DISTORTION MITIGATION TECHNIQUE FOR LIGHTWEIGHT SHIP STRUCTURE FABRICATION

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ABSTRACT

Shipboard applications of lightweight structures have increased over recent years in both military and commercial vessels. Thin steel reduces topside weight, enhances mission capability, and improves performance and vessel stability, but the propensity of buckling distortion has increased significantly. At present, several U.S. Navy construction programs are experiencing high rates of buckling distortion on thin steel structures. The standard shipyard practice of fabricating stiffened steel panels by arc welding is one of major contributors to this distortion. Correcting the distortion is a necessary but time-consuming operation that adds no value and ultimately tends to degrade the quality of the ship structure.

With a major initiative funded by the U.S. Navy, Northrop Grumman Ship Systems (NGSS) has undertaken a comprehensive assessment of lightweight structure fabrication technology since 2002. Through the collaborative research works, significant progresses have been achieved in the development of distortion control techniques. Reverse arching, transient thermal tensioning (TTT), stiffener assembly sequencing, and other preferred manufacturing techniques were developed at NGSS to reduce distortion and eliminate the high rework costs associated with correcting that distortion.

Complex lightweight panel structures, which are reinforced by long slender stiffeners along with numerous cutouts and inserts, pose a major challenge for distortion control. The geometric complexity yields a more complicated buckling behavior, which drives the need to develop a more fine-tuned finite element model to determine critical parameters and heating patterns for the TTT process. NGSS has recently teamed with Edison Welding Institute (EWI), Battelle Memorial Institute and the University of New Orleans on a Navy project to further refine TTT procedures for complex lightweight ship structures. In this paper, functional requirements and the design of TTT process and production equipment will be discussed. The refined TTT process will be benchmarked by the test panel observations and a laser scanning device, LIDAR, will be used to analyze panel distortion topography.

KEY WORDS: Thin steel, buckling, welding, distortion control, residual stress, complex panel, hard deck foundation, cutout, insert, reverse arching, heat patterns, transient thermal tensioning, hybrid arc-laser welding

INTRODUCTION

In recent years, ship designers have been forced to incorporate lighter, thinner steel structures to reduce topside weight, improve fuel economy, and enhance mission capability. Over the past decade, the production ratio of thin-steel (10 mm or less) to thick-plate structures for many naval vessels built at Northrop Grumman Ship Systems (NGSS) rose significantly. New designs are calling for the application of even thinner (e.g. 5-mm) high-strength steel grades to further reduce weight and improve performance. At the same time, both military and commercial owners have tightened the design requirements in strength, stiffness, and fitness to meet more stringent performance specifications [1–4].

Significant distortion problems have emerged as shipyards work to meet the new requirements. For the most part, the infrastructure, design methodologies, and construction techniques in U.S. shipyards are not designed to support such lightweight fabrications. Thin steel is more likely to deform and production is more difficult, because the panels lack rigidity until integrated into a structural unit. Ship panels are made as large as possible to minimize the number of erection joints. Typical panels are about 16-m x 16-m and require butt welding of several plates to achieve the design shape and dimension. To meet design requirements and optimize vessel stability and weight, "complex" ship panels are tailored with multiple inserts of different thickness. When stiffeners are attached, the large plate panels exhibit low buckling strength, because of their size and the large aspect ratio of the stiffener length to the stiffener spacing. Consequently, large out-of-plane deflections can result from welding-induced buckling.

The financial impacts of welding distortion are significant. Distortion results in schedule delays and increased fitting and welding labor costs. Gaps between stiffened panels must be reduced to bring the plates into sufficient proximity for welding. Hand-trimming of distorted structures and attachment of fitting aids increases the fitting time. These joints must often be welded manually due to the variation in joint fit-up and the poor access conditions created by rigging used to align plates. Excessive stiffener "leave-loose" to accommodate fitting of stiffeners on distorted units further increases the need for manual welding during unit erection. This combination of large joint gaps and manual welding leads to over-welding, which exacerbates the unit distortion. Additional costs and schedule delays are incurred from straightening operations to reduce distortion. Both the skilled labor to perform flame straightening and the labor to clean-up and repaint after straightening can be significant cost contributors. In extreme cases, flame straightening alone may not be adequate to meet fairness requirements; necessitating additional cutting and welding operations to correct severely buckled areas.

In 2002, Northrop Grumman Ship Systems initiated a multiyear program to develop distortion-control technologies for complex lightweight ship structures. The program initially focused on the panel line and investigated a range of techniques for control of distortion in panel fabrication operations including plate cutting, material handling, fitting, butt welding, and longitudinal stiffener welding [5]. A subsequent program focused on developing best-practices for control of distortion in subsequent unit construction operations [6]. In both programs a series of test structures were fabricated to assess the effectiveness of different welding distortion control approaches. These programs identified preferred methods for control of welding-induced buckling distortion, including:

- Optimizing joint fitting methods and welding sequences,
- Using new welding processes and automation to minimize welding heat input during butt and fillet welding operations,
- Implementation of tooling to provide restraint during welding operations, and
- Applying active distortion mitigation approaches.

The Shipboard Applications of Lightweight Structures Program has provided NGSS with an opportunity to place increased emphasis on dimensional management for thin steel structures. NGSS has, during the past three years, substantially increased its emphasis on dimensional management as a critical enabler to achieving its aggressive goals for the future [7]. These goals include reducing the cost and lead time for erecting a ship's hull and increasing the outfitting and pre-outfitting that is completed earlier in the production cycle. This effort includes the Design Engineering, Mold Loft, Quality and Process Improvement, and Accuracy Control Departments, as well as outside project team members from Edison Welding Institute, Battelle Memorial Institute, University of New Orleans, Dimensional Control Systems, University of Michigan and Penn State University Applied Research Laboratory. The overall goal of this effort is to establish a preferred process technology for the production of thin steel ship structures [6-8].

BUCKLING DISTORTION

There are several basic types of welding distortion which may occur on thin structures. As Figure 1 illustrates, the basic types include transverse shrinkage, longitudinal shrinkage, angular, longitudinal bowing, rotational, and buckling distortions. For large thin structures, buckling distortion is the dominant mode and is the primary focus of the NGSS distortion control efforts.

Ship unit welding operations include plate butt welding, longitudinal and transverse stiffener welding, partial sub-unit assembly welding, and block assembly welding. Buckling distortion can develop very early in the production sequence, during butt welding, and continues to increase during subsequent operations. For complex thin panels, buckling typically takes the form of edge "waviness" or "oil-canning" in the internal areas of the panel as shown in Figure 2. Unlike other forms of distortion, buckling can have multiple stable "modes" that cause the defected areas to move depending on how the panel is supported or restrained. Restraining one area can cause distortion to increase in other areas. This can be particularly problematic when thick-plate inserts are used that result in amplified distortion in regions surrounding the insert.

The fundamental cause of welding induced buckling distortion is longitudinal shrinkage forces generated from butt or stiffener welding. Figure 3 illustrates the stress state produced from an arc weld. High residual stresses (approaching the yield strength of the material) are produced in the weld fusion zone and heat affected zone. The area under the tensile stress region represents the total shrinkage force which is produced. In general, a higher welding heat-input will produce a larger tensile stress region and hence more total shrinkage force. To balance the tensile stress, a compressive zone develops after the weld cools. While these compressive zones exist in all arc welded structures, thin panels lack the inherent stiffness to resist this stress. Consequently, buckling occurs as a result of compressive residual stresses at some distance from the welds. As Figure 4 illustrates, buckling is typically found along plate edges, between stiffeners, and near inserts.

A number of strategies are available to reduce the occurrence of buckling, including the following:

Design – Design modifications can increase the stiffness of the structure and hence the shrinkage force required to buckle the structure. This may involve the use of thicker plate or closer stiffener spacing. Unfortunately, performance requirements generally preclude design modifications as a distortion control method.

Low Heat-input Welding - Arc welding is the primary means of joining plates and stiffeners to construct ship panels and units in the shipyard process. The heat generated during arc welding imparts residual stresses in the ship structure. Thin materials have inherently less ability to resist distortion, so lightweight structures experience much larger distortion problems if standard welding practices are used. Reducing welding heat-input can reduce the size of the tensile zone, and hence the total compressive forces generated. Welding heat input is closely related to weld size, so over-welding can have a pronounced effect on increasing buckling distortion. A number of techniques have been identified for minimizing welding heat-input, including the use of good fitting practices, automated welding, precision joint tracking, optimized process parameters, and lower heat-input processes such as tandem GMAW and laser-hybrid GMAW. Based on the panel testing and numerical studies, the laser-arc hybrid technology has shown positive signs of value to NGSS' needs in welding thin steel panels [8].

Weld Zone Stress Reduction – Reducing the peak tensile stress in the weld zone will have the effect of reducing the driving force for buckling. A number of techniques have been investigated to reduce the peak tensile stress. These techniques often involve applying an external tensile stress during welding which causes yielding in the areas of peak residual stress. When the external stress is removed after welding the peak tensile stress in the weld zone is reduced. Both mechanical and thermal means have been explored to provide the external tensile stress. While these approaches have been shown to be effective on relatively small components, they are difficult to scale-up and apply for large ship structures.

Reverse Arching – A new technique, *reverse arching*, developed after extensive numerical modeling, can effectively remove distortion immediately after the welding of T-beam stiffeners [6]. The process is based on removing the high-longitudinal residual stresses that develop under the T-joint. The high-magnitude compressive residual stress along the weld direction serves as the driving force for buckling distortion. With the proposed reverse-arching technique, a bending action is imposed as each T-stiffener fillet is completed, to subject the plate and fillet weld to tension. On release of the bending action, the longitudinal residual stresses can be significantly reduced, thus reducing the tendency for buckling distortion.

It was not feasible to perform the reverse-arching technique immediately after each T-stiffener was completed in the current shipyard process environments. Instead, the technique was evaluated by performing the reverse arching after all T-beam stiffeners were welded. Bending supports were placed under the test panel and hydraulic clamps at the double-sided fillet welder provided the force.

Hard Deck Foundation – A major problem at Northrop Grumman Ship Systems' New Orleans Operations was the work foundations, which are caster beds that have the casters staggered on a 2-m spacing. Thin-steel panels are relatively flexible and were found to significantly bow between the casters, making assembly, fit-up, and welding difficult. To evaluate a best-case condition for work support, a hard deck foundation (HDF) was proposed and built. The objective was to eliminate work-foundation-induced distortions by using the HDF as much as possible, so that other variables could be evaluated.

An HDF was designed using two 25-mm plates that were separated and reinforced with a grid of I-beams. The HDF was surveyed using lidar laser scanner and was found to be extremely flat after fabrication. The foundation was used to build all 12 test panel mock-ups in the improved manufacturing process—which included fit-up and double-sided SAW welding of butt seams, fit-up of stiffeners, and double-sided fillet welding.

Thermal Stress Stiffening – Thermal stress stiffening involves generating a tensile zone in regions which are susceptible to buckling due to the residual weld-induced compressive stresses [9]. The addition of a tensile band acts to stiffen the structure and thereby reduces the buckling tendency. Since Transient Thermal Tensioning (TTT) employs this method, the application of thermal stiffening is described in detail in the sections which follow.

CONTROLLED HEATING FOR DISTORTION REDUCTION

The application of thermal patterns to control distortion is not new. Flame straightening is a common example of how local heating can be used to remove distortion by shrinking buckled areas. A torch is used to heat local areas while cooling surrounding areas with water, as Figure 5 illustrates. The problems with flame straightening are numerous:

- From a Lean-manufacturing standpoint, flame-straightening is a non-value-added operation. The technique requires a separate operation that is labor intensive and requires a high degree of skill.
- It is often applied well after the distortion occurs and much of the increased fitting costs caused by the welding distortion have already been incurred by the time the straightening is performed.
- The application or flame heating and water cooling is disruptive to the other trades working in the area and requires additional clean-up activities.
- Flame straightening is often applied after the buckling has been locked-in to very localized regions. It is very difficult to remove the distortion at this point. In some cases buckled areas have to be cut out and re-welded to remove the distortion.
- Flame straightening causes stress redistributions not only in the longitudinal stiffener direction but also in the transverse direction. Flame-straightening of large areas can generate very high residual stresses that can buckle other areas of the structure, causing additional rework and expense.

An example of the application of control heating to prevent distortion is the use of web heating during stiffener fabrication. Figure 6 is a simple schematic to illustrate a fabricated T-beam cross-section. This type of shape is typically fabricated in with a mechanized welding system. Because all of the welding heat-input is applied on one side of the neutral axis (i.e., the center of mass of the cross-section), the fabricated shape will be bowed upon cooling. NGSS has developed a technique to avoid this bowing distortion by applying controlled heating patterns during the welding operation as shown in Figure 7. In essence, the approach entails balancing the heat input from welding on one side of the neutral axis with additional heat applied on the other side of the neutral axis. The result is a welded shape with very little distortion. Figure 8 shows a high tolerance stiffener produced by NGSS using this technique.

Like flame-straightening, the goal of TTT is the elimination of buckling distortion. But unlike flame straightening the goal of TTT is not to correct buckling distortion, but to prevent buckling distortion before it occurs. TTT has a number of benefits as compared with flame-straightening, including:

- TTT is performed during welding, and so a separate operation is not required.
- Because TTT prevents buckling distortion, subsequent fitting operations are made easier resulting in reduced fitting costs.
- TTT does not disrupt other trades since it is performed on the panel line during longitudinal stiffener welding.
- TTT is applied in a highly-productive, automated fashion with minimal skill requirements.
- TTT avoids locking-in buckled regions, and so eliminates the need to take extreme measures to remove buckling in final structures.
- TTT reduces the need for costly and disruptive flame-straightening operations.
- TTT redistributes stresses in the longitudinal stiffener direction, but it allows the transverse residual stresses to be released by plate shrinkage at the panel line, while the panel is still free to contract in the transverse direction. Thus, TTT can alleviate the problems of structural crippling resulted from repetitive straightening of adjacent areas in the deck and bulkhead structures at the final unit assembly stage of ship construction using flame-straightening methods.

TRANSIENT THERMAL TENSIONING

Thermal tensioning techniques have been under development at Edison Welding Institute (EWI) since the mid-1990's [9-10]. Early attempts to control buckling distortion focused on differential heating to reduce the magnitude of the residual weld tensile stress that leads to buckling. "Static Thermal Tensioning" (STT) is one method of reducing the weld residual stress. STT involves pre-stretching the weld area by means of an applied thermal gradient along the entire weld length. The gradient is achieved by raising the temperature on either side of the weld by resistive heating bands, while simultaneously quenching the weld zone (e.g., with a water-spray on the bottom of the plate). A schematic is shown in Figure 9. The stress field produced by the temperature gradient causes additional yielding, and reduces the peak tensile residual stresses in the weld. While the technique is effective, the required temperature differential is difficult to achieve on large ship structures. Equipment necessary to meet this requirement would be complex and costly. Also, the time required to set-up the equipment and achieve the temperature differential would increase the total welding cycle time.

TTT employs the principle of thermal stress stiffening. TTT does not require quenching and can be deployed on existing mechanized panel longitudinal stiffener welding equipment. TTT uses local heat sources (Figure 10) that move along the plate to induce zones of local plate tension where the weld compressive zones would normally exist. Oxy-fuel flame heaters (or other heat sources of sufficient intensity) are carried along with the welding head. The heat source locally yields and shrinks an area in the plate, in a similar manner as is done with flame straightening. Bands of residual tension stress are produced in the panel in opposition to the residual compressive buckling stress caused by welding, as Figure 11 illustrates.

Critical parameters for the TTT process include the size, location, travel-speed, and intensity of the heat sources. Because the TTT heating apparatus are attached to the mechanized stiffener welding carriage, the welding speed dictates the TTT travel speed. In general, the thickness of the plate dictates the required intensity, which is adjusted by means of oxy-fuel gas pressures and flow rates. The heat source must be concentrated enough to produce plasticity, though not enough to cause localized deformation.

Optimization of the approach for a given panel geometry requires selection of the preferred heating locations and patterns. Numerical modeling tools have been developed to support this optimization. To date, these models have been validated with testing on simple panels. Work is underway to refine and extend these numerical modeling approaches to more complex panels, and to improve the efficiency of the modeling tools for modeling more complex production panels [ ].

SHIPYARD TESTING OF TTT

TTT techniques were first tested at NGSS in 1999 for lightweight ship panel application on U.S. Navy vessel class DDG-51 in the Department of Defense's Manufacturing Technology (MANTECH) project, Distortion and Accuracy Control (S0916). In March 2003, EWI began working with NGSS on the U.S. Navy's Office of Naval Research's "Shipboard Applications of Lightweight Structures" program, which has tested TTT on a series of full-scale ship panels and found it to be partially successful. It was found to be particularly advantageous in adding tensile stress adjacent to free edges, where even small amounts of compressive stress can cause buckling. Work is underway to refine and implement the technology under the CNST-funded "Thermal Tensioning of Thin Steel Ship Panel Structures" program at NGSS.

INITIAL TESTING

Initial TTT testing involved two types of panel mock-ups:

- A simple mock-up having uniform 5-mm plate thickness (Figure 12), and
- A more complex mock-up having three 10-mm thick inserts (Figure 13).

Numerical models were developed to help guide selection of the thermal patterns. The following rules of thumb were used to select the thermal pattern:

- Heating lines are most effective near edges or halfway between stiffeners.
- Heating lines should total no more than twice the number of stiffeners.
- Heating lines should be separated from other bands, edges, and welds by at least 50-mm (2-in.)

Figure 14 shows the heating pattern applied for the simple mock-up. The tensioning pattern consisted of one line located 50-mm (2-in.) from each edge parallel to the stiffeners, along with one line between each adjacent pair of stiffeners, except the center two stiffeners. No line was required in the center because the longitudinal butt weld produced an adequate tension zone between the stiffeners.

The burners used for TTT were 150-mm (6-in.) long and oriented parallel to the direction of travel. The fuel used was natural gas (methane), and the oxygen flow rate was set to provide an oxidizing flame. While this process was under development, all welding was done at 0.5 m/min travel speed. For the welding of the lightweight panels in the preferred processes, travel speeds ranged from 0.5 to 1.0 m/min, and gas flow rates were scaled proportionally to the travel speed.

LIDAR scanning was used to measure out-of-plane distortion. Figure 15 presents a LIDAR comparison of the results for the simple panel. Figure 15a shows the LIDAR scan of the "control case", i.e., no TTT, while Figure 15b shows the scan of the "test case", i.e., with TTT. Careful examination of the figures show that TTT completely eliminated the buckling (as evidenced by the lack of variation in the LIDAR color along the edge of the panel in Figure 15b). While the buckling was eliminated, TTT did not reduce the overall bowing of the panel. Other techniques, such as the use of precision welding techniques to control heat-input, may help to reduce this panel bowing.

The complex panels required different tensioning patterns to accommodate the buckling force produced by the transverse seam welds between different thicknesses of the panel and the insert. The TTT for panel design 3 used thermal tension lines parallel to the fillet welds, as shown in Figure 16. The complex panel mock-ups also used small (3-mm) precision fillet welding procedures to reduce the buckling distortion by about 50%. However, even with precision fillet welds, the manually welded insert and transverse SAW seams caused enough additional stress that some buckling was observed. To increase the degree of restraint along the 5-mm plate edge, a temporary stiffener was tack welded along the free edges.

Figure 17 shows the results of a LIDAR scan following stiffener welding with TTT, and subsequent removal of the restraints. TTT eliminated all buckling in all areas except at the corners of the inserts. The complex panels did have significantly more bowing in the longitudinal plane near the insert, but the edges were not buckled (i.e., were not wavy). These findings suggested that with some additional development, TTT combined with precision welding could be used to eliminate buckling during the fabrication complex panels. The findings also indicated that additional work is needed to reduce the degree of panel bowing.

ON-GOING REFINEMENT FOR COMPLEX PANELS

Testing is on-going under a CNST funded program to refine techniques for more complex panels. The goal is to identify optimum technique to suppress buckling around the insert, while limiting the degree of bowing.

Nominally identical panels of the design shown in Figure 18 are being evaluated with varying degrees of TTT stress stiffening. The panel consists of the following:

- Two (2) Plasma-cut 5-mm plates DH-36 (95" x 240") base plate
- One (1) Plasma-cut 10mm insert EH-36 (69" x 66") insert
- Seven (7) AH-36 WT 100 x 7.5 x 20-ft longitudinal stiffeners
- Two (2) AH-36 WT 100 x 7.5 x 8-ft longitudinal stiffeners
- Two (2) AH-36 WT 100 x 7.5 x 6-ft longitudinal stiffeners

Precision plasma cutting was used to achieve good insert fit with a maximum gap of 3/32-inches. Double-sided submerged arc welding was employed to complete the longitudinal butt weld. Double-sided semi-automatic flux cored are welding was performed to complete the insert welding. During welding the test panels were rigidly restrained and the same welding sequence was followed for each panel, as illustrated in Figure 19.

Figure 20 illustrates that buckling in the region of the insert already occurs when the butt welds are produced. Past work on a similar panel design welded without the use of TTT shows the that the buckling distortion further increased after the longitudinal stiffeners are welded. The LIDAR scan of Figure 21 shows the out-of-plane distortion as a result of butt welding.

To test the effect of TTT, various heating patterns were applied during the welding of the eight (8) longitudinal stiffeners. Different TTT heating patterns were investigated to assess which patterns produce the greatest benefit. Numerical modeling was applied to select the patterns which produce the greatest stiffening effect. Figure 22 illustrates the selected patterns. All the patterns employ extra stress stiffening in the region of the insert, to compensate for the buckling distortion which occurs in that area.

In the initial testing, multiple heating lines are applied in an iterative fashion where necessary. Figure 23 illustrates the approach for a two-line heating pattern. The first line is applied by running the stiffener welding carriage down the plate prior to welding. The second line is applied during welding at about 50-mm offset in location. This multi-pass operation was necessary due to the limitations of the initial prototype equipment. A refined prototype will be constructed in the future which can produce multiple heating patterns in a single pass.

The LIDAR scan of Figure 24 shows the final panel out-of-plane deflection when the panel is welded without the use of TTT. Out of plane distortion exceeds 100-mm along the panel edge near the insert.

Figure 25 a-c illustrate the LIDAR distortion measurements of the panels produced with the various TTT heating patterns. The figures show that the optimum TTT effect is obtained with line-heating pattern B. In this can buckling was minimized for this panel design. These result will be used to validate and refine the TTT approach for more-complex production panels.

Testing is planned this year on a production panel. If successful, a more robust prototype production TTT system will be constructed with improved controls of TTT parameters. Reducing bowing distortion is another area for future work. A novel approach to reduce bowing will involve heating of the stiffener flange during the TTT process as shown in Figure 26. The approach is similar to that used in stiffener production to reduce bowing by balancing the heat about the neutral axis of the component.

REVERSE ARCHING

Another effective buckling distortion mitigation technique is referred to as "reverse arching" technique [6]. As demonstrated in Figure 27 using a model with a panel plate containing a single T-beam, the longitudinal residual stresses are about yield magnitude tension (red) within the weld area under as welded conditions (Figure 27a). During a slight arching (after applying a bending action), the corresponding stress distribution (residual stress plus bending-induced stresses) are shown in Figure 27b. On release or unloading, Figure 27c shows the final longitudinal residual stress distribution. Comparing with Figure 27a, the peak residual stresses in the weld in Figure 27c area are reduced to about one third of the original residual stresses shown in Figure 1a. As a result, a significantly increased buckling strength is expected after applying the reverse arching technique.

The reversed arching technique was first investigated on panel mockup as shown in Figure 28. In addition to reverse arching, T-beam stiffener assembly sequence was also investigated for this panel mockup. The distortion from assembly sequence 2 (center-out) was compared to sequence 1 using progressive fit-and-weld sequence. For panel mockup 2B, the T-beam assembly sequence was from inside out. The final distortion after all welding was less than produced with sequence 1. After reverse arching technique was used, the final distortion was very low. From this experiment, it was seen that the assembly sequence from inside out tended to reduce the buckling distortion. After reversed arching was applied, most of the buckling distortion was recovered. If the reversed arching technique was applied after each T-Stiffener weld was completed, the method would be more effective.

Among all test panel designs (1, 2 or 3), panel design 3 was the most complex since it included a thicker insert and transverse end plates. As a result, the buckling distortion in panel design 3 was the most severe, as observed from the first group of the test panels (4). In this investigation, the reverse arching technique was also evaluated on the most complex panel mockup 3C. The reverse arching technique was implemented in the same manner as that for panel mockup 2B. The LIDAR measurements of the buckling distortions are summarized in Figure 29. As shown, the reverse arching technique was capable of removing most of the arching from this panel and recovering the small buckles between stiffeners. The distortion near the panel edge on the insert side was significantly improved but still had several edge waves after reverse arching. Overall, the reverse arching was very effective and would provide an optimum solution if applied with the preferred manufacturing plan.

SUMMARY

A series of tests was conducted on candidate measures to improve the manufacturing quality of thin panels for ship structures. The tests built on the results of previous work that demonstrated the problems with manufacturing thin-steel ship structures [4-5]. The new tests concentrated on material-handling and storage processes, precision cutting of panel pieces, a new material-handling foundation system, new welding procedures for panel assembly, prefitting of stiffeners, precision high-speed welding, use of reverse arching and TTT-based distortion-prediction tools and hardware [6-7], use of hybrid arc-laser low-heat input [8] and improved manual welding. Those procedures and tools were found to significantly improve the quality of the panel construction process, reduce production time, and reduce ship-fitting costs. Many of these techniques have been implemented at NGSS for shipyard application to prevent buckling distortion in thin panels.

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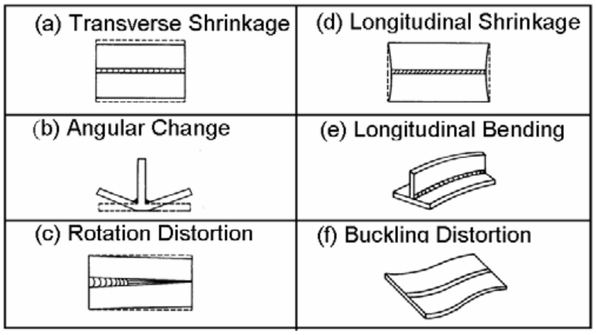


Figure 1 – Basic types of welding distortion. Buckling distortion dominates on thin panels.

Figure 2 – Buckling displayed as edge "waviness"

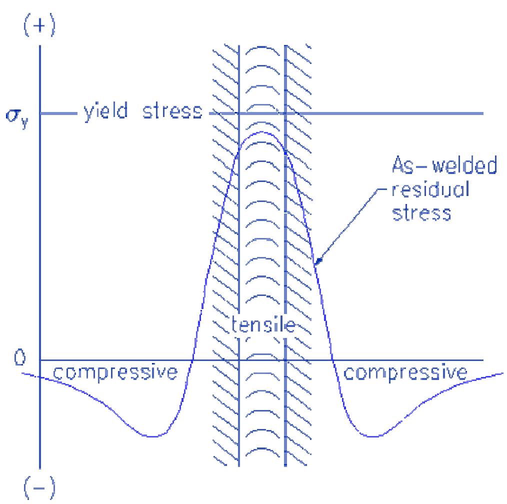


Figure 3 – Arc welding produces residual tensile stresses in the weld region and compressive stresses further away from the weld

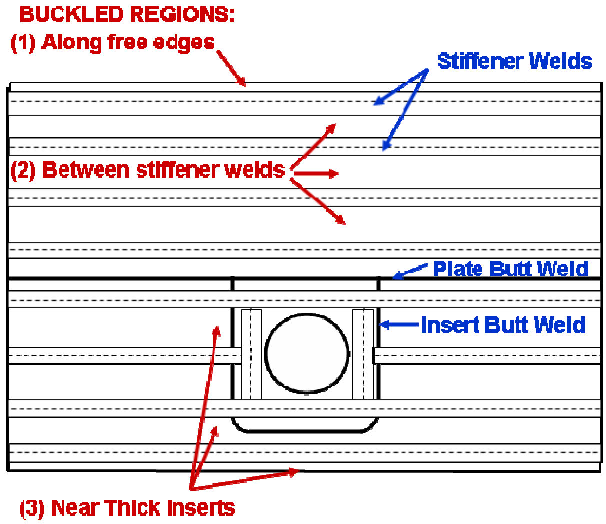


Figure 4 – Typical buckling locations include edges, areas between stiffeners, and areas around thick inserts.

Figure 5 – Flame straightening often entails manually producing a series of spot heat patterns with an oxy-fuel torch

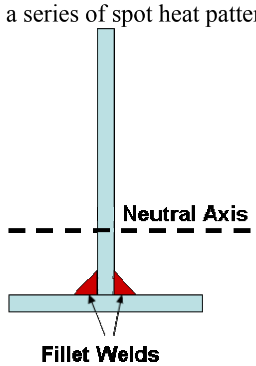


Figure 6 – Bowing occurs because all welding heat input (and shrinkage) is on one side of the neutral axis.

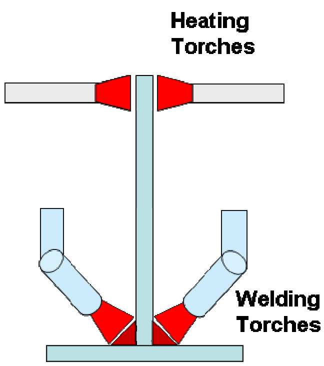


Figure 7 - Additional heat can be applied to balance the heating about the neutral axis to reduce beam bowing.

Figure 8 – NGSS produces highly accurate beams by the application of controlled heating

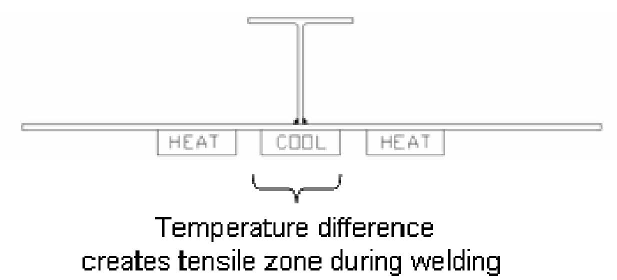


Figure 9 – Thermal tensioning initially used temperature gradients to produce stresses which oppose the development of welding stresses that cause buckling.

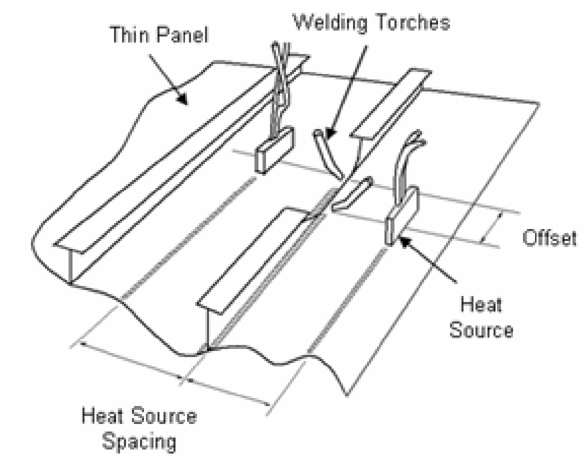


Figure 10 – Schematic representation of TTT

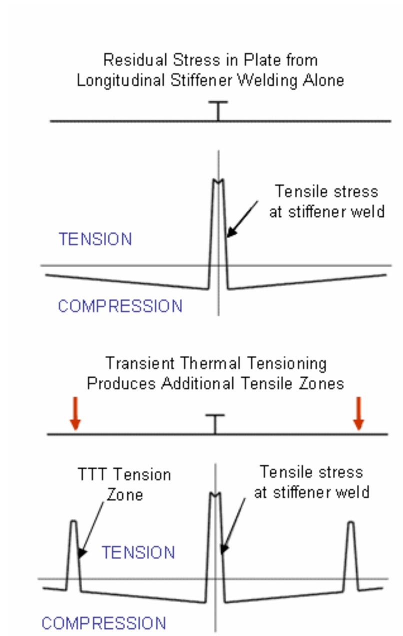


Figure 11 – Schematic illustration of the residual stress pattern produced without (top) and with (bottom) TTT

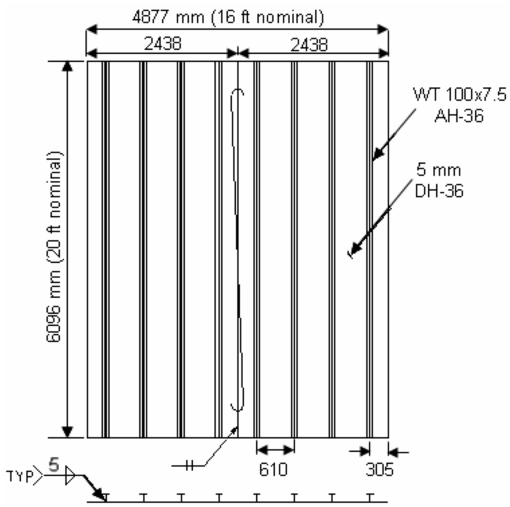


Figure 12 – Simple 5-mm thick mock-up to test TTT

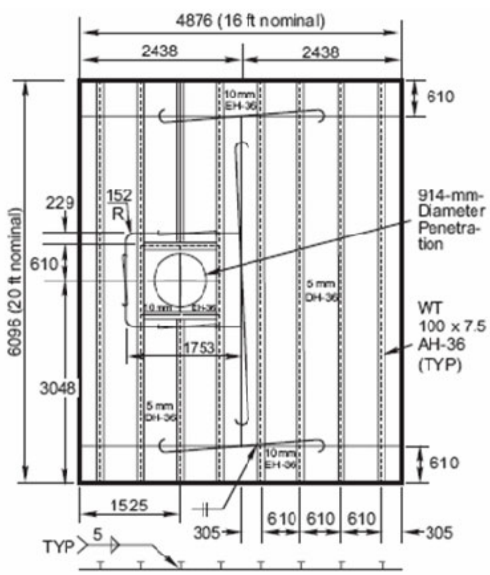


Figure 13 – Complex mock-up comprised of 5-mm plate with three 10-mm inserts

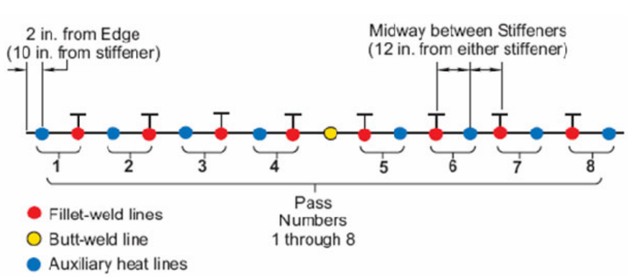


Figure 14 – Sequence of welding and TTT applied in the simple shipyard mock-up testing.

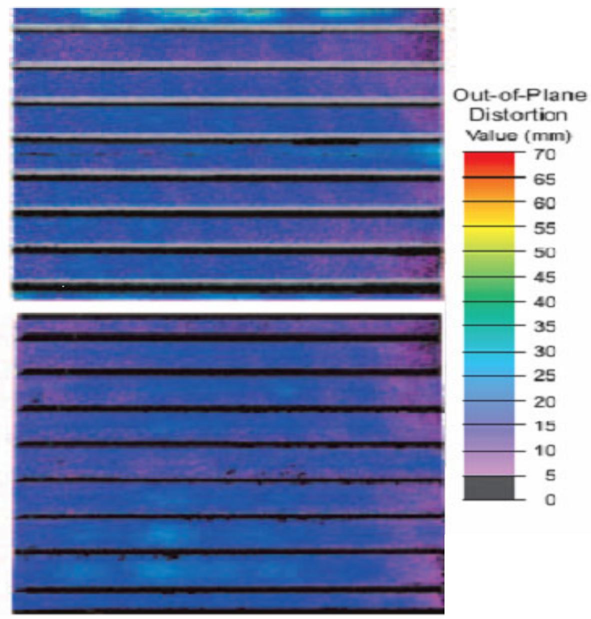


Figure 15 – LIDAR scan results compare the simple panel without TTT (Top) and with TTT (Bottom). The color variation along the edge of the top image indicates buckling.

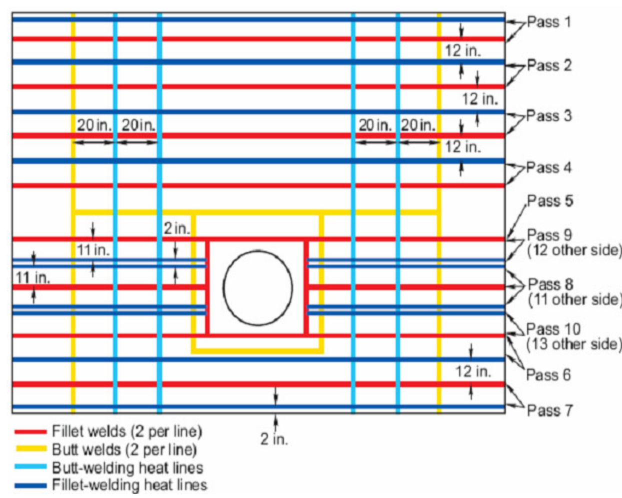


Figure 16 – TTT temperature patterns applied to the complex panel.

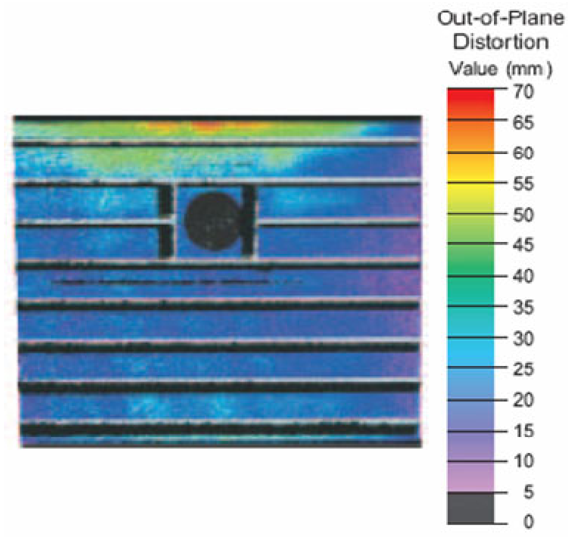


Figure 17 – LIDAR measurement results for TTT on complex panel

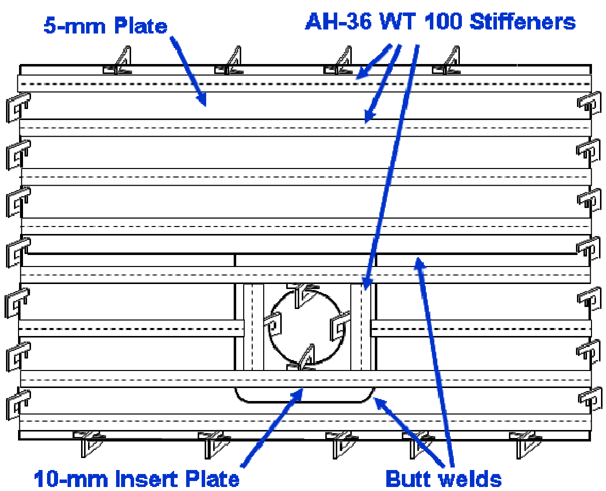


Figure 18 – Panel with insert used in TTT refinement testing.

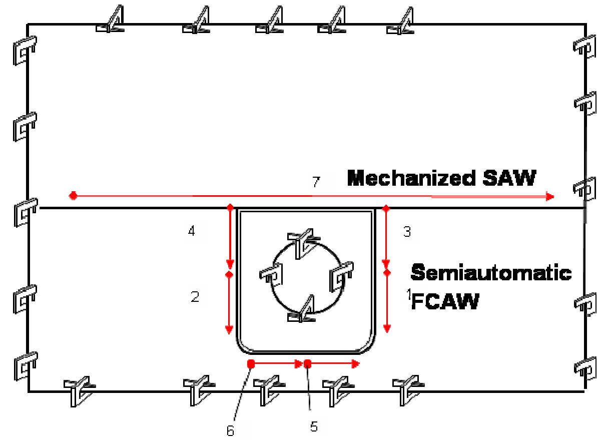


Figure 19 – The test panels were restrained and predetermined sequences were followed during butt welding

Figure 20 – Buckling occurs near the insert as a result of butt welding

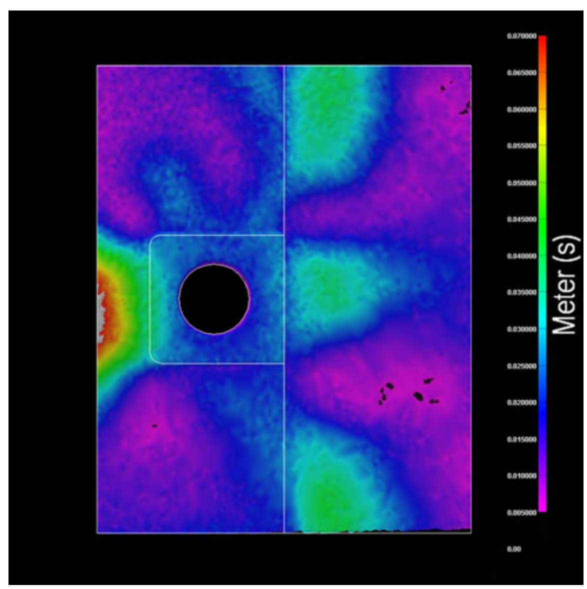
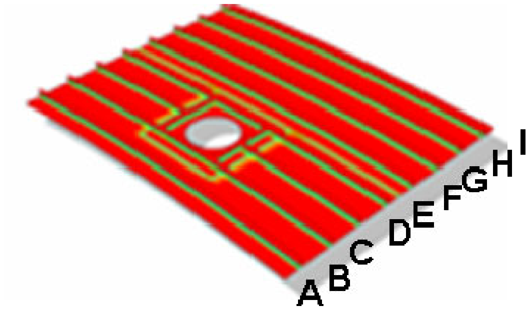


Figure 21 – LIDAR scan of a panel with butt joints welded



Trial	Zones A	B	C	D	E	F	G	H	I
1	1	1	2	2	butt	1	1	1	1
2	2	2	3	3	butt	1	1	1	1
3	2	2	2	2	butt	1	1	1	1

Figure 22 – Heating patterns selected for evaluation. Integers indicate the number of heat lines applied in each zone.

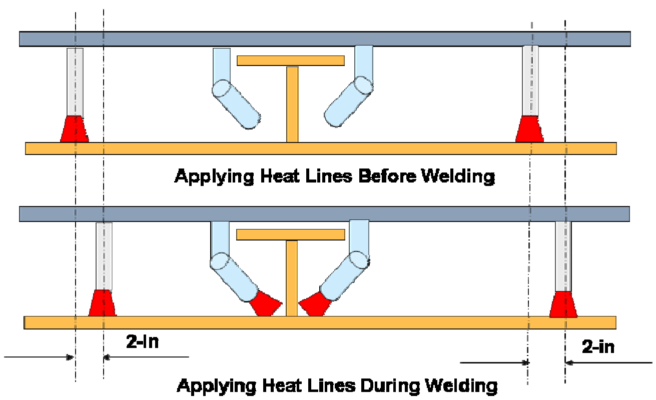


Figure 23 – Two heat lines are applied as a two-step operation. The first line is made prior to welding (top), the second line is made during welding (bottom). There is a 50-mm (2-in.) offset between each line.

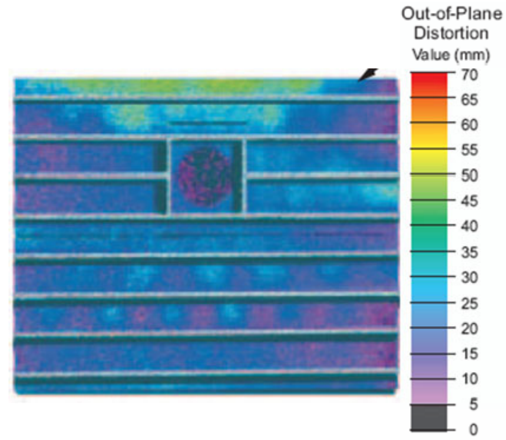


Figure 24 – LIDAR measurement for a panel without TTT showing multiple buckled regions.

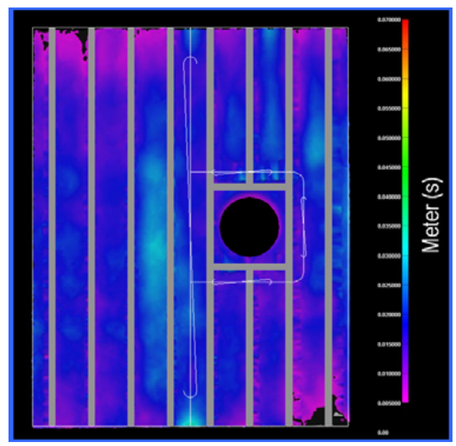


Figure 25 – LIDAR measurements of panels welded with TTT

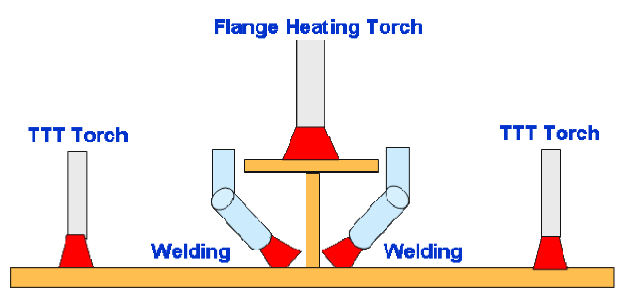
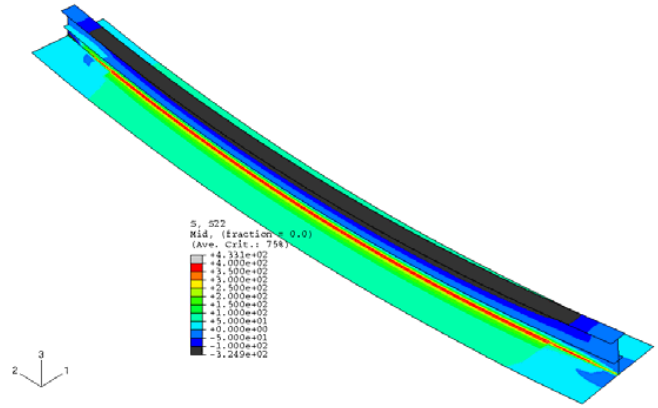
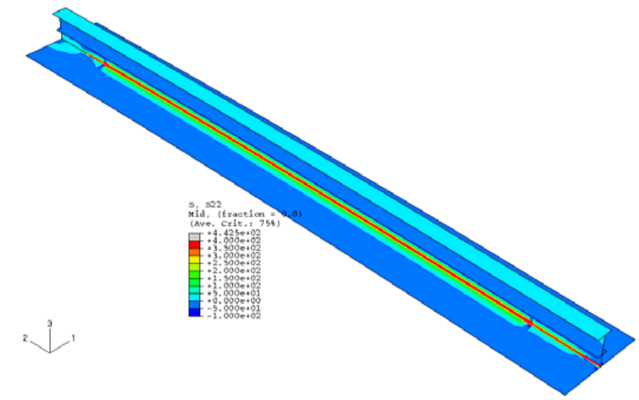


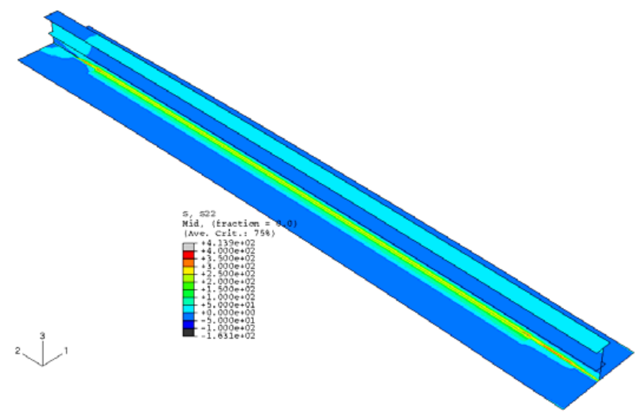
Figure 26 – Simultaneous heating of the stiffener flange will be evaluated as a means to control bowing distortion.



(a) Longitudinal residual stresses under as welded conditions



(b) Longitudinal residual stresses during reversed arching (applied bend loading)



(c) Longitudinal residual stresses after unloading

Figure 27 – An example showing how reversed arching technique works in mitigating residual stresses

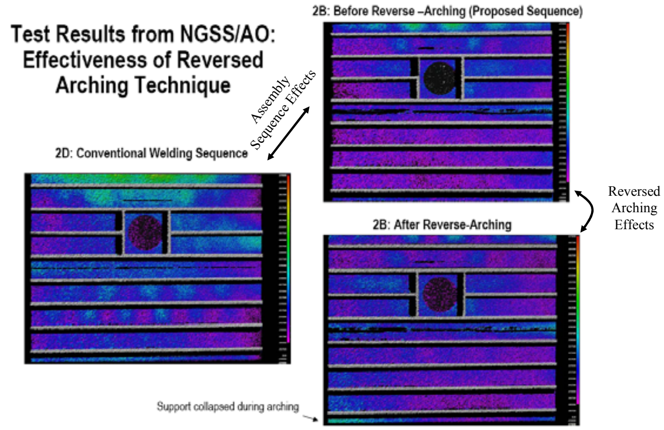
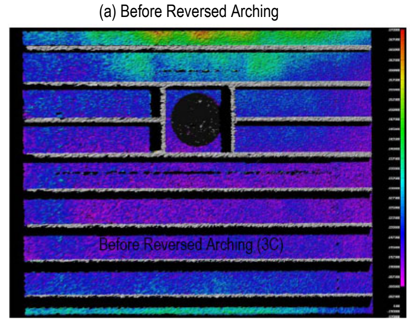
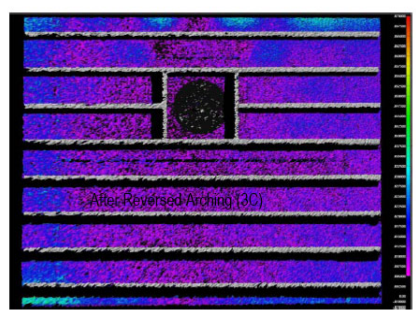


Figure 28 – Validation of the reverse arching technique developed: comparison of LIDAR measurements of out-of-plane buckling distortions with and without applying reversed arching technique and stiffener welding sequence effects

(a) Before Reversed Arching





(b) After Reversed Arching

Figure 29 – Validation of the reversed arching technique developed: comparison of LIDAR measurements of out-of-plane buckling distortions with and without applying reversed arching technique: complex panel