WELDING RESEARCH

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Fitness-for-Service Design for Underwater Wet Welds

A unique flexible connection for underwater welding repair is tested for performance

BY C. L. TSAI, L. R. ZIRKER, Z. L. FENG, J. A. GRANTHAM AND J. C. PAPRITAN

ABSTRACT. This paper presents a new concept of improving the use of wet welds for underwater structure repair or construction. A flexible intermediate connection pad, prefabricated on land and welded to the structural members in wet condition, cushions the stresses on joints. The inherently inferior impact property of the wet weldment can be coped with proper design of this cushion pad. The wet welded joint can therefore fit its designed purpose.

In this study, both design analysis and experimental tests were conducted to demonstrate the design solution using the cushion pad. A statistical data base on wet weld properties was first developed to define the performance level of wet welds. The fitness for service of the flexible connection was evaluated by impact testing. The results show that the performance level of the connection can be improved through proper design regardless of the low toughness of the wet weldment.

C. L. TSAI, J. A. GRANTHAM and Z. L. FENG are with the Department of Welding Engineering, The Ohio State University, Columbus, Ohio. L. R. ZIRKER is with Fuels and Processes Division, Argonne National Laboratory, Idaho Falls, Idaho. J. C. PAPRITAN is with the Department of Agricultural Engineering, The Ohio State University, Columbus, Ohio.

Introduction

Underwater wet welds are inherently inferior to those made in air. Rapid cooling and hydrogen-induced embrittlement in the weld heat-affected zone causes low impact strength of the weldment.

To solve this problem, most of the investigators have studied various means of removing water from joints during welding using mechanical enclosures (Ref. 1) or improving the impact strength by use of fluxcored wire (Ref. 2) or austenitic fluxcoated electrodes (Ref. 3). Some reports have indicated promising results (Refs. 1–3), but no evidence has been shown by these investigators to support their claims.

KEY WORDS

Fitness for Service
Underwater Wet Welds
Weld Connection Design
Joint Pad Connection
Flexible Joint Pad
Fillet Wet Welds
Padded T Joints
Impact Loading
Static Loading
Von Mises Stress

This paper presents a new concept of improving the use of wet welds for underwater structure repair or even construction. Typically, the members would have been directly joined. The new concept is to develop a novel design which cushions the stresses on joints by welding a metal "pad" between two structural members. Part of the welding is done in air and the final product of an underwater weld does not put the full impact energy on the structure nor the stresses it undergoes on the portion of the structure which is the weakest, namely at the underwater weld joints.

With the new design, a flexible intermediate connection pad is welded together outside the water. After the critical pieces are connected, the assembly is submerged and attached to the underwater structure using wet welding.

In order to develop this design concept, the performance level of wet welds must be known. In this paper the performance level is judged by static strength, Charpy impact strength, and microhardness. A statistical data base, which was developed based on literature review and experimental tests, is presented.

The next step in the study was to conduct connection design iterations using the finite element method. In the design analysis, the stress distribution in the wet welds and the strain energy absorbed in the flexible connection pad were deter-

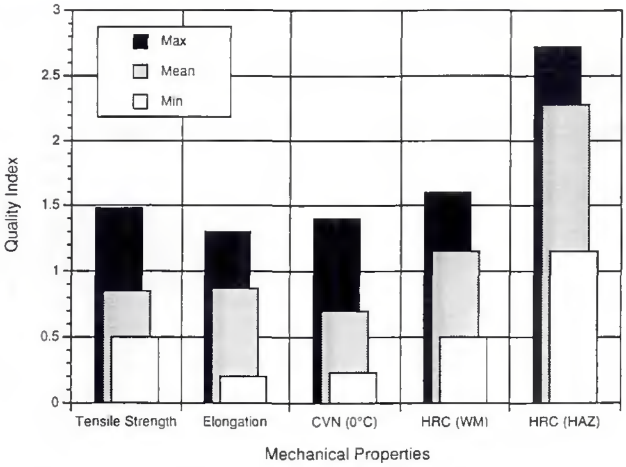


Fig. 1 — Quality index. Reference values of air weld: tensile strength, 498 MPa; elongation (%), 25; hardness (RC), 18 weld metal, 25 HAZ.

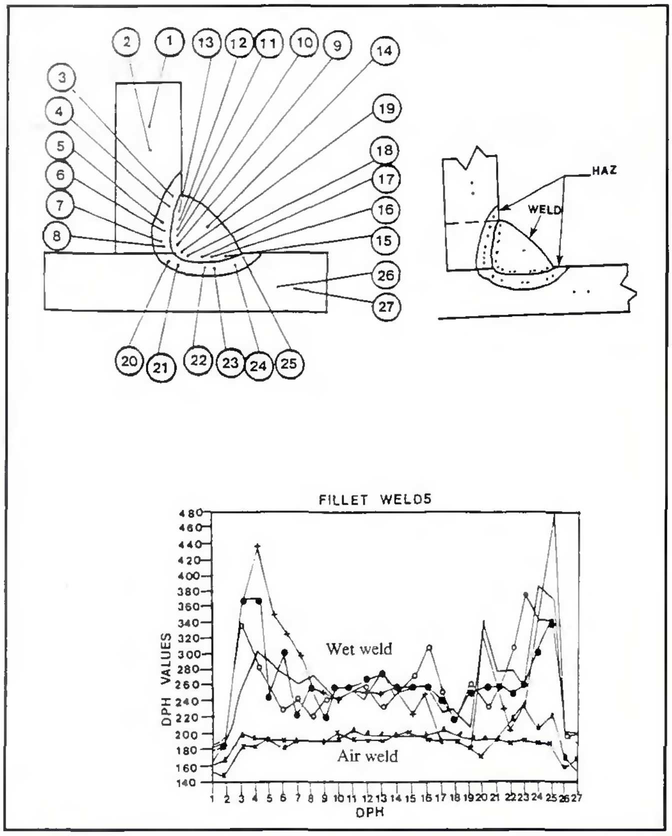


Fig. 2 — Plot of weld hardness.

mined for the minimum weld size and the optimum flexible connection pad dimensions for different loading conditions. The weld performance data were used as the design criteria in the analysis.

Finally, tests were conducted in the laboratories to demonstrate the effectiveness of this design approach. These tests indicated agreement in trends between computer predictions of impact strength and the laboratory trials.

Mechanical Properties of Wet Welds

American Welding Society (AWS) D3.6, *Specification for Underwater Welding,* defines a set of criteria for weld mechanical properties that must be established during procedure qualification, and a set of weld soundness requirements that are to be verified during construction. Four weld types, A, B, C and O, are also defined by the same specification with each weld type encompassing the range of quality and properties currently produced in field practice.

The mechanical properties defined by D3.6 include ductility, toughness, hardness and ultimate tensile strength. With these properties, there exist trade-offs between ductility/toughness and hardness/ultimate tensile strength. One often increases at the expense of another.

The identification of mechanical properties of wet welds has been collected from current literature and the testing of welds made under simulated offshore conditions (*i.e.,* welds were made in a diving tank) in this study. A data base was developed. This data base was divided into two parts. The first part (134 data points) was derived from the literature search and covered a full range of various underwater wet welding activities. The second part (17 data points) consisted of test results from actual mechanical tests from the test welds in this study and from other test data that exactly matched the welding procedure for this research (*i.e.,* shielded metal arc welding of ASTM A36 base material with tensile, Charpy V-notch and hardness tests). The compilation of the data base is shown in Zirker's M.S. thesis (Ref. 5).

As a relative measure of the mechanical properties of wet welds with respect to their air-weld counterpart, quality indexes, which were defined as the ratio of wet to in-air weld properties, were used for the statistical data analysis. The statistical analysis of this data base is shown in the form of a bar chart graph — Fig. 1.

Figure 2 shows the diamond pyramid hardness (DPH) distributions in the various metallurgical zones of underwater "wet" welds and air-weld counterparts. The hardest zone on a ASTM A36 steel weldment made underwater is about 0.5 mm (0.02 in.) from the fusion line. The overall hardness of the underwater wet weld is much higher than its air-weld counterpart due to the rapid quench effect.

To characterize the true performance level of joints with Type B welds in comparison with Type A welds, a three-axis fitness-for-purpose index (FFPI) system was developed based on the test results to show the relationship of three mechanical properties: tensile strength, Charpy V-notch and hardness. Each axis corresponds to one of the properties. Each property axis was divided into six ranges along the axis — Fig. 3. The algorithm tables were derived by inserting data points that fall into test range cells in the planes along the hardness axis.

Also shown in Fig. 3 are the six algorithm tables. The values of each of the 17 data points were placed in the appropriate cell within one of the tables. Each table corresponds to one of the ranges on the hardness axis in the FFPI system.

The points within the plane cells were plotted on the three-way FFPI axis. By way of comparison, a super-imposed box shows the approximate quality range for a Type A weld.

Confidence factors were computed from the Type B data range along the hardness axis. However, 90% of the FFPI welds fell within the Type A range when

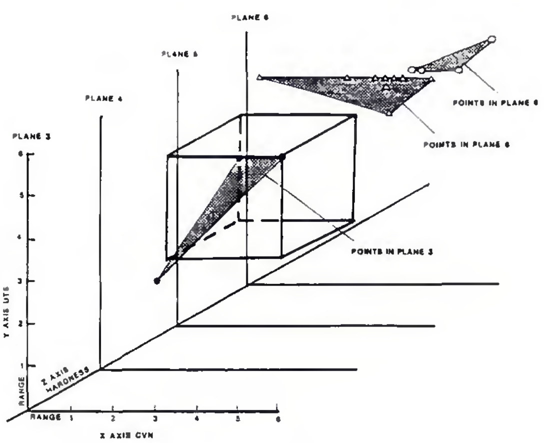


Fig. 3 — Fitness-for-purpose index.

Plane ranges defined by six equal divisions of hardness values

Graph Axis	plane 1	plane 2	plane 3	plane 4	plane 5	plane 6
Z axis (hardness)*	0-80.0	80-160	160-240	240-320	320-400	400-480

* Maximum hardness of HAZ with a 500g load on Vickers:DPH

X and Y coordinates in each plane defined by range divisions of values

Graph Axis	range 1	range 2	range 3	range 4	range 5	range 6
X axis (CVN)**	0-6	6-12	12-18	18-24	24-30	30-36
Y axis (UTS)***	40-46	46-52	52-58	58-64	64-70	70-76

** Charpy impact tests on weld metal at 32°F
***Reduced section tensile tests
Units: CVN (ft-lb) UTS (ksi)

considering tensile strength and Charpy V-notch values. The hardness limitation of 325 Vickers (DPH) is the most difficult of the mechanical properties to achieve.

Welded Connection Design

Knowing the true performance level of wet welds, a good wet welded connection design places the wet weld on the joint in a noncritical, but structurally sound location. Obviously, defect-free wet welding would be ideal, but is unfeasible. The use of full- penetration V-groove joints is not conducive to defect-free underwater welding, especially for pipe or tubing. Groove welds are inherently difficult, but in the wet weld environment, the overhead portion of the joint is very difficult. For these reasons, the choice of fillet wet welds is more desirable since they are usually more defect free and easier to install underwater.

A wet welded joint must support the applied design load. Initial design criteria must allow determination of connections strong enough to withstand these applied loads, with appropriate safety

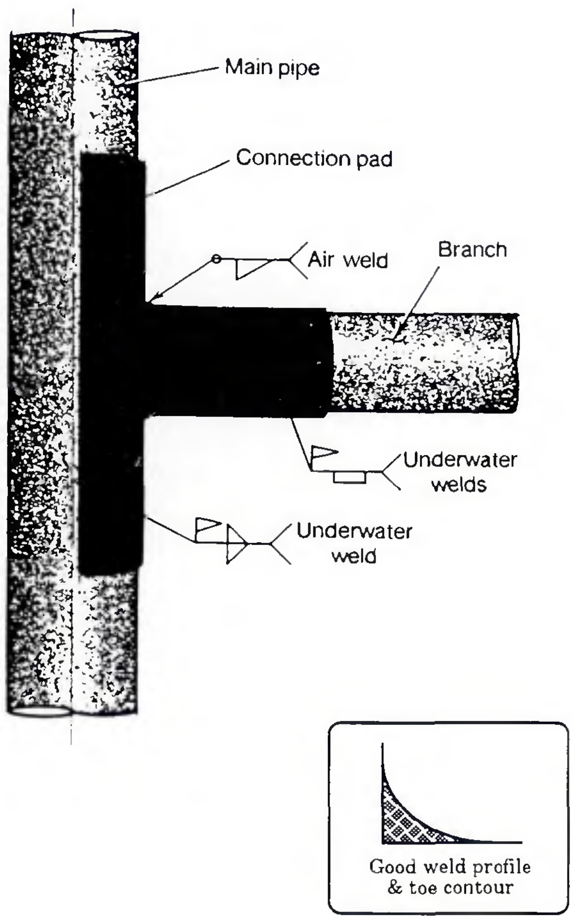


Fig. 4 — Flexible pad connection concept.

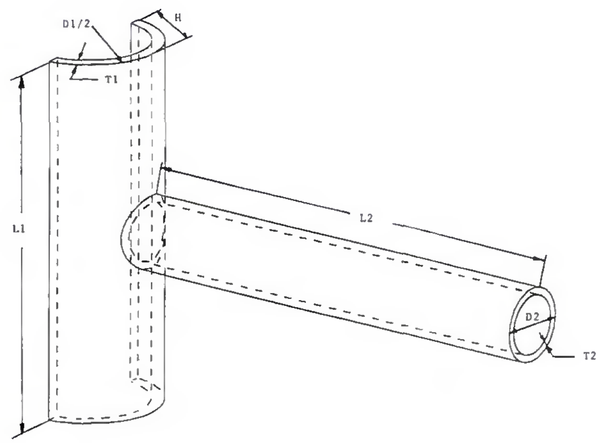


Fig. 5 — Geometric variables of flexible pad.

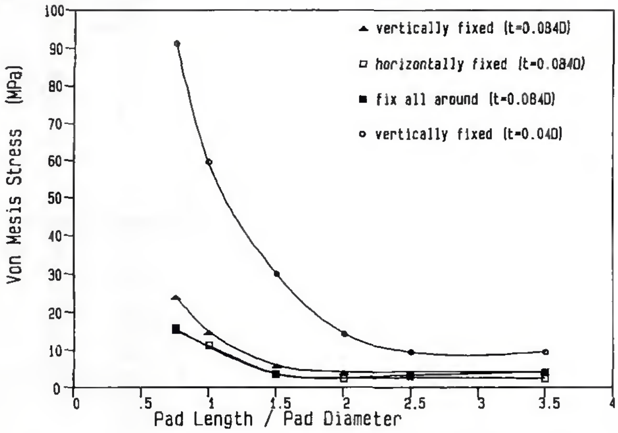


Fig. 6 — Effect of L1, T1 and weld position on S_w (bending).

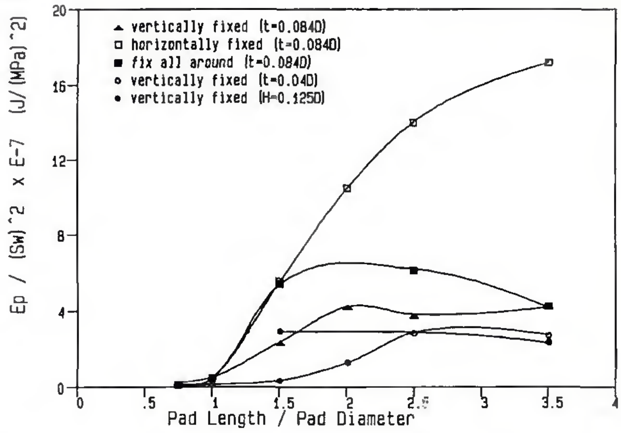


Fig. 7 — Effect of L1, T1, H and weld position on Ep/Sw^2 (bending).

factors. The other considerations are such problems as fatigue and brittle fracture.

The fatigue design is primarily a geometric problem. The AWS D1.1 code defines levels of fatigue performance using the stress range vs. life cycle (S-N) curves for different geometric categories of the welded joints. In addition, the weld profile, especially at the weld toe, causes stress concentration and initiates premature cracking. The wet welded joint must be designed so that acting cyclic stress at the weld toe be less than the allowable stress.

When the welded structure is subject to impact loading, or dynamic loading at high rate, the kinetic energy due to impact must be transformed into either motion (*i.e.*, kinetic energy) or deformation (*i.e.*, strain energy) of the structural members, or a combination of both effects. The resulting motion of the structural members dissipates the energy into the surrounding environment. The remaining energy stresses the structural members, including the connections joining the structural members.

The welded connections, as an integral part of the structure, play a significant role in determining the proportion of these two types of energy transformations in the structure. Cracking will occur if the strain energy density in the weldment exceeds the resilience of the weld metal or heat-affected zone. Charpy V-notch toughness indicates the impact resistance of the bulk material with the effect of notch stress concentration. Therefore, Charpy V-notch toughness of the weldment can be used to characterize the weld strength to resist impact loads.

As indicated by the weld property database, underwater wet welds are statically strong enough to carry any structural loads. However, these welds are of low Charpy toughness and high hardness and have little capacity of absorbing the impact energy. Brittle fracture will occur if these welds are subject to a direct impact.

Combining energy loss with energy absorption devices like springs or rubber shock absorbers, total impact energy absorbed by the connecting underwater welds can be minimized by using a flexible, intermediate connection pad. By design, the energy dissipates into the connection pad before reaching the underwater welds, and the impact energy at the underwater welds is minimized. The strain energy density in these welds is, therefore, kept below its toughness (resilience) limit. Brittle fracture of underwater weldments due to impact loading can be eliminated. The underwater wet welds are able to perform the intended structural functions.

Flexible Pad for Tubular Structural Connections

The design philosophy of a flexible connection pad is that an air weld can be substituted for a wet weld at critical positions where stress concentrations and high stress fields exist — Fig. 4. The wet welds are placed at low stress locations and the flexibility of the pad improves the energy absorption. Also, the weld profile and toe contour of the air weld, with higher stress capacity, is more consistent, controllable and capable of withstanding higher stress concentration factors. This design concept can be expanded even further for conditions requiring increased flexibility by using a multilayer pad design.

Typical tubular connections are the T, K, Y and X. Often these connections in offshore structures are braced in multiple planes, and the use or analysis of such a structure would be beyond the scope of this study. The T connection shown in Fig. 4 could be modified to include other connections, but for simplicity, the T connection and single layer pad design was used for this study.

The finite element method was used to analyze the stress distributions and energy absorption of the tubular connection. Optimum pad dimensions were determined for different variations of loading conditions. Figure 5 shows the geometric variables studied.

The design variables related to the pad geometry are pad length, L1; thickness, T1; and height of the arc, H. These variables were normalized with respect to a constant pad diameter, D1. The branch pipe dimensions are constant. The branch pipe diameter, D2, is half the pad diameter, D1. Thickness, T2 is 0.054 D1 and length, L2 is 3.0 D1.

The radial measurements represent diameters at the pad and branch pipe middle faces. Because of symmetric loading conditions, only half of the pad is required for finite element analysis. A linear elastic, thin-shell finite element was employed to accommodate computer storage space limitations and the nature of tubular geometry.

The flexibility of the pad, which is a function of pad geometry, improves the energy-absorption ability of the connection. Optimizing the connection pad design for different types of loading conditions, requires minimizing the stresses in the wet welds. Originally, flexible pad lengths were determined by consideration of the wet weld allowable static strength. Adding more weld length than necessary to the pad compensated for the wet welding degraded properties.

Several factors should be considered for pad design: maximum Von Mises equivalent stress in the weld (S_W), maximum Von Mises equivalent stress in the pad (S_P), total strain energy absorbed in the pad (E_P), ratio E_P/S_W^2 and ratio E_P/S_P^2. According to linear elasticity, the energy absorbed in the pad is linearly

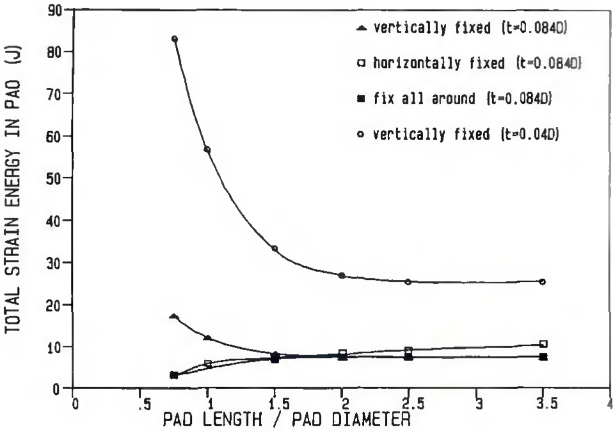


Fig. 8 — Variation of strain energy in pad (bending).

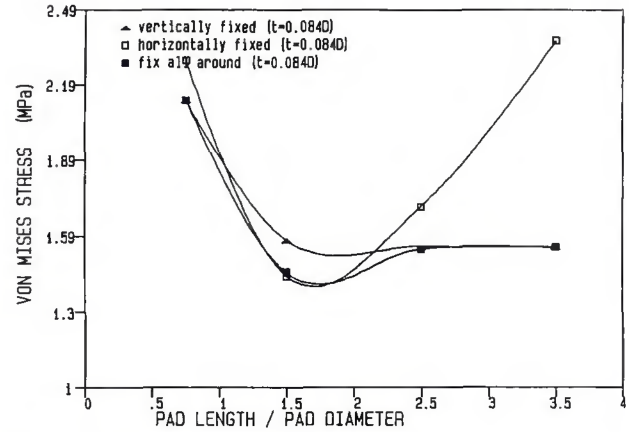


Fig. 9 — Effect of L_1, T_1 and weld position on S_W (tension).

proportional to the square of stress. The maximum Von Mises equivalent stress is different for each case. Therefore, it is necessary to use the ratio of the total strain energy in the pad to the square of the maximum Von Mises equivalent stress to compare the strain energy absorption for different pads, under the condition of sustaining the same maximum Von Mises equivalent stress.

An ideal pad design should minimize S_W and S_P, and have the maximum ratio for E_P/S_W^2 and E_P/S_P^2. However, practical engineering situations may not be this straightforward. It is quite possible that these conditions may not be agreeable with each other. A trade-off among these four factors may be required. Also, for different service purposes of the connection pad, changes in the optimization criteria may be necessary. Since underwater welding is widely used in the offshore petroleum industry, where the fatigue life is most important, minimizing the maximum Von Mises equivalent stress in the weld is a first priority, followed by maximizing E_P/S_W^2, and then maximizing total strain energy absorbed in the pad under a given loading level. Since the service performance of the pad can be improved by using a higher grade of material, the least priority is placed on those factors related to S_P.

Considering a typical flexible connection pad, which sustains a concentrated bending force parallel to the axis of the main pipe and applied at the end of the branch pipe, Fig. 6 shows the maximum Von Mises equivalent stress in the underwater welds as functions of the length to diameter ratio of the pad. Several weld conditions, such as welding along two vertical sides, along two horizontal sides, or along all four sides, as well as two different pad thicknesses, 0.084 and 0.04 times the pad diameter, were studied.

Reducing the pad thickness significantly increases the maximum Von Mises equivalent stress in the weld (S_W). When reducing the pad length to a given level, dependent upon the pad thickness, S_W increases. The weld position has less effect on S_W, compared with the other two factors. Horizontally placed welds exhibited the smallest S_W in the weld for the three weld positions examined.

The position of the weld has a predominant influence on the strain energy absorption in the pad (E_P). Figure 7 shows the effect of pad dimensions and weld positions on E_p/S_W^2 ratio. Horizontally welding the top and bottom of the pad creates a larger E_P/S_W^2 ratio when compared to the other welding positions. This is particularly true when the pad length becomes larger. When the pad length becomes equal to 3.5 D_1, the E_P/S_W^2 ratio for the horizontal welds is four times greater than those for the other two welding positions, provided that the remaining variables stay the same. Figure 7 also shows that the E_P/S_W^2 ratio becomes larger by increasing the pad thickness and the height of the pad arc H.

Variations of total strain energy in the pad are illustrated in Fig. 8. Maximum strain energy absorption (E_P) occurs when the connection pad is thin and short. For vertically placed welds, a larger E_P value is obtained by reducing the pad length. For the other two weld-

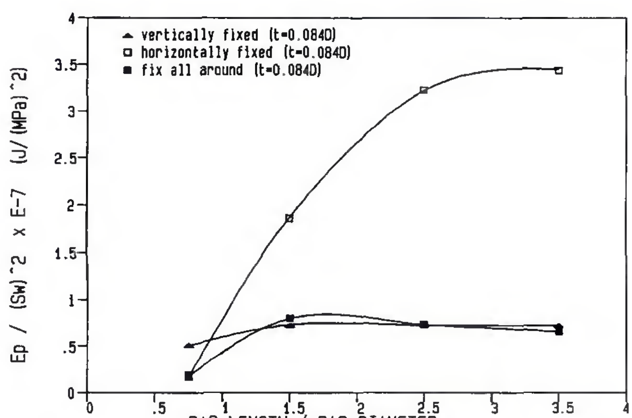


Fig. 10 — Effect of L_1, T_1, H and weld position on E_p/S_w^2 (tension).

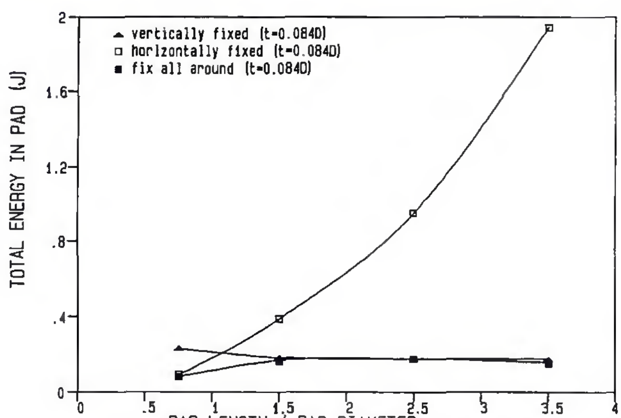


Fig. 11 — Variation of strain energy in pad (tension).

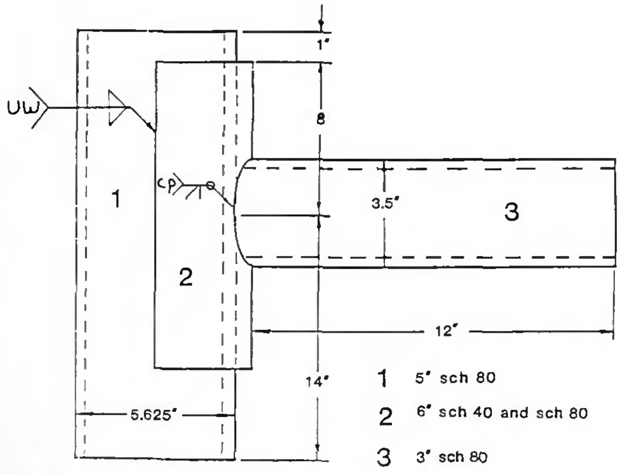


Fig. 12 — Details of pad connection for tests.

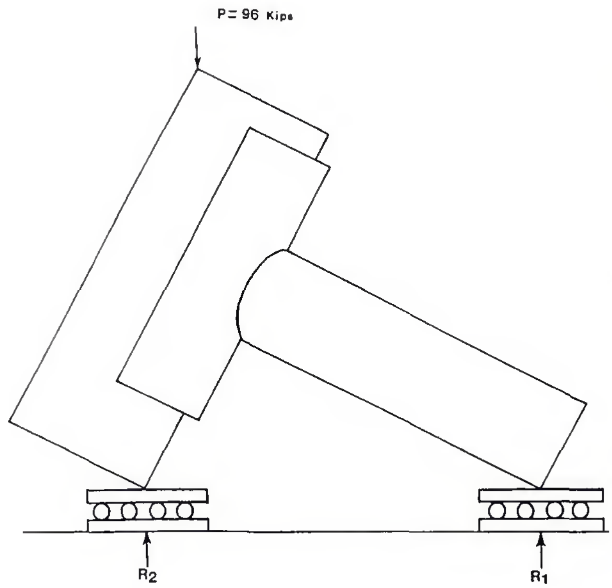


Fig. 13 — Static loading of T connections.

ing positions, a longer pad creates a larger E_P value.

By taking all of the above into consideration, and following the previously stated optimization criteria, it is not difficult to determine the optimum pad design under a bending load. The trend is to use a long, thick and large arc height pad, with underwater welds placed at the top and bottom of the pad. For the cases studied, the best pad design is as follows: pad length (L_1) = 3.5 x pad diameter (D_1); pad thickness (T_1) = 0.084 D_1; and the height of pad arc (H) = 0.5 D_1; the underwater welds should be placed on the top and bottom of the pad.

When the branch pipe is loaded in tension only, in contrast to the bending case, very small stress concentration is observed near the connection line between the pad and the branch pipe. Instead, the Von Mises equivalent stress in the pad always reaches its maximum value in the welds. This is true for all three welding conditions.

Figure 9 shows the relationship between the maximum Von Mises equivalent stress in the weld and the pad length. The maximum Von Mises equivalent stress reaches its minimum value when the pad length is between 1.5 and 2.0 D_1, and the pad is welded horizontally or all around to the main pipe.

Figures 10 and 11 present the effects of pad length on E_P/S_W^2 and E_P. The combination of horizontal welds and a long pad is most desirable for obtaining a high E_P/S_W^2 ratio and E_P value. However, the pad length should not exceed 2.0 D_1, or the maximum Von Mises equivalent stress will increase rapidly in the case of horizontal welds — Fig. 9.

Under tensile loading, the optimum pad length should be 2.0 D_1 and the pad should be welded horizontally. Clearly, this situation differs from the optimum pad design for the bending load. There are many situations where both tensile and bending loads are present at the same time. For these situations, a connection pad of length 2.0 D_1 with horizontal welds would result in low maximum Von Mises equivalent stress in the welds, and a relatively high E_P/W_S^2 ratio and E_P value.

In summary, the optimum dimensions for the length of the pad is 2 times the diameter of the main pipe, thickness is 0.084 times the diameter and arc height is 0.5 times the diameter. The optimum welding positions between the main pipe and the pad are all around the pad.

When the flexible connections are used, the whole structure will also respond to the change of the connection rigidity. Several design elements, such as possible reduction of structural rigidity, change of natural frequency, and increase in structural value requirements, must be considered.

Experimental Verifications

A total of 21 T connections were fabricated in a simulated diving condition (*i.e.*, diving tank). Of this total, six were used for static loading and seven for impact loading. There were four types of tubular T connections: thin flexible pad, thick flexible pad, air welded and underwater wet welded T. The pad connections varied only in the thickness of the pad, and the regular T connections varied only in that some were welded in the air and some were welded underwater. The fabrication of the pad connections followed the basic design shown in Fig. 12. The fabrication of the regular T connections was without the pad.

The T connection parts were cut using an oxyacetylene torch. The 6-in. (152-mm) piping was cut into 11-in. (279-mm) pieces and then sliced longitudinally for two pad pieces. The inside diameter of the Schedule 80 pipe closely matched the outside diameter of the 5-in. pipe and did not require much deflection to force the sides of the pad to touch the 5-in. (127-mm) pipe. The inside diameter of the Schedule 40 pipe is larger than the 5-in. pipe and required more deflection to have a snug fit on the 5-in. The Schedule 80 pieces were heated slightly to aid in the compression of the pad, and because of the thickness of 0.432 in. (11 mm), it was hard to bend.

The pad was tacked onto the main pipe, and then as the sides were compressed in a vise onto the main pipe, the pad was tack welded four places. After the pad was tacked in place, the 3-in. branch pipe was welded to the pad. The 3-in. (76-mm) piece was saddled and beveled to allow for a full penetration weld. The saddle was custom cut to allow 0.125-in. (3-mm) root opening with a 45-deg bevel.

This weld was accomplished using an open butt joint. The root and hot pass were welded with 0.125-in. (3-mm) E6010 electrodes, and the fill and cap beads with 3/32-in. (2-mm) E7018. Between the root and hot passes, the weld was ground out and brushed. The remainder of the welds were wire brushed between the layers.

After the T weld was finished, the

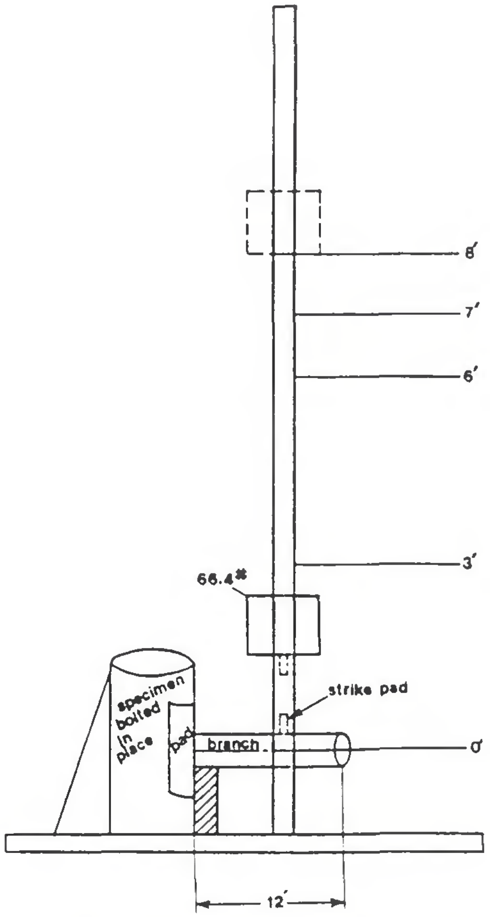
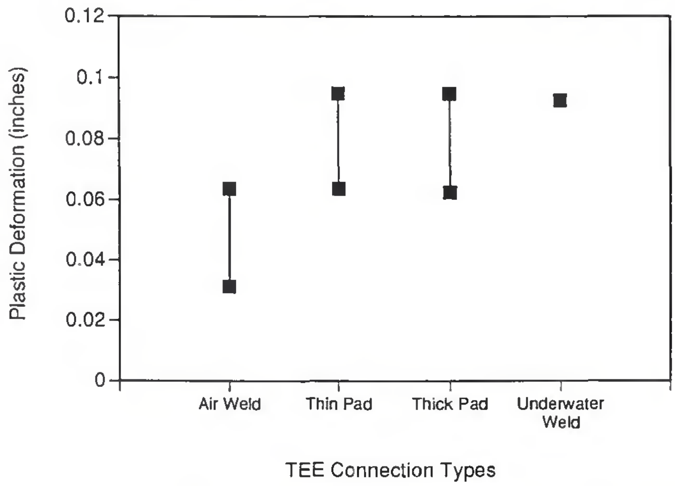


Fig. 14 — Impact loading of T connections.

Fig. 15 — Plastic deformation of T connection under impact load.



pad-to-main-pipe underwater welds were made. Each side of the pad was welded with three stringer beads. The top and bottom of the fillet welds were rounded to give a slight end-return. The underwater pad-to-main-pipe welds were fillet welds. The first attempt was made with 0.125-in. electrodes, but more satisfactory results were achieved with 5/32-in. (4-mm) electrodes.

The testing of the flexible pad connections included a static and impact loading condition. The connections for each test were selected by its weld quality. The static loading placed the bottom half of the T in tension, while the impact loading test stressed the top half. Therefore, the regions of the underwater welds with the best quality were selected for the particular test. The goal of the testing is to verify the fitness-for-service and not to see if a defect will cause or add to a failure.

Static Loading

The joints were tested under a static loading condition to compare the strength of the pad and fillet welds to the in-the-air welded structure. The static loading induced both a bending and shear stress. During the first test, the sharp corner edges of the joint gouged into the fixture and the fixture failed by bending under a 140 ksi (623 kN) load. The joint did not bend, because the structure had become as a rigid frame.

A second attempt was made using roller bearings sandwiched between 4.0 x 6.0 x 0.625-in. (102 x 152 x 16-mm) thick machined plates beneath the T joint during loading. This rolling base would allow the ends of the T to move or roll — Fig. 13.

Six of the T connections were given a compressive load of 96 ksi (427 kN). None of the connections failed from the loading. The loading condition was two times higher than the calculated yield point of 48 ksi (213.5 kN). The contact points of the T connections were severely deformed, but no plastic deformation of the branch tube at the weld was observed.

Impact Loading

A fixture device was designed to secure and hold a test joint in place while a weight was dropped on the end of the branch tube — Fig. 14. The branch tube had a clamped striking pad bolted 11 in. (279 mm) from the main tube. This strike point served to concentrate the impact at the end of the tube. Through calculations, it was determined that four pounds dropped from 6 ft (1.83 m) would cause a plastic deformation in the branch tube of 0.1 in. (2.54 mm). The hypothesis was that if the plastic limit of the tube was reached before the welds failed, then the strength level of the joint exceeded the strength of the material, and the welds passed on a fitness-for-purpose test.

The first trial joint gave a 0.125-in. deflection with 33 lb (147 N) from 5 ft (1.52 m) in height. In order to achieve greater deflection and see a greater discrepancy between the regular T and the pad concept T, the weight was doubled and raised to 7 ft (2.13 m) high. Each joint was fitted and bolted in place, the distance between the base plate and a gauge mark was measured. The weight was dropped and impacted the tube. It was then lifted off the end of the tube before measuring the deformation.

The weld areas were checked with dye penetrant after testing. None of the connections impact tested showed any surface cracking. However, the plastic deformation from impact loading was higher for the underwater welded T joint than the padded Ts. The completely air-welded T connection had lowest plastic deformation. Figure 15 shows the plastic deformation of various types of T connections from the impact loading.

Upon a macro examination of the weld cross-section, two root bead cracks were noticed in the underwater welded T joint. The top crack traversed one-third of the thickness of the branch tube. No crack was found in the padded joints, nor in the air-welded T joints. These cracks may explain why the deformation from impact was greater than with the padded T. In comparison to the air-welded T connections, the flexible pad caused greater plastic deformation in the padded T.

Conclusions

The most significant finding of this study was the flexible pad concept for a joint connection. The energy dissipates in the connection pad before it reaches the welds made underwater, and the energy stress in the welds is minimal. The stress in the underwater welds is kept below the endurance limit for infinite fatigue life. The joint performance under impact loading would also be improved. Several other advantages with this connection would include quick installation; little or no fit-up time; better weld quality with fillet welds but not groove welds, which typically are of poor quality in subsea conditions; premade parts for ready installation; and viability for new construction or fabrication. This concept appears to be a feasible method of circumventing the expected pejorative consequences of degraded mechanical properties in a connection, maintaining performance limits, and economically benefiting from connections which are less expensive and easier to install.

Through this research on the degraded Type B weld properties and underwater welding, several specific conclusions can be made.

1) Statistically, 11% of Type B welds meet Type A hardness criteria; whereas, 90% of Type B welds meet Type A Charpy V-notch and ultimate tensile strength requirements.

2) The ultimate tensile strength of an underwater wet weld is equal to that of an air weld, but the Charpy V-notch values are 62% to 75% less.

3) In a static loading condition, the flexible pad Ts were as strong as the air-welded Ts.

4) The flexible pad Ts displayed more deflection than the air weld Ts, hereby reducing the amount of stress affecting or acting on the welds.

5) The impact stress caused cracking in the underwater welded T, but not the other Ts.

6) For a connection pad sustaining a concentrated bending force parallel to the axis of the main pipe and applied at the end of the branch pipe, its optimum geometry is L1 = 3.5 D1, T1 = 0.084 D1 and H = 0.5 D1, when the diameter of the branch pipe (D2) is half of the pad diameter (D1). The welds connecting the pad and the main pipe should be placed on the top and bottom of the pad.

7) When a tensile force is applied uniformly along the axis of the branch pipe of the connection pad with D2 = 0.5 D1, the optimum pad length (L1) is 2.0 D1, and the optimum welding positions between the main pipe and the pad are the top and bottom of the pad.

In summary, underwater wet welds can be used in their present state for structure repair or construction if a proper design procedure is adopted. The idea is to solve the weld impact problem by reducing the stress in the wet welds through proper design. The wet welding processes currently used by the offshore industries can still be used without any modifications. The wet welded joints will fit for their intended service without compromising the economical advantages.

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