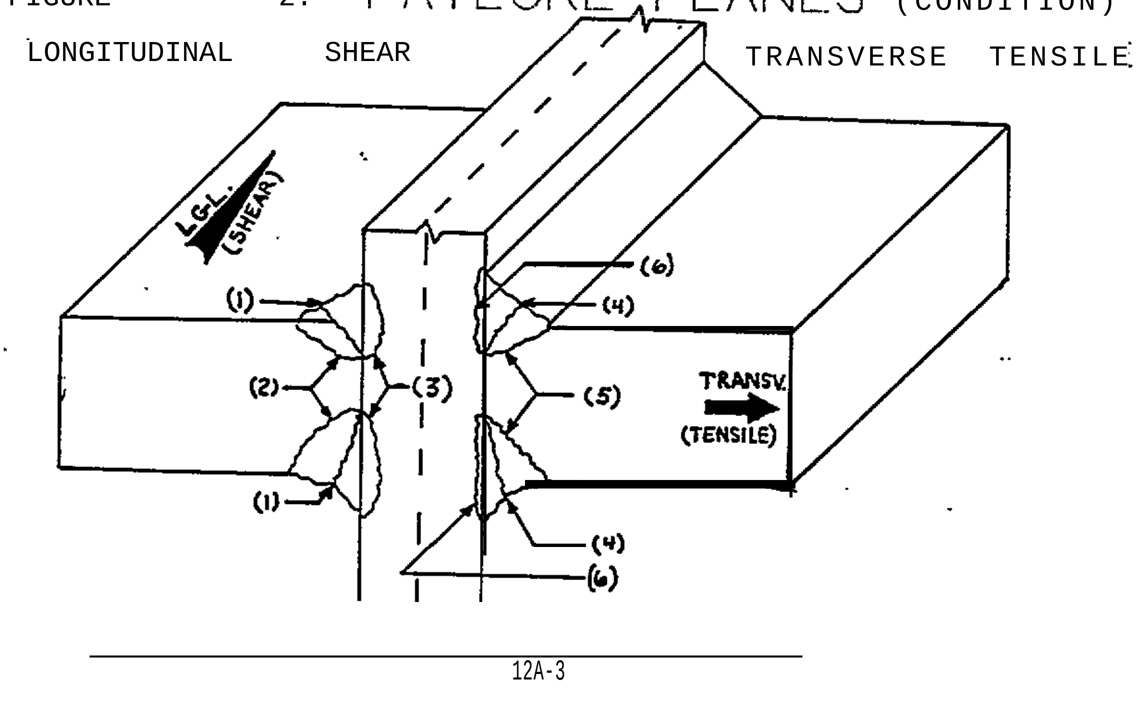
For geometry "B", where the bevel height is larger than the fillet,

(1B) throat length = SQRT(SA2 + BA2)

Condition 2- Relates load capacity of the intercostal member HAZB (heat affected zone boundary) to the intercostal member load capacity under longitudinal shear loading. The HAZB of a steel weldment is also a possible failure location due to embrittlement, grain growth and thermal residual stresses. In the case of shipbuilding steels, the HAZ does not necessariiy weaken the joint. The HAZB of an aluminum weldment is a 1ikely failure location due to annealing and residual tnerma1 stresses. In the case of aluminum ship design, the annealing effect is offset by use of the annealed material strength for design.

The strength of the weld is the intercostal member ultimate shear strengtn times the total length of the intercostal member HAZB. This is related by the required efficiency to the

FIGURE 2: FAILURE PLANES (CONDITION)



intercostal member shear strength using the following equation:

(2) TI < (total intercostal HAZB Length) / E

In developing the equations for fillet welds loaded in longitudinal shear in reference (1), the HAZB was assumed 10% longer than the length of the fillet leg to account for the penetration of the heat. Based on examination of macro-etched weld samples this was reasonably accurate. See figure 3 for an illustration of the HAZB in a partial penetration joint.

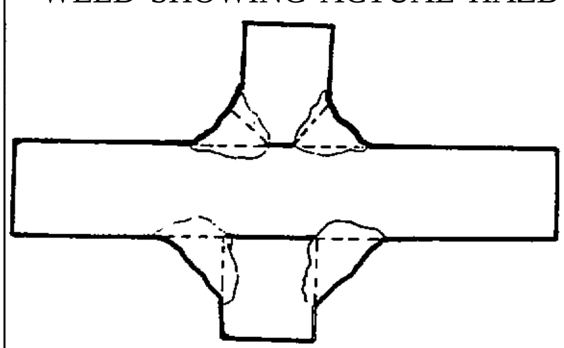
For geometry "A" only, the actual HAZB length is not easy to calculate. To permit development of simple equations, a very conservative assumption is used to estimate this HAZB length for the proposed design method. First, the HAZB is assumed to be the shortest distance between the top of the fillet leg and the root edge of the bevel (no credit for root penetration of fillet oversizing). Second, the 10% extension for heat penetration is not used. The 10% extension was used in references (1) -(3) to design square edge filiets. It was valid then, and would be valid for most, but not all, bevelled joint designs.

Thus for geometry "A" where the bevel height is smaller than the fillet (B < S / TAN(AB)),

(2A) HAZB length = SQRT(SA2 + BA2)

When B=O, geometry "A" is applicable and it can be seen that this equation differs from equation (2) of reference (1) only by the 10 percent HAZB length increase which is not used here (due to conservative approach).

FIGURE 3:
MACRO-ETCHED ALUMINUM
WELD SHOWING ACTUAL HAZB



For geometry "d", the HAZB will always be longer than the shortest distance between the root and the fillet toe. Therefore, the 10% increase of references (1) - (3) is used. For geometry "B" where the bevel height is larger than the fillet,

(2B) HAZB length = m

Condition 3- Relates the capacity of the continuous member HAZB (heat affected zone boundary) to the intercostal member capacity under longitudinal shear loading. The HAZB of the continuous member is also a possible failure location due to the same reasons as outlined in condition 2. The strength of the HAZB is the continuous member ultimate shear strengtn times the total lengtn of the continuous member HAZB. This is related by the required efficiency to the intercostal member shear strength using the following equation:

(3) TI < (Cont. mem. HAZB Length * SUC) / (SUI * E)

The HAZB length is assumed 10% greater than geometric length. This assumption was used in references (1)-(3) and examination of macro-etched samples shows this assumption remains valid. For both geometry "A" & "B";

(3A) & (3B) HAZB length = 1.1 * (S + B)

When B=O, this equation is the identical to equation(3) of reference (1).

TRAKSVERSE TENSILE LOADING

Condition 4- Relates load capacity of the weld throat to the load capacity of the intercostal member for transverse loading across the weld throat. In this case the lengths of the right and left throats are calculated assuming a 45 degree angle of the failure plane to give minimum length. This is conservative because actual (and theoretical) failures show a failure Plane of about 60-70 degrees. The strength of the weld is the weld transverse shear strength times the total throat failure plane length. This is related by the required efficiency to the intercostal member tensile strength using the following equation:

(4) TI < (SWT * total throat Length) / (TUI * E)

For **geometry "A"**, where the **bevel** height is smaller than the fillet height (B < S / TAN(AB)),

(4A) throat length = 707 * (S+B)

When B=0, this equation is identical to **equation (4) of reference** (1). **When B=0,** only geometry “A” is applicable.

For geometry “B’, Where the bevel height is larger than the fillet,

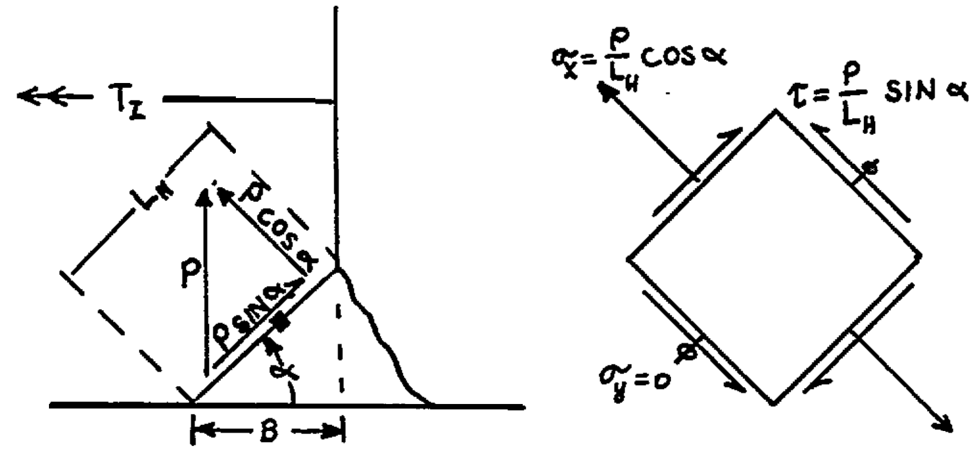
(4B) throat length = SQRT(SA2 + BA2)

Condition 5- Relates the load capacity of the intercostal member HAZB (heat affected zone boundary) to the load capacity of the intercostal member under **transverse** tensile loading. The HAZB of the intercostal member is also a possible failure location due to the same **reasons as outlined** in condition 2. When calculating **the strength of the** intercostal HAZB the directionality of the capacities **must be** considered, Mohr’s stress transformation is used to calculate the maximum shear stress along the HAZB, When the geometry satisfies the equation below, the maximum shear stress will be less than the intercostal member ultimate shear stress. The derivation is show in figure 4. The intercostal **member** HAZB capacity is related by the required efficiency to the intercostal member tensile strength using the following equation:

(5) TI< (I’costal **HAZB Length * SUI)** / E*SQRT((COS(AH)/2)A2~+SIN(AH)A2)

A Mohr’s transformation for principal tensile **stress** less **than** intercostal member ultimate tensile stress was

FIGURE 4: Development of equation (5) using Mohr’s approach.



P= TUI (T_I) **α = HAZB ANGLE= AH**

L_H= HAZB LENGTH

SATISFACTORY IF MAXIMUM SHEAR $\tau_{MAX} \leq$ SUI

WHERE $\tau_{MAX} = \pm\sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau^2}$ GIVES

$$SUI \geq \sqrt{\left(\frac{P}{L_H}\frac{\cos\alpha}{2}\right)^2 + \left(\frac{P}{L_H}\sin\alpha\right)^2}$$

REARRANGING GIVES

$$T_I \leq \left(\frac{SUI}{TUI}\right)\frac{L_H}{\sqrt{\left(\frac{\cos\alpha}{2}\right)^2 + (\sin\alpha)^2}}$$

considered when developing the proposed design method. In the case of a balanced joint wih a sixty degree bevel, this. works out to a minimum bevel depth of (.29) T. This value is the same as the American Welding Society recommended design from page 157 of reference (6). However. the shear comparison is used for this paper so that when considering a square edge (B=O) Joint, equation (5) in this proposed method will match equation (5) of reference (1).

For geometry "A", where the bevel height is smaller than the fillet leg height (B < S / TAN(AB)),

(5A) HAZB length = 1.1 * SQRT(SA2 + BA2)
HAZB angle = ARCTAN(S/B)

For a fillet where B=O and AB=90, the proposed equation (5) is identical to equation (5) of reference (1).

For geometry "B" where the bevel height is larger than the fillet,

(5B) HAZb length = 1.1 * B / COS(AB)
HAZB angle = AB

Condition 6- Relates load capacity of the continuous member HAZB to the load capacity of the intercostal member under transverse tensile loading. The HAZB of the continuous member is also a possible failure location for the same reasons as outlined in condition 2. The strength of this HAZB is the continuous member ultimate tensile strength times the total length of the continuous member HAZB. This is related by the required efficiency to the intercostal member ultimate tensile strength times it's thickness using the following equation:

$$(6)\ TI < \frac{(\text{cont. mem. HAZB Length} * TUC)}{(TUI * E)}$$

Because the continuous member HAZB is loaded transversely (tensile), the HAZB length was assumed as the projected length. For both geometry "A" & "B";

(6A) & (6B) HAZB length = (S + B)

When B=O, this equation is identical to equation (6) of reference (1).

EXISTING DESIGN CRITERIA

The existing approved U.S. Navy method for design of partial penetration beveled tee weld geometry is published in section 5.3 of reference (5). That criteria has several significant shortcomings. It is not as precise or accurate as the proposed method. Also, it usually requires excessively large welds in most cases, but could result in inadequate joints in other cases. Finally, the existing calculation method is applicable only to symmetrically beveled joints, even though unbalanced joint designs are permitted.

First, let us see an example showing now conservative the existlng Criteria is. Examine the design requirements for HS steel (TUI= 75 Ksi) welded with 7018 SMA filler (SWL= 59 ksi). From section 5.3.1.1 of reference (4) we get the equation

$$(7)\ D = \text{Design Factor} = \frac{E\ (T)\ TUI}{(2\ SWL)} = (.635)\ T$$

When D is less than .707 inch (T less than 1.112 inch for this material combination), section 5.3.1.2.1 would control and require:

(8) B = D / 1.414 = (.449) T

If this equation were applied to a one inch thick intercostal member, the bevel depth required would be .449 inches, and the required fillet would be 1/2 inch. By contrast, the method proposed in this paper would only require a 3/8 incn fillet and bevel depth (both sides).

However, the weld calculated in equation (8) above would not be permitted because the land width above is .105 inches and the minimum land width permitted by note 1 in figure 23 of reference (5) is 3/16 inch. When the minimum required land width is substituted into the land width equation of section 5.3.1.3 of reference (4) as shown in equation (9), we find the minimum thickness of 1.84 inches is greater than the maximum thickness (1.112 above) for which equation (8) is valid.

(9) 3/16 = Z = T - 2 B = (.102) T
Tmin = .1875 / .102 = 1.84

If we were to assume a member thickness of 1 1/4 inches, then section 5.3.1.2.2 would be govern because D is greater than .707 inches. B would be found using the following equation:

(10) B= SQRT (D*D - 0.25) = .616

This yields a land width of 0.017 inches which again does not meet the minimum land requirement of reference (5). Thus, there is no valid solution by the published U.S. Navy design criteria for a 100% efficient partial penetration weldment of this material combination for this range of thicknesses.

However, it is also possible to use the published design method to design an inadequate joint. Let's examine the result of severely overmatching the filler to the steel. Assume a 3/4 inch thick mild steel (TUI = 60 ksi) intercostal member is welded to a thick HY-100 continuous member with 11018 SMA filler (SWL = 87 ksi). For this combination, D= 0.259, B = .183, Z = .384 and S = B = 3/16. It should be apparent that the heat affected zone boundary does not increase in strength when the filler metal does. From equation 4 we find this joint, although 100% efficient by the existing criteria, is only 89% efficient by the proposed method. The difference is that the existing criteria does not take into account the strength of the HAZB (which is a common failure location of partial penetration weldments), while the alternate method does.

One final note, the American Welding Society Handbook includes a simple approach to designing full capacity partial penetration tee joints shown on page 157 of reference (6). This design criteria recommends a symmetric design with a 60 degree bevel to a depth of (0.29) T with a fillet of (0.29) T. This apparently was derived from a Mohr's stress transformation. This particular equation can be found if we require principal tensile stress at the bevel (HAZB) to be less than the intercostal ultimate tensile strength for transverse tensile load "P" in figure 4). One of the example applications of the proposed method included in this paper (third design example in Table 2) shows that the alternate method would recommend a depth and fillet of (0.34) T.

While the American Welding Society method from reference (6) is indeed simple, it does not account for longitudinal shear loading of the weld nor for possible variable mismatch between base material and filler metal. It is interesting, though, that there is no minimum land width recommended in this simple design method.

SELECTION OF MATERIAL PROPERTIES

It can be seen from the previous discussion that the alternate fillet sizing method requires material properties not previously required to satisfy the standard method. The standard method from reference (4), equations (7) - (10), required tensile strengths of the continuous and intercostal base materials, and the longitudinal shear strength of the weld material. The proposed method, equations (1) through (6), requires, in addition to the above mentioned properties, the ultimate shear strengths of the continuous and intercostal base materials, and the transverse shear strength of the weld material. Based upon material test data and application of weld and metallurgical theory, NAVSEA has approved the use of some ratios to approximate the additional material properties.

First, the ultimate shear strengths of the base materials are related to their ultimate tensile strengths. For steels, NAVSEA has approved the conservative assumption that the ultimate shear strength is 75% of the tensile strength. For aluminum, NAVSEA has approved the assumption that the ultimate shear strength is 60% of the tensile strength. This results in the following equations:

(11a) SUI = TUI * (0.75 for steel)
(11b) SUI = TUI * (0.60 for aluminum)

(12a) SUC = TUC * (0.75 for steel)
(12b) SUC = TUC * (0.60 for aluminum)

The strength of HSLA80 (a modified A-710 steel recently developed for Navy applications) is not listed in reference (4), but NAVSEA has approved the use of HY-80 tensile strength to determine weld properties. This simplifies table design and appears to be conservative, based upon the slightly lower permissible design stress for HSLA80.

Second, the transverse shear strength of the weld is related to its longitudinal shear strength. For steels, NAVSEA has approved a ratio of 1.44. For aluminum, the approved ratio is 1.58. This results in the following equations:

(13a) SWT = SWL * (1.44 for steel)
(13b) SWT = SWL * (1..58 for aluminum)

NAVSEA has approved some significant changes in weld properties for use in design calculations. These changes are based upon various test programs undertaken since reference (4) was publishes. A list of the pertinent weld properties currently in use at Ingalls Shipbuilding and their sources are shown in table 1.

TABLE 1

WELD LONGITUDINAL SHEAR STRENGTH (KSI)

FILLER METAL	NAVSHIP 0900-000-1000	MIL-STD 1628	APPROVED AT ISD
18	58.1	59	59
10018	71	N/A	78
11018	75.3	87	87
100S-1	N/A	83	83
5556	19.2	20	26; ref 7

SPREADSHEET ANALYSIS BY ALTERNATE METHOD

A Printout of a simple spreadsheet analysis is shown below. This "program" is a Lotus 123 template that allows the user to interactively change any of the variables and instantly see the result. The user can expand the template to develop an entire weld table, including fillets. This template is available from the author at cost of diskette & mailing. To run it you will need a IBM-PC compatible with a 5 1/4 inch disk drive and a Lotus 123 or compatible spreadsheet program.

TABLE 2: SPRERDSHEET ANALYSIS BY LOTUS 123

PROPOSED METHOD FOR PARTIAL PENETRATION JOINT DESIGN

	INTERCOSTAL MATERIAL	HS	CONTINUOUS MATERIAL	HS	WELD MATERIAL	E7018	
TENS. ULT		75.00	TENS. ULT	75.00	LGL SHEAR	59.00	User input material properties.
SHEAR ULT		56.25	SHEAR ULT	56.20	TRANS	04.96	

SIDE A						
BEV DEPTH	0.3750	0.5000	0.5000	0.6250	0.0000	User input joint descriptions
ANGLE(DEG)	45.0000	45.0000	60.0000	45.0000	89.0000	
ANGLE (RAD)	0.7854	0.7854	1.0472	0.7854	1.5533	
FILLET	0.3750	0.5000	0.5000	0.5000	0.5000	
GEAM A=1	1	1	0	0	1	Find geometry type
EQN 1	0 .5562	0.7416	0.7417	0.8395	0.3708	Program solves equations for the joint designs. <inches thickness per side)
EQN 2	0.5303	0.7071	I.1000	0.9723	0.5000	
EQN 3	0.8250	1.1000	1.1000	1.2375	0.5500	
EQN 4	0.6007	0.8009	0.0010	0.9067	0.4005	
EQN 5	0.5534	0.7373	0.9153	0.9224	0.4125	
EQN 6	0.7500	1.0000	1.0000	1.1250	0.5000	

SIDE B						
BEV DEPTH	0.3790	0.5000	0.5000	0.0000	0.0000	User input joint descriptions
ANGLE(DEG)	45.0000	45.0000	60.0000	45.0000	45.0000	
ANGLE(RAD)	0.7854	0.7054	1.0472	0.7054	0.7G854	
FILLET	0.3750	0.5000	0.5000	0.5000	0.5000	
GFUM A=1	1	1	0	1	1	Find geometry type
EQN 1	0.5562	0.7416	0.7417	0.3708	0.3708	Program solves equations for the joint designs. (inches thickness per side)
EQN 2	0.5303	0.7071	1.1000	0.5000	0.5000	
EQN 3	0.8250	1.1000	1.1000	0.5500	0.5500	
EQN 4	0.6007	0.0009	0.8010	0.4004	0.4004	
EQN 5	0.5534	0.7379	0.9153	0.4125	0.4125	
EQN 6	0.7500	1 .0000	1 .0000	0.5000	0.5000	
CONTROL	1.0607	1.4142	1.4834	1.2103	0.7416	control is least sum for each side for each load direction.

T (MAX) VS FFF	MAXIMUM ALLOWABLE INTERCOSTAL THICKNESSES FOR ABOVE JOINT DESIGN (VS. EFFICIENCY)					
100.00%	1.0607	I.4142	1.4834	1.2103	0.7416	Control equation determines table of maximum intercostal thickness vs. joint efficiency.
75.00%	1.4142	1.8056	1.9778	1.6137	0.9888	
60.00%	1.7678	2.3570	2.4723	2.0172	1.2360	
50.00%	2.1213	2.8284	2.9667	2.4206	1.4831	
COMMENTS	3/8" BEV. & FILLET	1/2"BE. & FILLET	60 DEG. BEVEL	UNBAL-ANCED	SQUARE EDGE	

IMPACT FROM USE OF ALTERNATE METHOD

Implementation of the alternate joint design method impacts cost both directly and indirectly. The savings directly related to substitution of partial penetration for full penetration joints are primarily due to deletion of the backgouge. The real justification for the use of partial penetration welds is that circumstances exist where partial penetration welds are more economical than either fillet or full penetration welds while still meeting strength and service requirements.

Where do the savings come from? Because the minimum backgouge size is pretty large, there is significant savings because the oversize "hole" does not have to be filled in by weld metal. In addition, the extra cleanup of the gouged out material is not necessary. There are indirect savings because distortion is minimized (weld volume is less), and NDT is much less costly. For full penetration joints, there is an additional backgouge inspection plus random test gouges to verify. In some categories of structure, full penetration joints may require additional NDT (UT/MT/PT) not required for partial penetration joint designs.

The weld design changes made at Ingalls initially were part of an effort to reduce weld caused distortion. However, a very beneficial side effect of the distortion reduction is a significant cost reduction. Weld savings are passed on to the Navy by reduced bid estimates, and benefit the shipyard by increased competitiveness.

CONCLUSION

The alternate design method for partial penetration joint designs is a marked improvement over existing published navy design criteria. By comparison, it permits a more economical design for common material and filler combinations. It may also prevent unsatisfactory designs which could result from application of the existing criteria. One added benefit is that the alternate method is applicable to unbalanced joint designs. There is currently no published Navy design criteria for unbalanced partial penetration joint designs.

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