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Some Extreme Effects of Residual Stresses in Shipbuilding

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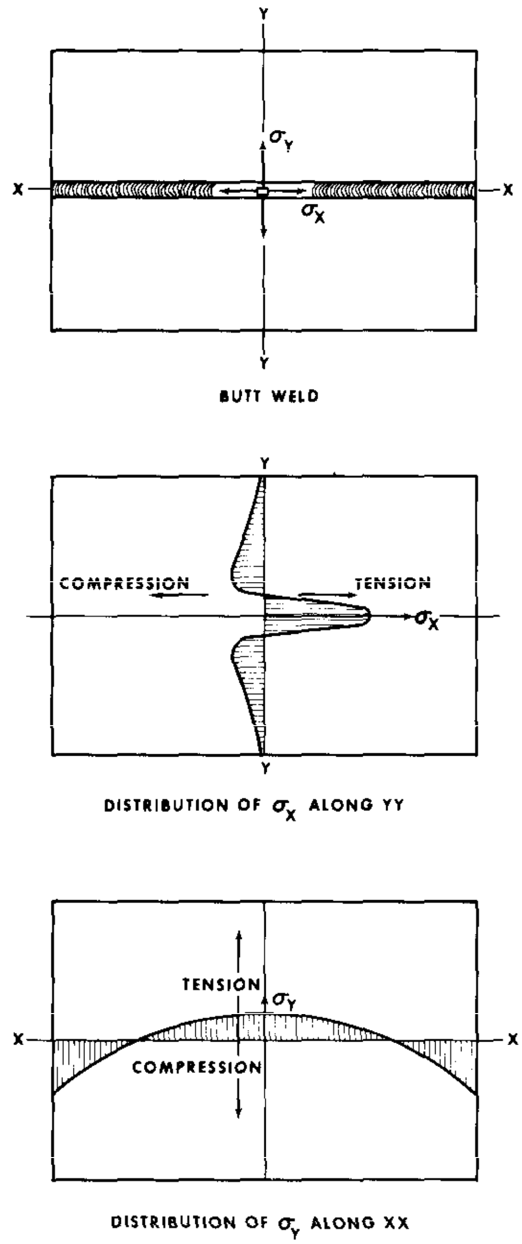
ABSTRACT

During the past four decades, a wealth of information has been written on the subject of residual stresses and their effects on structural materials. Of particular interest has been the role of residual stresses in contributing to brittle failures. Such failures usually occur without warning, in low stress conditions, and often are catastrophic. These failures, or fractures, are the more dramatic manifestations of a number of contributing factors which may include residual stresses. A number of different sources may generate residual stresses, but the one source having the greatest significance to shipbuilding is welding. The distortional effects of residual stresses are visibly evident after welding a fabricated structure and it is this distortion that is a cause of continual straightening problems.

A more pragmatic approach is used in this paper to look at residual stresses than is usually found in other papers on the subject. Following a brief description of the nature of residual stresses in welded construction and their effects on structures, three recent case histories of the kind of problems facing shipbuilders are discussed. The first case reviews the multiple fractures experienced on a hawse pipe weld overlay during fabrication and the subsequent changes in procedures employed to remedy the cracking problem. The second concerns the angular distortion produced by butt welding thick steel plates and describes a welding test undertaken to minimize the problem. The third case describes the fracture of the trailing edge casting of an oil tanker during construction and reviews the contributing causes and their effects.



RESIDUAL STRESS DISTRIBUTIONS IN A BUTT WELD

FIGURE 1

INTRODUCTION

Residual stresses are the internal stresses which remain within the material of a plate or shape after the thermal cycle of welding. They are generated by the highly localized heating and subsequent cooling of the weld metal causing thermal contraction of the surrounding base metal in the heat-affected zone. As the molten weld metal solidifies, it exerts tensile shrinkage stresses on the adjacent metal which usually increase to the yield point of the material as the ambient temperature is reached. Welding is normally performed linearly in a progressive manner so that the completed portion of the weld resists the weld bead deposited beyond it. This produces longitudinal tensile stresses in the weld and in the adjacent base metal. Other tensile residual stresses are also produced in the transverse direction of a butt weld as the cooler underlying weld passes resist the shrinkage of subsequent depositions. These stresses exist in any weldment without the presence of external forces and consist of a system of opposing stresses which balance one another. Figure 1 illustrates the longitudinal and transverse residual stress distributions in a butt weld without external restraint (1).

Residual stresses are also known by a variety of other names such as initial stresses, locked-in stresses, reaction stresses, shrinkage or contraction stresses, and inherent stresses. These stresses may also be thermal stresses, which are internal stresses that exist during the process of heating and cooling when the temperature change is nonuniform and a stress remains. Residual stresses exist in various kinds of metals and are produced by many sources. Among these are the rolling, forging, and casting operations necessary to produce shapes and plates. In addition, the working and shaping processes applied to metals such as machining, cutting, grinding, burning, and bending will also develop residual stresses to varying levels.

There are two major effects of residual stresses in welded structures. The first is distortion which is caused by the shrinkage stresses acting on a welded joint from localized heating and cooling. The weldment deviates from its prior position as the stresses produce local yielding and a permanent redistribution occurs. The resulting dimensional change is usually a reduction in size accompanied by overall warpage in several directions. Distortion is always present in varying degrees when welding materials of any thickness and it must be taken into consideration in order to remain within most construction tolerances.

The second major effect of residual stresses is that they may be the cause of premature failure by brittle fracture at low applied stress levels. All weldments contain multiaxial stresses at or near the heat-affected zone of the weld and these stresses may be of yield point magnitude. When a small flaw occurs in a region of high tensile residual stress, the stress intensity is increased considerably. The defect or crack may grow in an unstable manner until it passes out of the tensile residual stress region. If the applied stress level is low, the crack may arrest or may continue to grow depending on the overall state of stress at the crack tip and the inherent toughness of the material. Brittle fracture may be the end result of the crack propagation which may not occur without the presence of residual stress (1,2).

CASE HISTORIES OF SOME EXTREME EFFECTS OF RESIDUAL STRESSES

Welded construction of naval and commercial ship structures involves a wide variety of applications, many of which require state-of-the-art techniques needed to effectively join numerous types of materials. The effects of residual stresses provide challenges to the shipbuilder to improve the reliability of welded structures. The three case studies discussed below are some of those challenges.

Aircraft Carrier Hawse Pipe Fractures

During the construction of an aircraft carrier at Newport News Shipbuilding, severe fractures occurred during the fabrication of the port hawse pipe prior to shipboard installation. Residual stresses caused by the weld deposition of the required hard-surface overlay were initially thought to be the principal cause of the problem, but subsequent examinations revealed that there were other contributing factors as well. The exterior portion of the hawse pipe as it extends through the ship's shell near the bow is shown in Figure 2.

The hawse pipe was constructed by welding two different castings to the ends of a center section 1220 mm (48 in.) in diameter and about 2.4 m (8 ft) long. This center section is comprised of two semi-circular, rolled, mild-steel plates, 44 mm (1.75 in.) thick above and 70 mm (2.75 in.) below, welded together longitudinally. The total weight of 15.38 Mg[1] (33 900 lb) is almost equally distributed among the three main pieces. The material used for the upper and lower castings is similar to mild steel and meets the requirements of Military Specification MIL-S-15083B(NAVY) for Grade B steel with a yield strength of 207 MPa (30 000 psi) and a tensile strength of 414 MPa (60 000 psi).

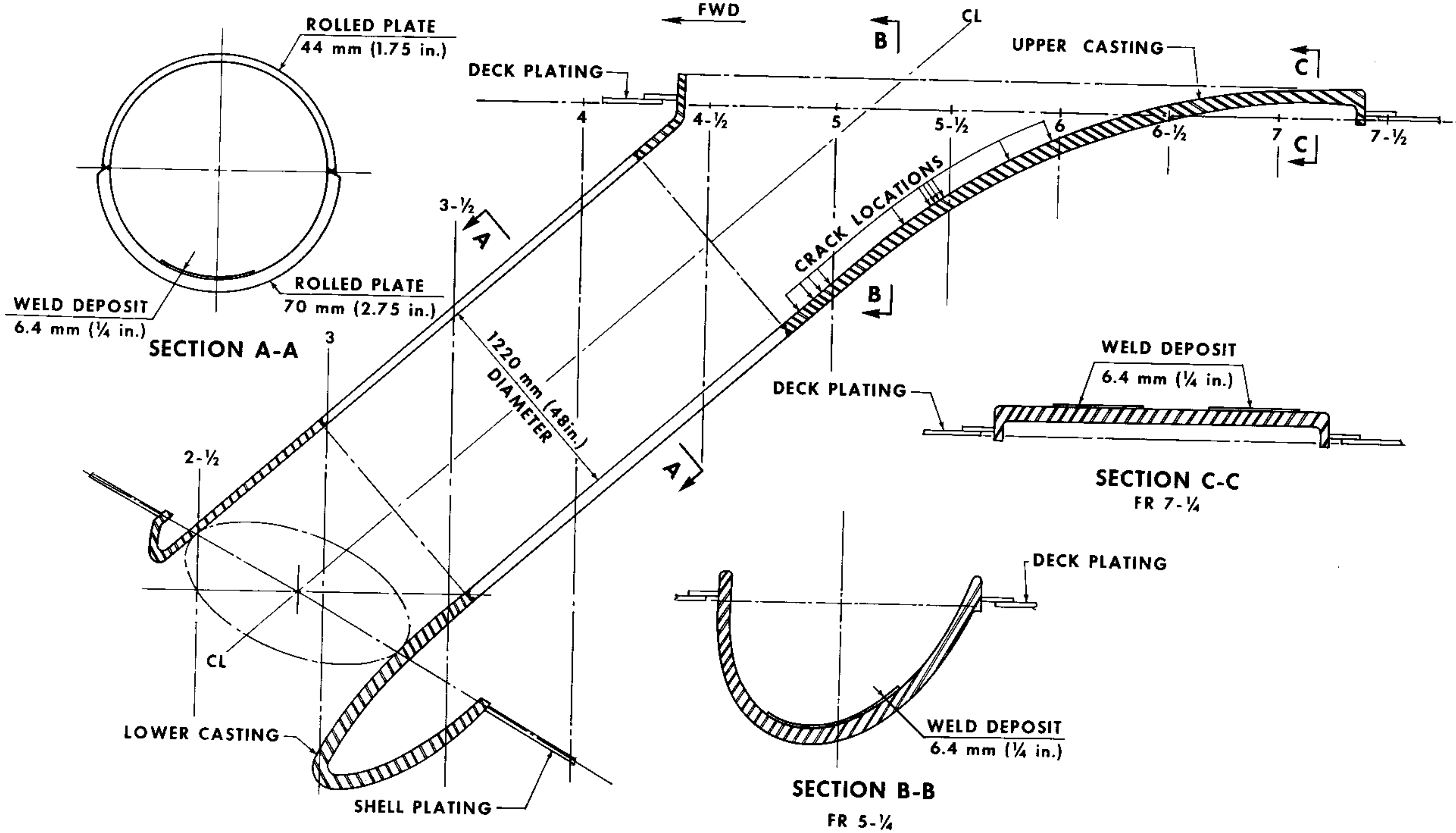
The planned sequence of assembly was to butt weld the upper casting to the center rolled section, add the weld overlay to the lower interior surface in the fabrication shop, and then install these two sections into position onboard the ship. The lower casting, forming the exterior portion of the assembly, was also clad in the shop and then erected onboard the ship by welding to the center section and to the ship's shell plating. Figure 3 illustrates the completed port hawse pipe assembly after erection.

No cracking problems were encountered with the upper casting until the required hard-surface overlay was deposited by welding to the interior surface of the hawse pipe. This 510-mm (20-in.) wide weld deposit extends for the full length of the assembly and spreads out to 1020 mm (40 in.) where the upper casting flattens out and widens to accommodate the two different lead angles of the anchor chain. The purpose of this 6.4-mm (1/4-in.) thick weld deposit is to provide an abrasion-resistant surface to prevent excessive wearing of the hawse pipe by the anchor chain. After preheating the assembly to a minimum of 121°C (250°F), the overlay was deposited using a semi-automatic flux cored arc welding process with a qualified, commercial, hard-surfacing electrode. The maximum interpass temperature allowed was 204°C (400°F).

[1] Megagrams (1 Mg = 1 metric ton). The International System of Units (SI) used in this paper follows the guidance of the ASTM E380-79 "Standard for METRIC PRACTICE".

AIRCRAFT CARRIER HAWSE PIPE EXTERIOR

FIGURE 2



PORT HAWSE PIPE

ELEVATION AT CENTERLINE

FIGURE 3

After the hard-surface overlay was deposited along a partial length of the hawse pipe, a fracture occurred in the upper casting during a weekend when no work was being performed on it. The crack had formed at the top surface of the overlay in the transverse direction and had propagated into the casting to a depth of 25 mm (1 in.) and had extended for a length of 610 mm (24 in.). The casting was weld repaired in accordance with approved procedures with peening being employed on alternate layers of weld metal. A magnetic particle inspection was performed on the root after gouging to sound metal and also on the final surface. The hard-surface overlay was reapplied using a wandering sequence to avoid local overheating and, upon completion of the welding, the preheat was slowly removed.

During the next 6 months, 10 additional fractures occurred in the upper casting at different locations as shown in Figure 3. These cracks ranged from 25 mm (1 in.) to 79 mm (3-1/8 in.) deep and from 406 mm (16 in.) to 840 mm (33 in.) in length and were spread out over an area of 1.1-m^2 (12-ft^2) in the upper casting. The casting thicknesses in the affected areas varied from 83 mm (3-1/4 in.) to 95 mm (3-3/4 in.) plus 6.4 mm (1/4 in.) for the weld overlay. After several fractures were repaired with the flux cored electrode, the weld overlay was deposited using a covered welding electrode conforming to Military Specification MIL-E-19141C, type MIL-I-A2a, which has a required minimum Brinell hardness of 200-400 (as deposited). This electrode is made from an iron-based alloy and the weld was deposited in a wandering sequence by shielded metal arc welding. Since additional fractures continued to occur after the electrode was changed, it was concluded that the hard-surfacing deposit was being subjected to tensile stresses after welding and that the removal of the preheat and subsequent movement of the assembly was the likely cause of the cracking. The last weld repair was accomplished after the hawse pipe was welded into its final position onboard the ship in an effort to restrain the movement from preheating. The hard-surfacing was applied after the casting was preheated to only 16°C (60°F) and skip welding, using short increments, was employed with a 66°C (150°F) maximum interpass temperature. The final weld repair, which was later ground smooth to preclude wearing of the chain, is visible in Figure 4.

The causes of the multiple fractures experienced on the port hawse pipe described above are interrelated and their combined effects contributed to the unfortunate end result. Residual stresses due to shrinkage of the weld overlay are high on the list of likely contributing factors. Some of the other causes that were believed to add to the problem were:

- the basic metallurgical structure of the iron-based hard-surfacing alloy which is inherently prone to cracking;

- the characteristic shape of the surface and subsurface weld deposit from flux cored arc welding which creates potential discontinuities as compared to shielded metal arc welding;

- the complex shape of the upper casting since it is a compound curve and varies rapidly from a circular section to a "U" shape and then to a flat section;

- the preheating of the underside of the casting causing thermal expansion to change the shape of the casting; and

- the lack of restraint of the hawse pipe since it rested on blocks in the shop permitting the casting to expand and contract freely.

The initial response to the problem was to excavate the cracks and complete the necessary weld repairs. This approach was insufficient as the fractures continued to occur without a specific pattern from which definite conclusions could be drawn. The resolution to the cracking problem described above involved eliminating as many of the likely causes as possible. The various changes that were employed were:

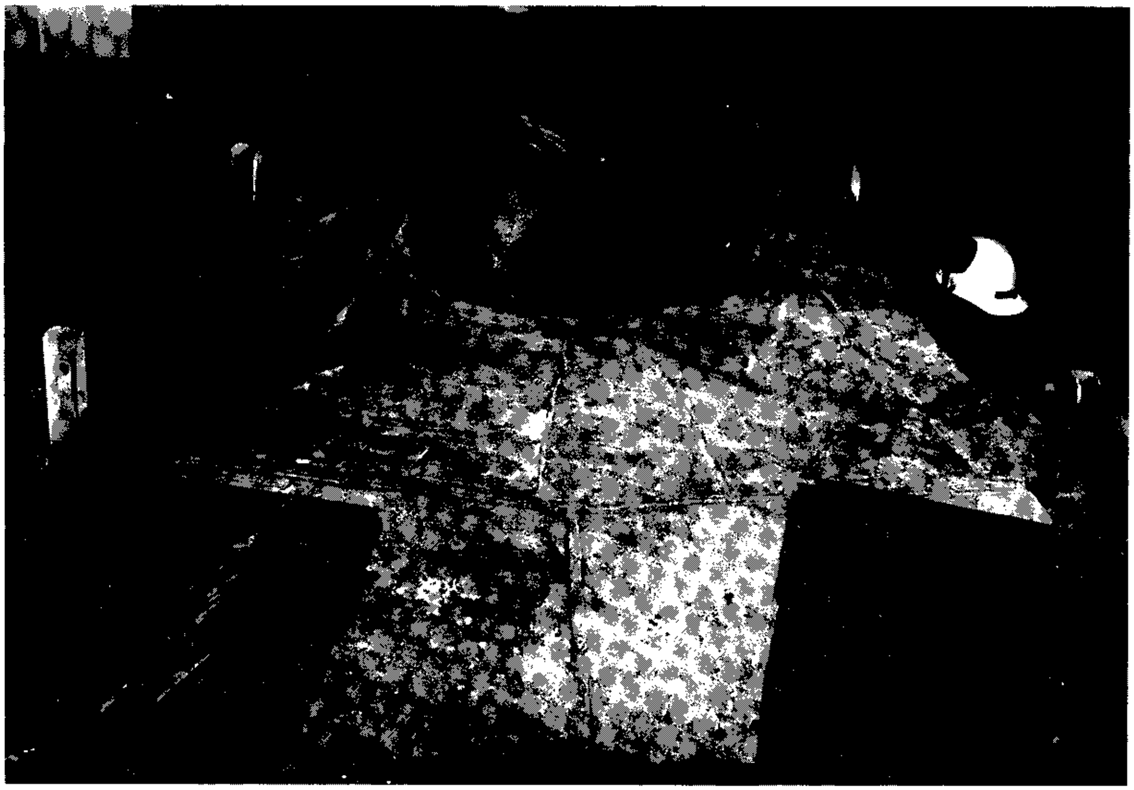
- switching from flux cored arc to shielded metal arc welding with a corresponding change in electrodes;

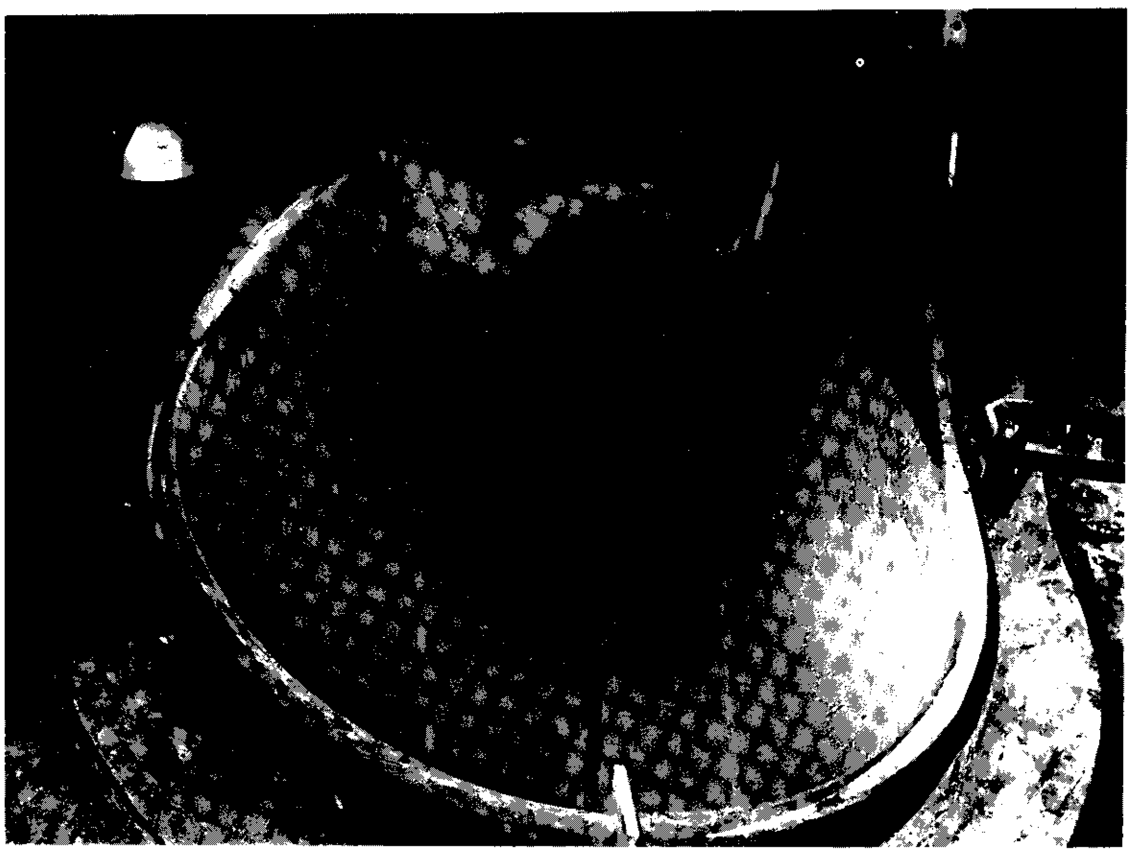
- reducing the preheat from 121°C (250°F) to 16°C (60°F) prior to welding;

- installing the hawse pipe onboard the ship to prevent movement during the repair welding of the overlay; and

- controlling the local heat build-up by using a wandering welding sequence and a 66°C (150°F) maximum interpass temperature.

It should be pointed out that these solutions evolved over a period of time and are not necessarily hard-and-fast rules to be applied elsewhere. In fact, there are many vagaries in welding that still defy explanation. For instance, the starboard hawse pipe, which is a mirror image of the port hawse pipe, was fabricated in a similar manner with fewer cracking problems. The upper casting was overlaid with weld deposited by shielded metal arc welding in the shop after preheating the casting to 121°C (250°F). Two transverse cracks developed that were 25 mm (1 in.) deep and 610 mm (24 in.) long which were repaired. No further occurrences were encountered as the overlay welding progressed to completion. The starboard hawse pipe assembly unit was then successfully welded to the ship's deck and shell structure as originally planned without inducing any additional fractures to the casting or to the hard-surface overlay.



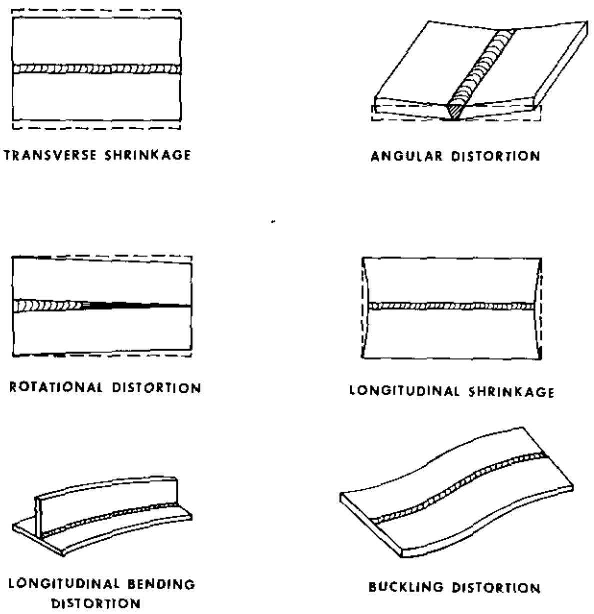


PORT HAWSE PIPE-FINAL WELD REPAIR

FIGURE 4

Angular Distortion in Thick Plates

The welding of materials produces undesirable side effects commonly called distortion. Occurring in many forms, distortion is the visible result of residual stresses produced by the welding process. Due to the extreme heating of the material during weld metal deposition and the subsequent cooling to ambient temperature, thermal strains are imposed on the grain structure throughout the material within the heat-affected zone. As the weld metal solidifies, it shrinks slightly, but it cannot generate the stresses that are responsible for reduced dimensional changes or other changes to the weldment's shape. After solidification occurs, the weld metal continues to cool and contract. This thermal contraction can generate stress in the solidified metal, but the maximum stress is limited to the yield strength of the weld metal. The internal forces generated result in plastic deformation which causes various displacements by bending, buckling, rotating, or shrinking the plate or shape. Various types of weld distortion are shown in Figure 5.



TYPES OF WELD DISTORTION

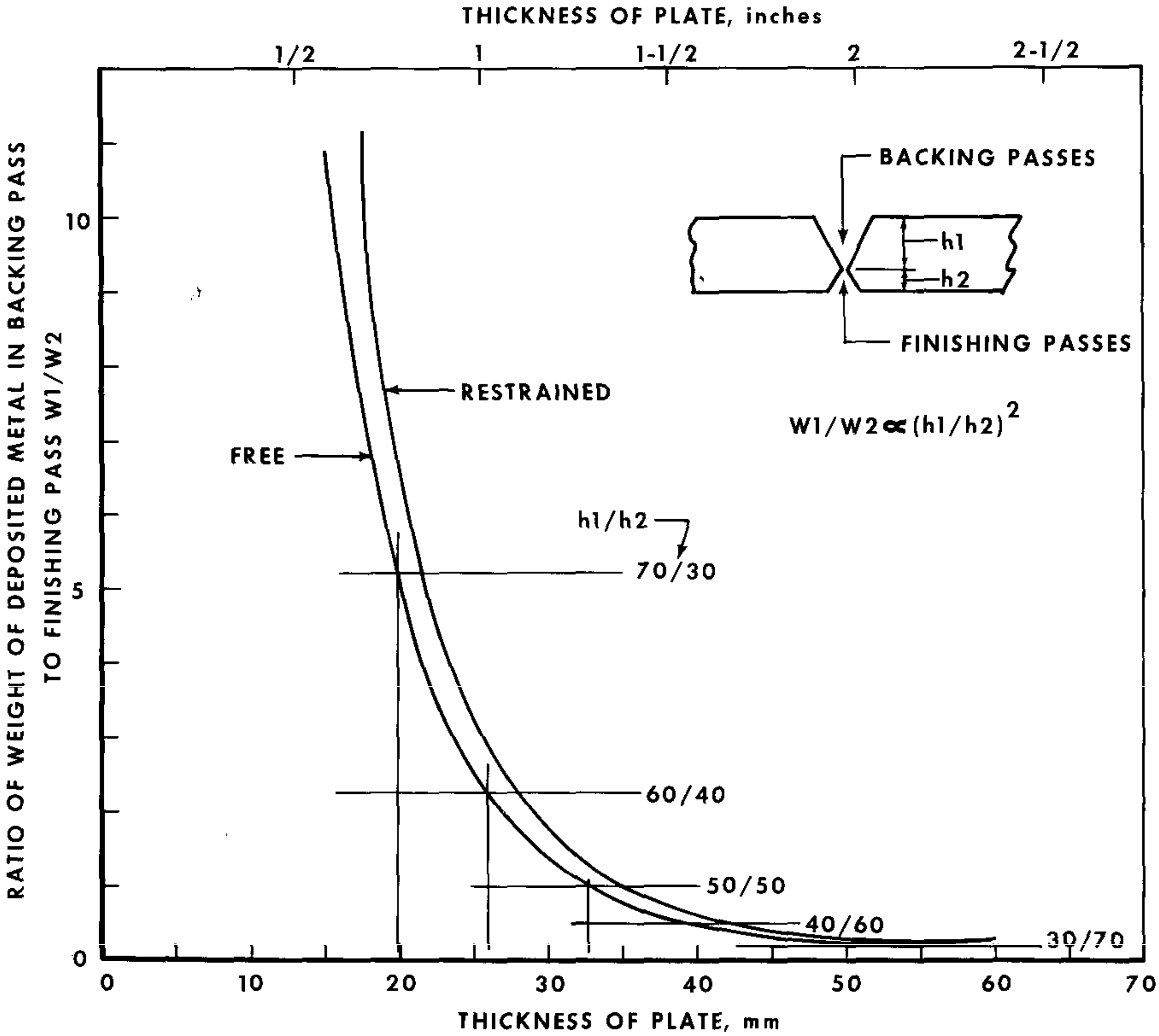
FIGURE 5

As the thickness of the material increases, the problem of distortion becomes more significant because the degree of difficulty of eliminating or controlling these unwanted displacements also increases. Distortion in a welded structure cannot be eliminated entirely because of the complex variables associated with the welding process. A prudent approach to resolving the problem of distortion is to minimize or reduce it to an acceptable level that is appropriate for the intended service of the structure. It is generally easier and more cost effective to achieve reductions in distortion through proper planning of the weld joint design rather than postweld plate straightening during the construction phase.

One of the most common types of distortion found in welding thick plates is angular distortion at butt-welded joints. Rotation about the longitudinal axis of the weld occurs when the weld metal at the face of the weld shrinks more than at the root. Traditional shipbuilding practice for the welding of thick plates in excess of 25 mm (1 in.) has been to use an offset double-beveled joint design. The bevel is offset in order to control distortion and the included angle of the bevel is held to a minimum which is usually 45°. The larger bevel is partially welded on the first side and then the plate is turned over to backgouge the root to sound metal. The smaller bevel is filled with weld metal and then the plate is turned back over to the first side to complete the joint. If excessive angular distortion is experienced during the welding operation on a particular side, the welding is halted prematurely and the plate is turned over to weld on the other side to "pull" the plate back into position, thereby requiring several additional turns to finish the joint. It is relatively easy to visualize how distortion can disrupt production schedules and quickly increase costs. The associated problems become more acute as plate thicknesses increase since straightening thick plates after welding is difficult and time-consuming. As a last resort, the weld must be cut out to a sufficient depth to permit a hydraulic press to flatten out the plates which are then rewelded to achieve the required flatness tolerance. This approach cannot be implemented onboard a ship under construction and, therefore, mechanical straightening methods must be employed.

The angular distortion in butt welds was extensively studied by the Shipbuilding Research Association of Japan as reported by Masubuchi (3). Double-beveled butt welds with several offset groove depths were investigated in order to minimize the angular change due to welding from both sides with and without joint restraint. The graph in Figure 6 illustrates the weld joint design for various thicknesses which most successfully minimized the angular distortion with a single turn of the plate (3). For example, when welding a butt joint in a 25-mm (1-in.) plate without joint restraint, the ratio of bevel depths for minimizing angular distortion, expressed as a percentage of the total plate thickness, is 60 to 40. The corresponding ratio of the weight of weld metal deposited (w_1/w_2) will be 0.36 to 0.16, or 2.25. Therefore, it takes over twice as much weld metal on the backing side to eliminate the distortion. A balanced weld joint design should be used on a 32-mm (1.25-in.) plate. For thicker plates up to 64 mm (2.5 in.), 40/60 and 30/70 joints are recommended to reduce distortion which positions the larger bevel on the finishing side.

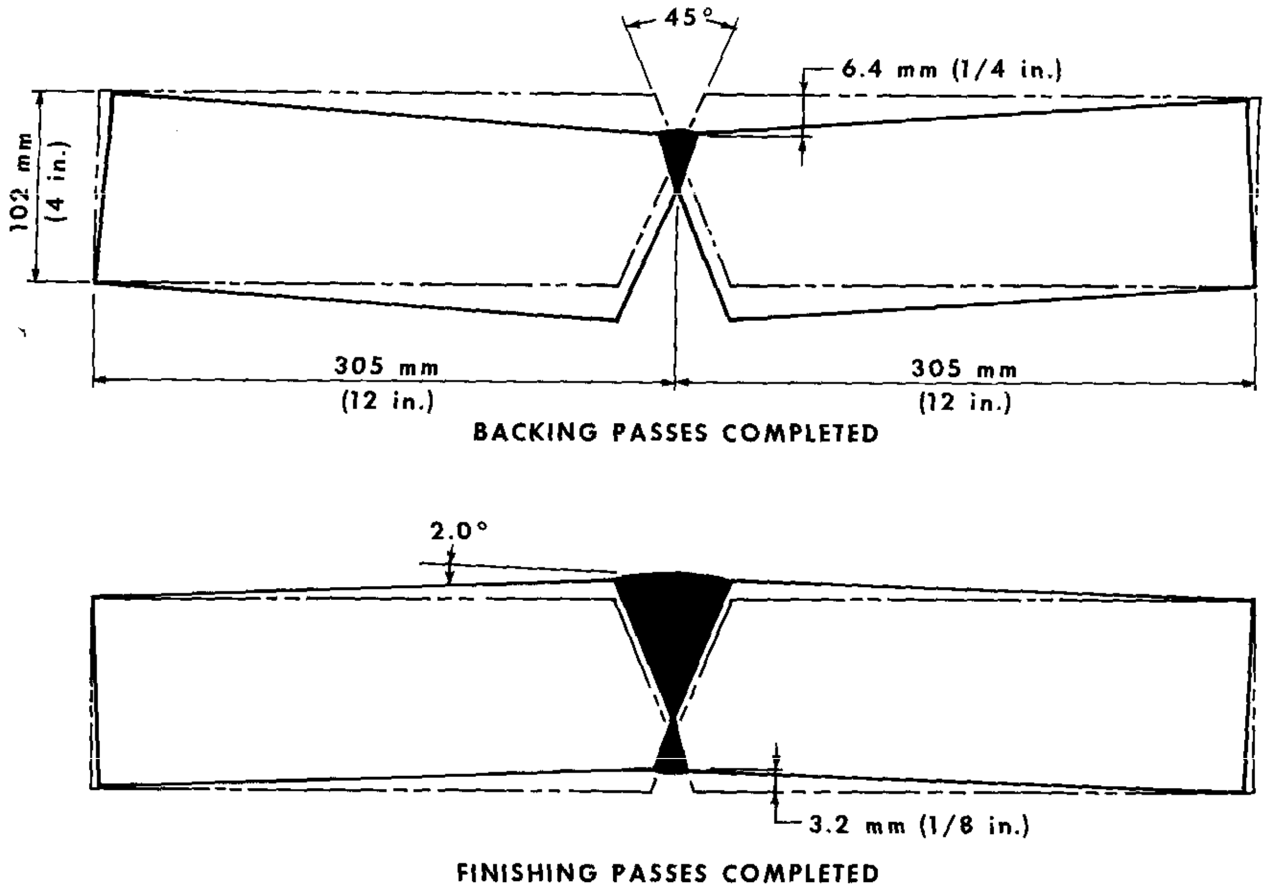
In order to further investigate the potential of welding thick plates and reducing plate handling without increasing the angular distortion, a welding test was recently conducted at Newport News Shipbuilding. Two 102-mm (4-in.) plates made of HY-80 steel were beveled to a 30/70 joint configuration. Each plate was approximately 305 mm (12 in.) wide and 1520 mm (60 in.) long. Measurements taken prior to welding indicated that the plates were fair to within 0.80 mm (1/32 in.). Figure 7 illustrates the test plates in their distorted positions (exaggerated) after each side was welded. The backing passes on the 30 percent side were deposited in the flat position by submerged arc weld-



OPTIMUM BUTT WELD GEOMETRY TO MINIMIZE ANGULAR DISTORTION

FIGURE 6

ing in 12 passes without restraining the plate. A displacement of 6.4 mm (1/4 in.) was measured at the edge of the weld by placing a straight edge between the outer edges of the plate and then measuring down to the plate. The plates were turned and the root of the weld was inspected for cracking after removing the ceramic backing tape used to eliminate the backgouging to sound metal. The finishing passes on the 70 percent side were completed in 43 additional passes using a 2.4-mm (3/32-in.) wire electrode designated as 100S-1. The preheat temperature was 93°C (200°F) minimum and the interpass temperature was held to 149°C (300°F) maximum. The welding of the finishing side reduced the distortion by 3.2 mm (1/8 in.) leaving an the overall distortion of 3.2 mm (1/8 in.). Since the width of the plates must be taken into consideration when discussing measurements of angular distortion, it is more appropriate to refer to the angle formed by the intersecting surface planes of the plates. This angle, representing the overall distortion, was approximately 2.0° which would result in significant unfairness when welding wide plates.

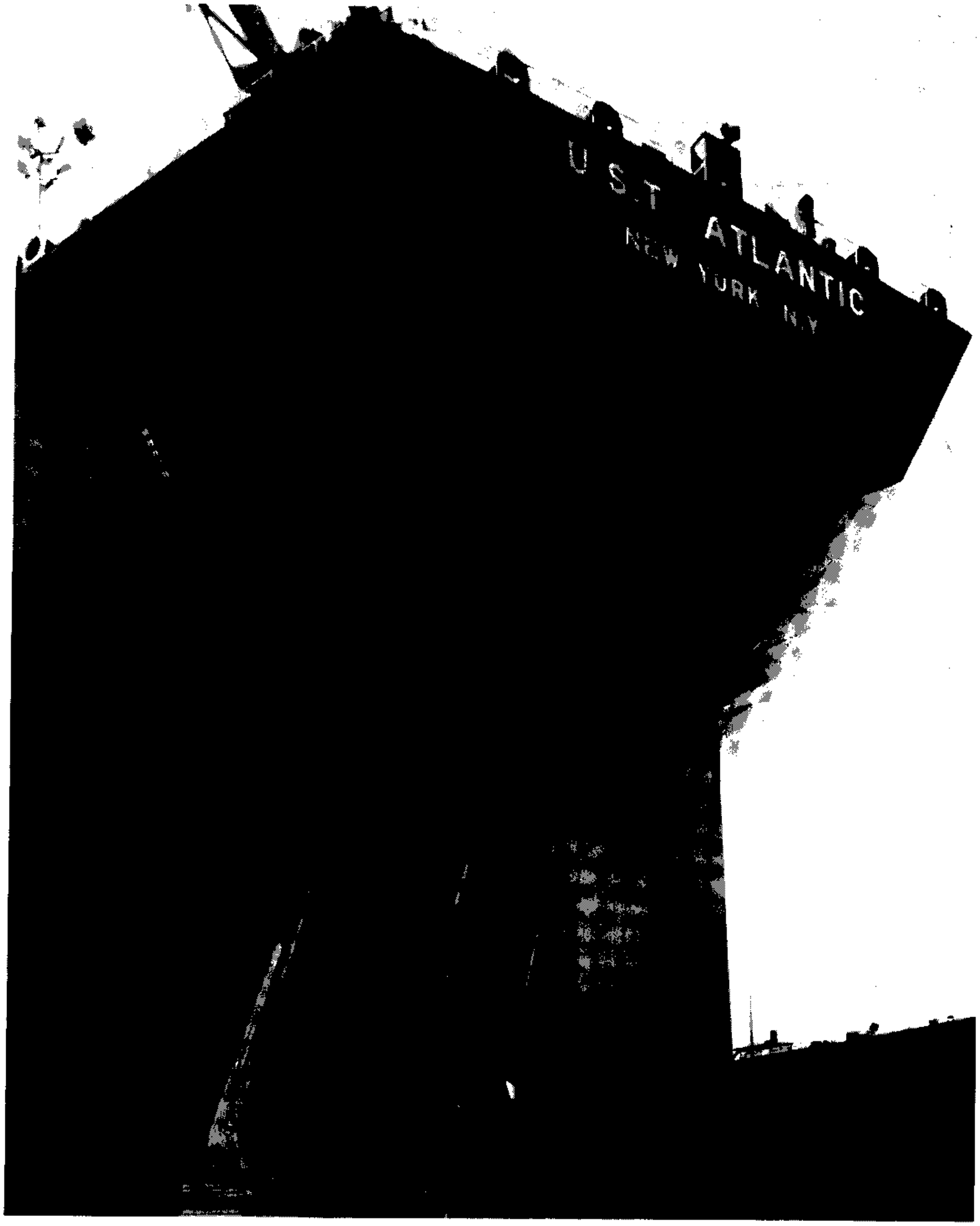


ANGULAR DISTORTION FROM BUTT WELDING THICK PLATES

FIGURE 7

A subsequent welding test using a 25/75 joint configuration was performed in order to further reduce the angular distortion. The test parameters were the same as those used for the previous 30/70 joint test except that a 4.8-mm (3/16-in.) root gap was added to the joint and a 3.2-mm (1/8-in.) wire electrode was used for the submerged arc welding. The first side was completed in 17 passes and the second side required 65 passes. A transverse shrinkage of 4 mm (0.16-in.) was measured on the finishing side. The angular distortion, for all practical purposes, was eliminated as the resulting angular change was reduced to 0.62° which is significantly less than the angle of 2.0° remaining after the 30/70 joint test. While the angular distortion was diminished with the 25/75 joint configuration, the number of total weld passes increased by almost 50%. This increased weld deposition can be attributed to the larger root gap used to facilitate access to the weld root on the finishing side.

While these limited tests did not completely substantiate that angular distortion could be eliminated in thick plates, they did exhibit a potential for reducing plate handling. It was evident as the tests were begun that the first few passes on the backing side would be the most critical, as it is these initial passes that produced the most angular distortion. In the actual practice, wider plates than those tested will normally be used and the weight of the plate will provide a substantial restraint on the joint. The tests did indicate that the previous joint design, requiring welding of the larger beveled side first, could be modified to take advantage of a single turn of the plates.



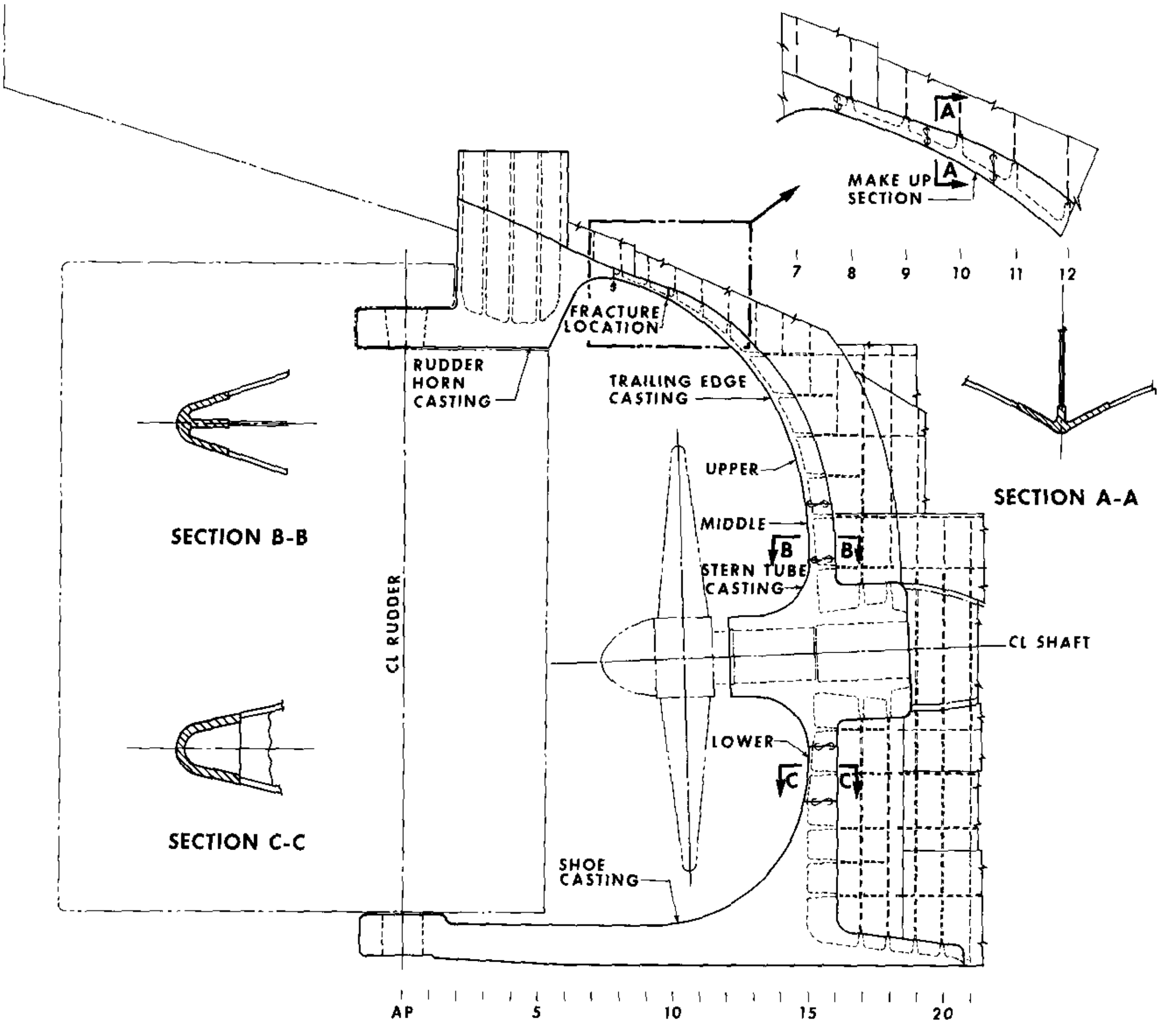
ULCC STERN VIEW

FIGURE 8

ULCC Trailing Edge Casting Fracture

In 1978, during the latter phase of hull construction, the ultralarge crude carrier U.S.T. ATLANTIC experienced a severe fracture in its trailing edge casting connecting the stern tube and the rudder horn castings. Forming the terminus of the longitudinal bulkhead and the port and starboard shell plating at the ship's stern, the trailing edge casting had been welded into its final position onboard the ship and was undergoing stress relief of the last welded butt joint. Thermal stresses set up during the postweld heat treatment were the principal cause of the casting fracture during the cooling-down period, although residual stresses from installation may have been an important contributing factor. Figure 8 shows an overall view of the area under consideration between the stern tube casting and the rudder horn casting.

The trailing edge casting actually consists of three separate castings located between other massive structural castings as illustrated in Figure 9. The lower piece is a make-up section that connects the shoe casting with the stern tube casting and is 1220 mm (48 in.) long and weighs 1.13 Mg (2500 lb). Just above the stern tube casting there is another make-up section of about the same size and weight which is designated as the middle piece of the trailing edge casting. Above the middle piece is the 7.6-m (25-ft) long, curved upper piece of the trailing edge casting which terminates at the rudder horn casting and weighs about 8.71 Mg (19 200 lb). The three prongs of the casting are designed to be welded to the centerline longitudinal bulkhead and the port and starboard shell plating, thereby completing the termination of the triple plate intersection. The characteristic pitchfork shape of the cross section at the bottom of the lower piece changes as it rises, flattening out substantially at



TRAILING EDGE CASTING

FIGURE 9

the top of the upper piece. The 64-mm (2.5-in.) thickness is constant throughout the casting length except at the transition radii. The distance along the outer surface from the port shell butt weld to the starboard shell butt weld varies from 1520 mm (60 in.) at the bottom to 1220 mm (48 in.) at the top. The casting material selected meets the requirements of ASTM A27 for Grade 60-30 steel which has a minimum yield strength of 207 MPa (30 000 psi) and a minimum tensile strength of 414 MPa (60 000 psi).

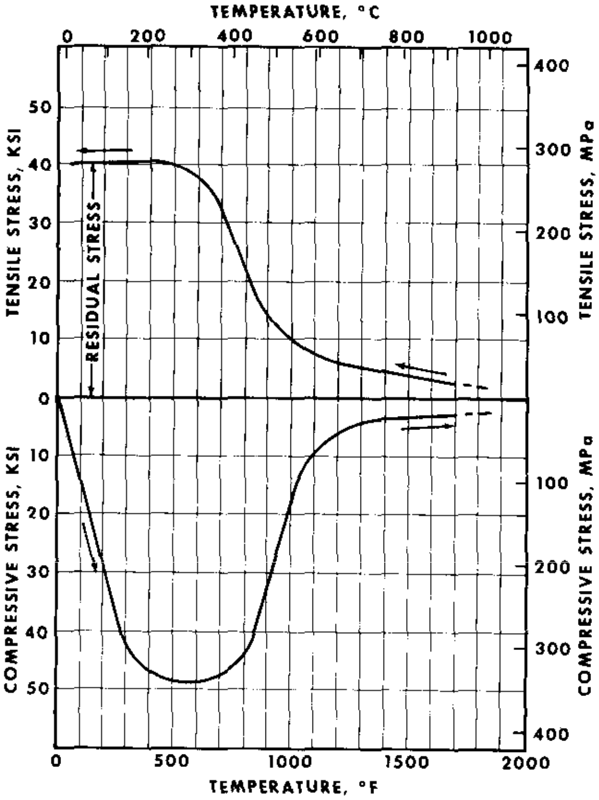
The three sections of the trailing edge casting were butt welded at five locations which required postweld stress-relief heat treatment. Stress relieving is accomplished by heating to a suitable temperature, holding the temperature constant long enough to reduce the residual stresses, and then cooling at a slow rate in order to minimize the development of new residual stresses. The postweld heat treatment was conducted using resistance type heating over a 305-mm (12-in.) wide band monitored by thermocouples according to the following procedure:

- The rate of temperature rise above 260°C (500°F) shall be less than 149°C (300°F) per hour.
- The holding time shall be 3 hours for the lower piece and 5 hours for the middle and upper pieces at a temperature of 621 $\pm$ 28°C (1150 $\pm$ 50°F).
- The maximum rate of temperature decrease shall be less than 93°C (200°F) per hour.
- The maximum temperature difference between any two thermocouples shall not exceed 93°C (200°F) while below the stress relieving temperature and 38°C (100°F) while at the stress relieving temperature.
- Stress relieving shall be considered complete when the weldment has cooled to below 260°C (500°F).

The shipboard installation of the three sections of the trailing edge casting began with the lower unit and the work progressed upward toward the rudder horn casting. The five major butt joints at the ends of the sections were preheated to a temperature range of 121°C to 149°C (250°F to 300°F) and then were welded with low hydrogen E7018 electrodes by the manual shielded metal arc welding process. No problems were encountered during the welding operations on any of these joints and the residual stresses due to transverse shrinkage were relieved according to the procedure described above.

As the last major weld joint just forward of the rudder horn casting was being cooled down after stress relieving, a brittle fracture occurred that was accompanied by a loud report as if from a cannon. The separation of the casting was located about 1220 mm (48 in.) forward of the weld joint undergoing stress relief and extended completely through the 839-cm^2 (130-in.^{2}) cross section. A gap width of approximately 6.4 mm (1/4 in.) remained after the casting cooled down to the ambient temperature of 24°C (75°F).

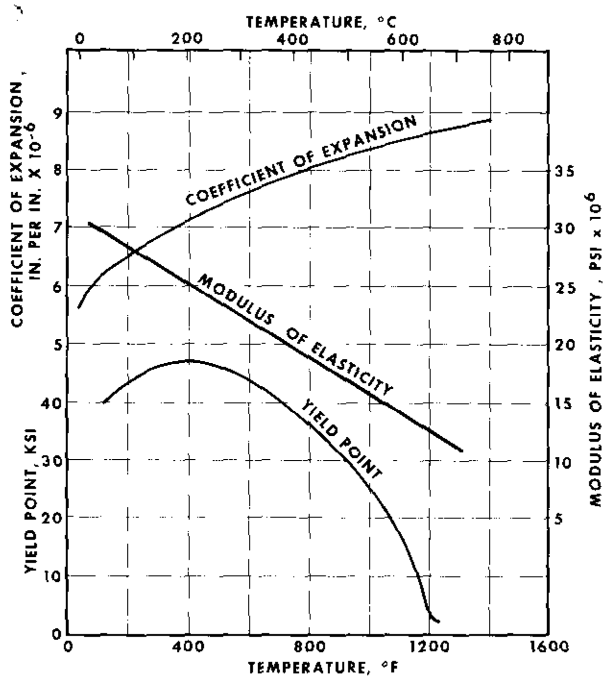
An examination of the circumstances leading up to the fracture may be of value to aid in understanding the reasons for the occurrence of the failure. The casting was not welded to the centerline longitudinal bulkhead nor to the shell plating for a length of 1830 mm (72 in.) aft of the fracture. The upper end of the casting was welded to the rudder horn casting and the remainder below the fracture had been joined to the ship's hull structure. The model of the structure, in essence, was a bar, fully restrained at its ends, which was heated to as much as 649°C (1200°F) on one end. The butt weld at the aft end of the bar was undergoing stress relief to eliminate the residual or shrinkage stresses from welding the joint. Since this butt weld was joining two massive sections that were fixed in place, reaction stresses were also present in the bar and were added to the local residual stresses at the weld joint. Reaction stresses are tensile stresses which exist after welding only because of the restraint at the ends of the bar. When combined with residual stresses some permanent deformation may have resulted if the yield strength was exceeded.



STRESSES FROM HEATING AND COOLING A RESTRAINED MILD STEEL BAR

FIGURE 10

The heat-affected zone of base metal adjacent to a weld, which is surrounded by cooler metal, is analogous to a bar with restrained ends which is heated and then cooled to ambient temperature. Figure 10 illustrates the stresses developed in a mild steel bar during the heating and cooling cycle (2). When the bar is heated, compressive stresses are produced due to the end restraint. At 135°C (275°F) the yield stress is reached and maintained as the temperature increases. This is due to the decreasing yield point in steel corresponding to increasing temperatures as shown in Figure 11 (2). Other changes to the physical and mechanical properties also occur as the temperature rises; the coefficient of expansion increases, while the modulus of elasticity decreases. At 649°C (1200°F) the yield point approaches zero and the compressive stress is low, decreasing further as the temperature reaches 927°C (1700°F). Upon cooling under restraint, tensile shrinkage stresses are created since contraction is prevented. At 649°C (1200°F) the steel regains its elastic properties as the yield point rises. As the ambient temperature is reached, the tensile stresses rise to the yield strength where they remain thereafter until the restraint is removed (2).



PHYSICAL AND MECHANICAL PROPERTY CHANGES IN MILD STEEL

FIGURE 11

When the postweld stress relief heat treatment was applied to the welded joint, the residual and reaction stresses at the joint were reduced to a low level. Through the first 204°C (400°F) the shrinkage stresses decrease due to a phenomenon called recovery which is a reduction in internal stress associated with a rise in temperature. At 649°C (1200°F) the shrinkage stresses are dissipated almost completely as relaxation occurs in the material and permanent yielding results. Uneven or rapid cooling from stress-relieving temperatures may reimpose internal stresses and therefore excessive thermal gradients must be avoided.

Since the fracture occurred about 1220 mm (48 in.) from the weld undergoing stress relief as it was cooling down to the ambient temperature, it is likely that the thermal stresses generated during contraction combined with the tensile reaction stresses from welding to produce the failure. If the entire length of the casting from the butt weld to the fracture had been heated to the stress-relieving temperature, the fracture may not have happened as it would have been uniformly relieved over its length. The weld joint was effectively stress relieved, but the entire bar was not.

There were other factors which may have been responsible for the failure. One is that the cross-sectional shape as shown in Figure 9 is not structurally efficient in its inherent ability to resist a bending moment. Due to the curvature at the upper end of the casting, the centroids of the cross-sectional areas were not completely in alignment, thereby inducing a bending moment from any axial forces present. The resulting bending stresses would have combined with the thermal stresses during contraction and could have quickly reached the breaking strength of the mild steel material.

A second factor contributing to the failure may have been the jacking and strongbacking needed to bring the upper end of the casting into alignment with the rudder horn prior to welding. In order to achieve the required fairness without having a short make-up piece to facilitate fitting, it is possible that high bending stresses were locked into the material before the final joint was welded, thereby setting the stage for failure.

A third possibility that requires mentioning is that a significant defect or flaw may have been present at the fracture location. This is a common explanation and is often given when a casting is involved with a fracture. Nevertheless, casting defects do exist all too often and, in spite of the best quality controls and inspections, will continue to cause problems.

While this failure was not catastrophic in the sense that it did not result in the loss of life or threaten the ship itself, it was of some concern. With only three months until launch, this 396 000-Mg (390 000-dwt) oil tanker, the largest vessel ever constructed in the Western Hemisphere, had a fractured stern in need of immediate repair. A 910-mm (36-in.) section of the cracked casting was cut out and replaced by a matching section "borrowed" from a follow ship of the same design. The edges of the new weld joints were clad with 6.4 mm (1/4 in.) of weld and the section was stress relieved in the furnace. The edges of the ship casting joints were also clad welded and stress relieved locally by postheating. The new section was fitted into place, and the aft weld joint was completed and stress relieved by heating as previously performed. The final joint was welded and peening was heavily employed to mechanically stress relieve each layer of weld except the first and last layers. A magnetic particle inspection was performed on the last two joints on the backgouged weld root, on the final weld surface, and also during the course of the welding. The final casting-to-casting joint was not subjected to any postheat treatment other than the normal preheat for welding. Upon the successful completion of the final joint, the internal ship structure was fitted and welded to the casting which was followed by the attachment of the port and starboard shell plating.

The solution employed to solve the fracture problem on this casting was to create an opening and then to insert a short make-up section without postweld heat treatment on the final weld joint. This technique was successfully employed during the construction of the follow ship. A question arises, however, as to why fractures were not encountered on the lower and middle trailing edge castings located above and below the stern tube. The welds of these make-up sections were stress relieved by postweld heat treatment on both ships. One explanation may be that since their length and degree of curvature were substantially reduced, the induced bending stresses were less severe. Another explanation may be that these sections were less difficult to fit into place and did not require extensive jacking, creating locked-in residual stresses in the material. A third explanation may be that these make-up sections were defect-free, whereas the upper casting may have contained a small defect or discontinuity at the location of the fracture which only required the presence of a tensile force to cause failure.

The above account is just one example of how difficult it is to accurately assess the effects of residual stresses. In the attempt to relieve residual stresses from welding at one location, more severe stresses were induced elsewhere. Unfortunately, it is surmised that this is not a unique occurrence in shipbuilding.

SUMMARY

The effects of residual stresses on welded structures have been studied extensively in numerous areas related to the cases discussed above. While it may appear that externally applied tensile loads should produce stresses that would be superimposed on local residual stresses to cause failure, the research conducted does not support this contention. Since the internal system of tensile and compressive stresses is in equilibrium, a redistribution results from stresses caused by external loads and the residual stresses are significantly increased only in areas away from the weld. When the level of applied stress is increased beyond yielding, the effect of residual stress is negligible and essentially disappears as the stress distribution becomes uniform throughtout the cross section. After the applied stress has been removed, the residual stresses decrease to a point below their initial stress levels.

The significance of residual stress effects becomes of importance under low applied stress conditions and may result in brittle fracture. Extensive experimental studies have demonstrated that an unstable fracture may develop from a small defect or flaw which would be stable if there were no residual stresses present.

In order to realize the goal of improving the reliability of welded structures under demanding service conditions, the effects of residual stresses and distortion must be minimized. This may be accomplished by expanding the working knowledge on the subject of residual stress and applying new techniques and effective procedures to solve recurring problems.

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REFERENCES

1. K. Masubuchi, "Residual Stresses and Distortion" in Welding Handbook, seventh edition, volume 1, edited by C. Weisman, Miami, American Welding Society, 1976

2. George E. Linnert, Welding Metallurgy, third edition, volume 2, New York, American Welding Society, 1967

3. Koichi Masubuchi, Analysis of Welded Structures, first edition, London, Pergamon Press Ltd., 1980

SUPPLEMENTARY READING LIST

1. Residual Stresses in Metals and Metal Construction, edited by W. R. Osgood, New York, Reinhold Publishing Corp., 1954

2. W. J. Hall, H. Kihara, W. Soete, A. A. Wells, Brittle Fracture of Welded Plate, Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 1967

3. Residual Stresses in Welded Construction and Their Effects, International Conference, London, November 15-17, 1977, Volume 1 - Papers, The Welding Institute, Cambridge, England, 1978