

# **Best Practices**

## **Distortions of Ship Hull during Construction: Causes and Preventive Measures**

**August 2026**



**IRCLASS**  
Indian Register of Shipping

## **Distortions of Ship Hull during Construction – Causes and Preventive Measures**

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### **Contents**

### **Introduction**

### **Sections**

- 1. Introduction**
  - 1.1 Types of Plate Distortion During Construction
  - 1.2 Applicability
  - 1.3 Abbreviations and Acronyms
  - 1.4 Normative References
- 2. Weld Induced Distortion**
  - 2.1 Root Causes of Weld Induced Distortions
  - 2.2 Weld Induced Distortions
  - 2.3 Preventive Measures – Design & Planning Stage
  - 2.4 Preventive Measures - Welding Practices
  - 2.5 Corrective Methods for Distorted Structure
  - 2.6 Summary
- 3. Mechanical and Load Induced Distortion**
  - 3.1 Mechanism and Root Cause
  - 3.2 Assembly and Fabrication Operations
  - 3.3 Lifting and Handling Operations
  - 3.4 Support, Block Arrangement, and Keel Blocks
  - 3.5 Equipment
  - 3.6 Workmanship and Personnel
  - 3.7 Preventive Measures — Mechanical Distortion
- 4. Environmental and Storage-Related Distortion**
  - 4.1 Improper Storage
  - 4.2 Temperature Variation
  - 4.3 Environmental Degradation
  - 4.4 Preventive Measures — Environmental and Storage
- 5. Material-Related Distortion**
  - 5.1 Residual Stresses from Plate Rolling
  - 5.2 Material Defects
  - 5.3 Preventive Measures — Material
- 6. Workmanship, Equipment Condition, and Process Automation**
  - 6.1 Workmanship and Operator Competence
  - 6.2 Equipment Condition and Calibration
  - 6.3 Process Automation and Mechanization
  - 6.4 Preventive Measures — Workmanship, Equipment Condition, and Automation
- 7. Summary and Conclusion**
  - 7.1 Control of Distortion
  - 7.2 Concluding Remarks

## **Section 1**

### **Introduction**

Ship hull construction involves the fabrication and assembly of large, relatively slender steel structures that are inherently susceptible to distortion throughout the production cycle. Distortion may develop at any stage of construction as a result of welding-induced thermal effects, mechanical forming operations, residual stresses in materials, improper handling and lifting, storage conditions, environmental exposure, inadequate workmanship, or the application of temporary and permanent construction loads. Left uncontrolled, these influences can alter the intended geometry of structural members and assemblies, leading to dimensional inaccuracies, fit-up difficulties, increased rework, reduced productivity, and potential degradation of structural performance.

The magnitude and nature of distortion are governed by numerous interrelated parameters, including welding processes and heat input, weld sequence and restraint arrangements, plate thickness, structural stiffness, fabrication tolerances, material properties, lifting and transportation methods, storage and stacking practices, workmanship standards, and environmental conditions such as temperature variations, solar heating, humidity, and wind exposure. Load-induced distortion resulting from self-weight, temporary construction loads, erection forces, and unsupported spans during assembly is also a significant consideration, particularly in large blocks and thin-plated structures.

Effective distortion management requires a systematic approach that extends beyond welding control alone. It encompasses design considerations, production planning, fabrication methods, dimensional control procedures, inspection activities, storage and handling practices, and the competence of personnel performing the work. Prevention measures implemented during the early stages of fabrication are generally more effective and economical than corrective actions undertaken after distortion has occurred.

These Technical Notes provide guidance for identifying, preventing, monitoring, and correcting distortion during ship hull construction. They describe the principal distortion mechanisms encountered in shipyard operations, outline the factors that contribute to their occurrence, and establish recommended practices for maintaining dimensional accuracy and structural integrity throughout fabrication, assembly, block erection, and outfitting activities. The objective is to minimize distortion-related defects, reduce corrective work, improve production efficiency, and ensure that completed hull structures satisfy specified quality and dimensional requirements.

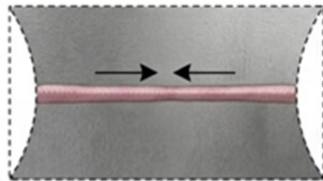
#### **1.1. Types of Plate Distortion During Construction**

Whatever its cause — welding, mechanical and load actions, environmental and storage conditions, or the properties of the plate itself — distortion during hull construction expresses itself in a limited set of geometric forms. These forms are governed less by the driving mechanism than by the structure's response to it: thin, weight-optimised hull plating has very low out-of-plane stiffness, so applied or residual stress is relieved by the plate changing shape. The same distortion type can therefore be produced by several different causes, and recognising these types as a common vocabulary is the first step in diagnosing a deformation and tracing it back to its source. The principal types are described below, grouped by the way the plate deforms rather than by what drives it.

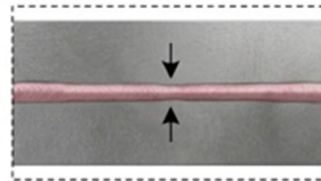
##### **1.1.1. In-Plane Shrinkage**

Shrinkage is a reduction in the plate's dimensions within its own plane, produced by contraction on cooling. It is most closely associated with welding and with thermal effects and, unlike the out-of-plane modes, it changes the size of the component rather than its shape.

- **Longitudinal shrinkage:** a shortening of the component along the length of a weld or heated line as the material contracts on cooling. It is most pronounced in long seam welds, accumulates along panel and shell seams, and pulls adjacent structure inward as overall length is reduced.
- **Transverse shrinkage:** a contraction across the width of a weld or heat line that reduces the effective breadth of a plate. It concentrates on panel-line butt joints and at shell and deck seams, and when it acts unevenly across a panel it also feeds angular and bowing distortion.



a) Longitudinal Shrinkage



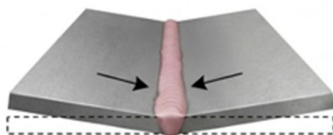
b) Transverse Shrinkage

Figure 1.1 Longitudinal and Transverse Shrinkage of Plates

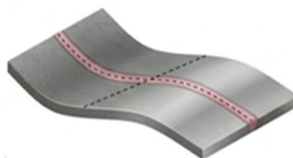
#### 1.1.2. Out-of-Plane Distortion

Out-of-plane modes are the most common and the most visible forms of plate distortion, and they are genuinely cause-independent. Each can be driven by weld shrinkage, by mechanical or support loads, by differential heating, or by the release of residual stress locked into the plate at the rolling mill.

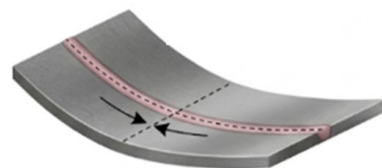
- **Angular distortion:** Rotation of the plate about the weld or bend line, so that the surface tilts out of its intended plane. It arises wherever shrinkage or force is distributed unevenly through the plate thickness — classically at fillet-welded stiffeners, T-joints, and single-sided butt welds, but equally from uneven forming or one-sided heating.
- **Bowing:** Smooth longitudinal arching of a panel or member produced whenever the driving stress acts eccentrically to the section's neutral axis. Weld shrinkage offset from the neutral axis, self-weight sag over an unsupported span, and released rolling stress in a wide plate all produce the same bowed shape in stiffened panels, fabricated girders, and long assemblies.
- **Buckling (waviness):** Multi-wave, out-of-plane rippling that appears when compressive stress in a thin plate exceeds its critical buckling threshold. Because that threshold is very low for thin plate, buckling can be triggered by weld-induced compression, by released mill residual stress, or by thermal compression, and is characteristic of thin decks, lightweight bulkheads, and deckhouse panels.
- **Twisting:** Torsional, propeller-like deformation of a panel or block, arising when angular distortion or support conditions vary across the width. It results from uneven weld completion across a block, from a plate resting on twisted or non-co-planar supports, and from torsional release of rolling residual stress in trimmed plate.



a) Angular Distortion



b) Buckling



c) Bowing

Figure 1.2 Out-of-Plane Distortion Modes

### 1.1.3. Local and Edge Distortion

Alongside the whole-panel modes, distortion also appears as localised deformation confined to part of a plate or to its edges. These forms are more closely associated with mechanical, support, and material causes than with welding, and they are easily overlooked because they do not change the overall shape of the component.

- **Local dishing:** A localized concave deflection of unsupported plating between structural members or supports, produced when the plate carries load — its own weight, stored material, or construction loads — across a span with no stiffening beneath it. It is a support-and-loading phenomenon rather than a welding one.
- **Edge waviness and camber:** A wandering or curved plate edge that appears after cutting or trimming, produced when the operation releases residual stress that was self-equilibrating across the original plate. A straight edge that develops a curve on being cut free is diagnostic of rolling-stress release rather than of any applied load.
- **Creasing and kinking:** A sharp, localised fold rather than a smooth curve, produced by a single excessive forming stroke or a concentrated mechanical impact. Unlike the elastic modes, a crease is a local plastic hinge and cannot be removed without cutting and re-forming.

### 1.2. Applicability

These guidelines apply to:

- Structural steel hull components fabricated from mild and high-strength hull steels including TMCP grades, conforming to IACS UR W11 and Classification Society rules.
- All principal distortion sources encountered in new construction: welding-induced thermal distortion, and mechanically induced distortion arising from lifting, handling, turning, impact, stacking, and uncontrolled external loading during fabrication.
- All construction stages from plate cutting through sub-assembly, panel fabrication, block assembly, grand-block integration, and final erection at the building berth.

### 1.3. Abbreviations and Acronyms

The following abbreviations and acronyms are used throughout this report.

| Abbreviation | Definition                                            |
|--------------|-------------------------------------------------------|
| AR           | As-rolled (steel delivery condition)                  |
| ASTM         | ASTM International (standards organisation)           |
| AWS          | American Welding Society                              |
| CAD          | Computer-Aided Design                                 |
| CNC          | Computer Numerical Control                            |
| DAF          | Dynamic Amplification Factor                          |
| DPI          | Dye Penetrant Inspection                              |
| EN           | European Standard (Norme Européenne)                  |
| GMAW         | Gas Metal Arc Welding                                 |
| GTAW         | Gas Tungsten Arc Welding (see TIG)                    |
| HTS          | Higher-Tensile Steel                                  |
| IACS         | International Association of Classification Societies |
| MAL          | Material Approval List                                |

**Best Practices – Distortions of Ship Hull during Construction –  
Causes and Preventive Measures  
August 2026**

|             |                                            |
|-------------|--------------------------------------------|
| <b>MPI</b>  | Magnetic Particle Inspection               |
| <b>N</b>    | Normalised (steel delivery condition)      |
| <b>NDE</b>  | Non-Destructive Examination                |
| <b>PQR</b>  | Procedure Qualification Record             |
| <b>PWHT</b> | Post-Weld Heat Treatment                   |
| <b>QA</b>   | Quality Assurance                          |
| <b>SAW</b>  | Submerged Arc Welding                      |
| <b>SR</b>   | Stress-Relieved (steel delivery condition) |
| <b>TIG</b>  | Tungsten Inert Gas welding (see GTAW)      |
| <b>TMCP</b> | Thermo-Mechanical Controlled Processing    |
| <b>UR</b>   | Unified Requirement (IACS)                 |
| <b>WPQR</b> | Welding Procedure Qualification Record     |
| <b>WPS</b>  | Welding Procedure Specification            |

#### **1.4. Normative References**

These guidelines shall be read in conjunction with the following documents:

- IACS Recommendation No. 47 (Rev. 11, 2025) — Shipbuilding and Repair Quality Standard for New Construction
- IACS UR W11 — Normal and Higher Strength Hull Structural Steels
- IACS UR W28 — Welding Procedure Qualification Tests for Hull Construction Steels
- IACS UR W32 — Qualification Scheme for Welders of Hull Structural Steels
- IACS UR W33 — Non-Destructive Testing of Ship Hull Steel Welds
- IACS W34 - Advanced non-destructive testing of materials and welds
- IACS UR Z23 — Hull Survey for New Construction
- AWS D1.1/D1.1M — Structural Welding Code — Steel
- Classification Society Rules applicable to the vessel type and flag state

## Section 2

### Weld Induced Distortion

#### 2.1 Root Causes of Weld Induced Distortions

The following can be identified as the most common root causes observed during ship hull fabrication:

- **Excessive heat input** — the single most frequently cited cause; high current, low travel speed, or oversized weld beads all magnify thermal distortion.
- **Improper welding sequence** — unidirectional, unsymmetrical, or otherwise unplanned weld deposition concentrates residual stresses.
- **Poor fit-up and edge preparation** — excessive root gaps require more weld metal and heat to bridge, amplifying shrinkage.
- **Thin plates** — flexural stiffness decreases rapidly with reducing thickness, making thin plates particularly susceptible to weld induced distortion even with moderate weld shrinkage forces
- **Inability to weld from both sides** — single-sided welding produces an asymmetric temperature gradient through the plate thickness, directly driving angular distortion.
- **Lack of, or excessive, restraints and fixtures** — insufficient restraint allows free deformation; excessive over-constraint locks in high reaction stresses that cause distortion or cracking on release.
- **Poor QA practices and non-compliance with fabrication tolerances** — cumulative dimensional deviations allowed to pass without correction at earlier stages compound into major misalignments at erection.

#### 2.2 Weld Induced Distortions

Six distinct modes of weld distortion are recognised in shipbuilding practice (Table 2.1):

| Table 2.1 — Typical modes of weld distortion |                                                             |
|----------------------------------------------|-------------------------------------------------------------|
| Type                                         | Common Structural Location                                  |
| Angular distortion                           | Fillet-welded stiffeners; T-joints; single-sided butt welds |
| Longitudinal shrinkage                       | Long seam welds                                             |
| Transverse shrinkage                         | Panel-line butt joints; shell and deck seams                |
| Buckling (waviness)                          | Thin decks, lightweight bulkheads, deckhouse panels         |

| Table 2.1 — Typical modes of weld distortion |                                                                          |
|----------------------------------------------|--------------------------------------------------------------------------|
| Type                                         | Common Structural Location                                               |
| Bowing                                       | Wide stiffened panels; fabricated girders; long fillet-welded assemblies |
| Twisting                                     | Multi-panel blocks; wide assemblies with uneven weld completion          |

### 2.3 Preventive Measures – Design & Planning Stage

The most cost-effective approach to distortion control is prevention — designing and planning to minimise the causes before any welding commences. The following measures apply at the design and production engineering stage.

#### 2.3.1 Joint Design: Minimise Weld Metal

The following can be identified as the most common root causes observed during ship hull fabrication:

The quantity of weld metal deposited in a joint is directly proportional to shrinkage forces. The designer shall select joint geometries that minimise weld volume while satisfying the structural requirement.

- **Use minimum weld size:** Fillet weld sizes shall not exceed the minimum leg length required by the structural calculation. Over-specification provides no strength benefit but significantly increases the weld metal volume, heat input, and associated shrinkage forces, thereby increasing the risk of angular distortion.

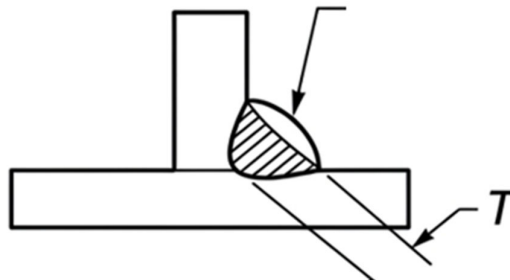


**Figure 2.1 Excessive reinforcement (greater than dimension T) increases distortion**

- **Prefer double-sided joints:** For groove welds in plate with higher thickness, a double-sided preparation (e.g., double-V or double-bevel) shall be preferred over a single-sided preparation. Double-sided joints require significantly less weld metal for the same penetration, and balanced passes on each side counteract angular distortion symmetrically. For heavy plate above 16 mm, double bevelling is specifically recommended.

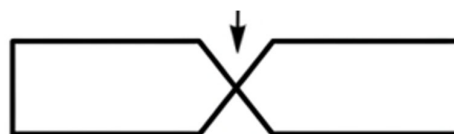


**Figure 2.2 Double-V preparation**

- **Weld along the neutral axis:** Joint and structural arrangements shall be selected so that weld lines are placed at or close to the neutral axis of the member's cross-section. Weld shrinkage forces applied at the neutral axis produce pure shrinkage without bending moment; eccentricity from the neutral axis converts shrinkage directly into a bowing moment.

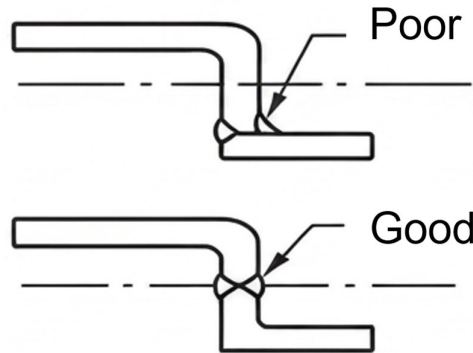


**Figure 2.3 Welding near Neutral Axis**

- **Use the most favourable joint geometry:** The joint profile should be selected so that weld stresses are balanced across the section. A joint requiring the least weld metal is to be preferred.

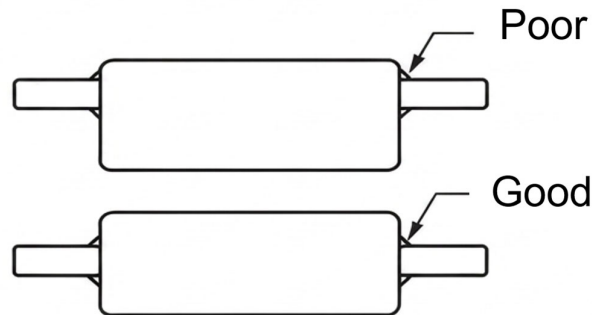


**Figure 2.4 Balancing Welds around Neutral Axis**

### 2.3.2 Intermittent Welding

Where structural requirements permit, intermittent (skip) welding shall be used instead of continuous runs to minimise total weld metal and heat input.

For attaching stiffeners to plate, intermittent fillet welds can reduce total weld metal and heat input by up to 75% compared with continuous welds, while maintaining the structural integrity of the joint for non-critical applications. The design engineer shall identify locations where intermittent welds are structurally permissible and mark these on the production drawing.

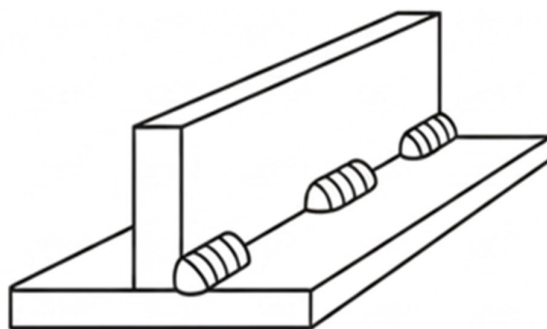


**Figure 2.5 Intermittent Welding**

An alternative to welded stiffeners is to use corrugated bulkheads wherever the structural design allows corrugation eliminates stiffener-to-plate welding entirely, removing maximum weld type and with it a major source of angular distortion in bulkhead panels.

#### 2.3.3 Pre-setting and Back Arching

Presetting — intentionally offsetting components before welding opposite to the direction of expected distortion — uses the weld shrinkage constructively: the distortion that welding inevitably produces pulls the structure back toward its correct alignment. This technique converts an unavoidable physical effect into a controlled corrective force.

- **Presetting for angular distortion:** Plates intended to form a flat joint shall be preset with the joint slightly open on the opposite face (back-angled) so that angular distortion on welding closes the gap and returns the assembly to a flat condition. The required preset angle is estimated from the expected angular distortion, which depends on plate thickness, heat input, and joint type.

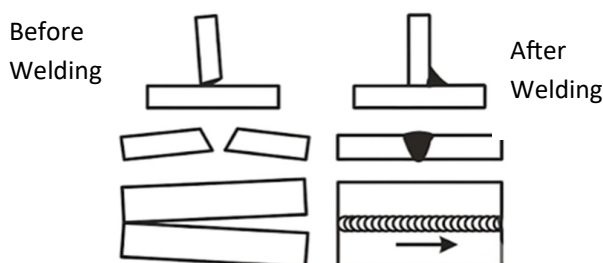


**Figure 2.6 Pre-setting Parts**

- **Back-arching for panel bowing:** For long stiffened panels prone to longitudinal bowing, the panel shall be back-arched (pre-bent opposite to the anticipated bow direction) before welding. Weld shrinkage on the stiffener face then pulls the panel toward the intended flat geometry as it cools. Back-arching is particularly effective for thin deckhouse panels and lightweight structural assemblies.

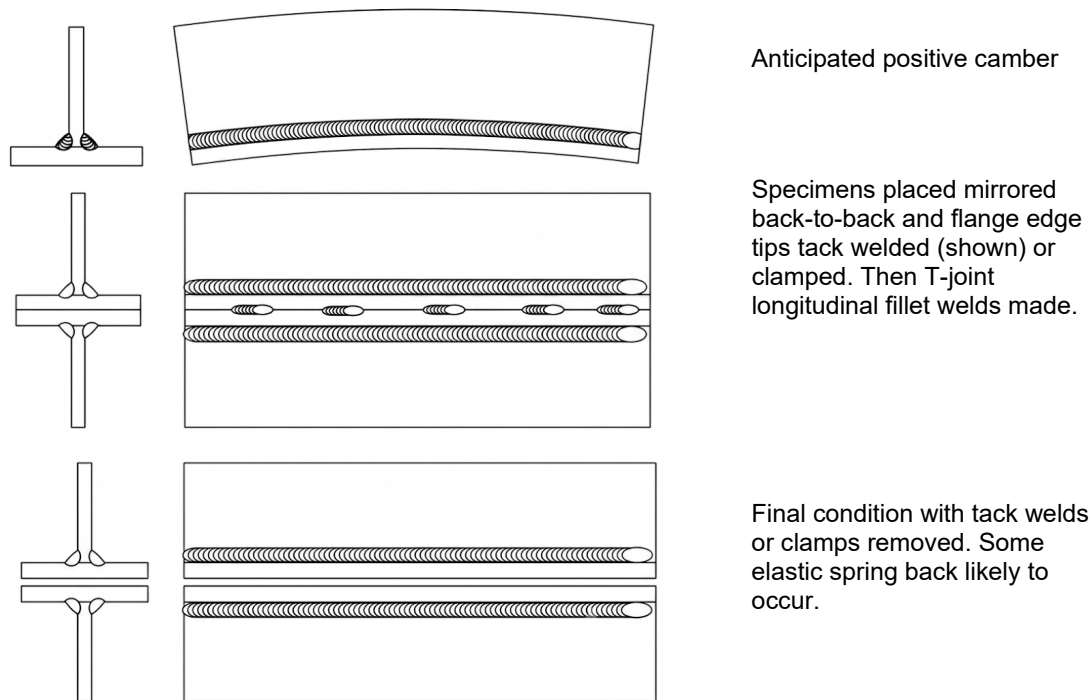


**Figure 2.7 Back Arching & symmetrical welding of identical components**

Sequencing subassemblies so that welds being made at each stage continually balance each other around the neutral axis of the section is the design-level extension of this principle: the assembly sequence itself is planned to exploit shrinkage in one region to counteract shrinkage in another.

#### **2.4 Preventive Measures - Welding Practices**

In-process welding practice is the most immediately actionable lever for distortion control. The following guidelines apply during all welding operations on hull structural assemblies.

##### **2.4.1 Control Heat Input**

Higher heat input produces greater and more severe shrinkage, directly increasing distortion. Heat input per unit length is controlled by the combination of current, voltage, and travel speed.

- **Use smaller weld passes:** Multi-pass welds using smaller individual passes deposit less energy per pass than large single passes, giving the structure more opportunity to dissipate heat between passes. Smaller passes also reduce the peak temperature of the weld zone, limiting the extent of the heat-affected zone. This method is good considering the metallurgical properties as well as longitudinal and transverse shrinkages but increases angular distortion which needs to be taken care of.
- **Minimise welding time:** It is desirable to complete each weld pass before a large volume of surrounding metal heats up and begins to expand. A practical illustration: depositing a given weld size at 175 A, 25 V, and 3 ipm requires approximately 87,500 J/in, while the same weld size at 310 A, 35 V, and 8 ipm requires only 81,400 J/in. The higher-speed, higher-current process produces less total distortion because less of the surrounding plate is heated. Mechanised welding equipment, which can maintain these parameters consistently, is strongly recommended.
- **Select the right process for the plate thickness:** Process selection shall account for plate thickness. Low heat-input processes (GTAW/TIG, pulsed GMAW, laser welding) are preferred for

thin gauge plate (below 8 mm). High heat-input processes such as SAW, while productive on thick plate, carry significant distortion risk on thin-plated structures and shall be used selectively.

- **Match parameters to WPS:** All welding parameters (current, voltage, travel speed, bead size) shall remain within the range validated by the Welding Procedure Qualification Record (WPQR / PQR). Deviations that increase heat input beyond the WPS range are not permitted without re-qualification.

#### 2.4.2 Welding Sequence

Balanced welding — distributing weld metal at different points across the structure so that shrinkage in one location counteracts shrinkage from welds already made — is the most powerful in-process distortion control available to the fabricator.

- **Center-out, symmetrical sequencing:** Welding shall always proceed from the geometric centre of the panel or block outward toward the free edges. This keeps the outer edges free to shrink during early passes, preventing the build-up of high compressive stress that drives buckling. Boundary and edge welds shall be completed last.
- **Weld alternately on opposite sides:** When multiple-pass double side welds are involved and access permits welding from both sides, passes shall alternate from side to side rather than completing all passes on one side first. This balances the angular contraction on each face, preventing cumulative angular distortion from pulling the joint to one side.

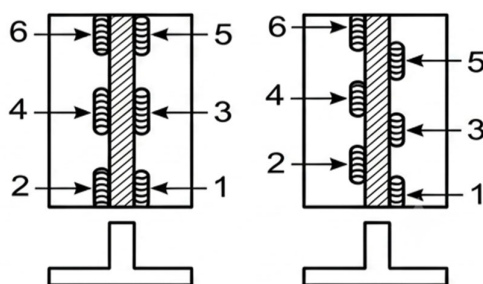


**Figure 2.8 Sequence Welds**

- **Backstep welding:** For long, continuous welds such as longitudinal stiffener-to-plate fillet runs, the joint shall be divided into segments of approximately 300–500 mm, with each segment welded in the direction opposite to the overall progression of the joint. This technique breaks the continuous thermal strain field into isolated zones, limiting global bowing. Backstep welding can reduce longitudinal bowing by up to 40% compared with unidirectional continuous welding.

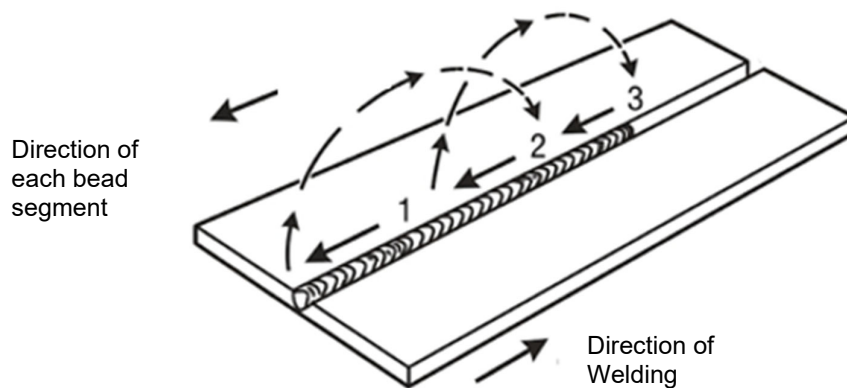


**Figure 2.9 Backstep Welding**

- **Skip (intermittent) welding sequence:** Where intermittent welds are structurally permitted, they shall be deposited in a skip pattern rather than sequentially. Completing every other segment first and then returning to fill intermediate segments distributes heat and residual stress more evenly across the joint length.
- **Block sequence for heavy assemblies:** Large structural assemblies shall be welded using a planned block sequence in which major sub-regions are completed in a controlled order so that shrinkage in later regions counteracts distortion introduced by earlier regions. The block sequence shall be documented in the weld plan before production commences.

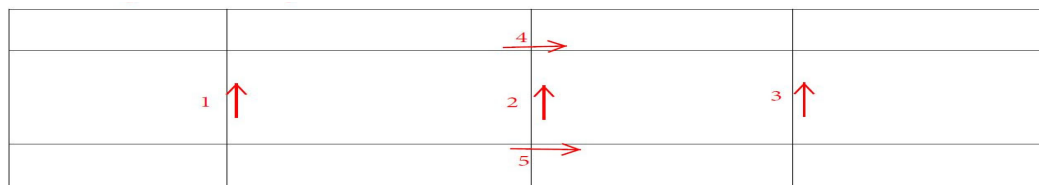


**Figure 2.10 Progressive Welding**

- **Weld toward the unrestrained end:** Where possible, welding shall progress toward the unrestrained (free) end of the joint. Welding toward a fixed boundary compresses the strain into the joint; welding toward a free end allows the end to yield and dissipates the residual strain.

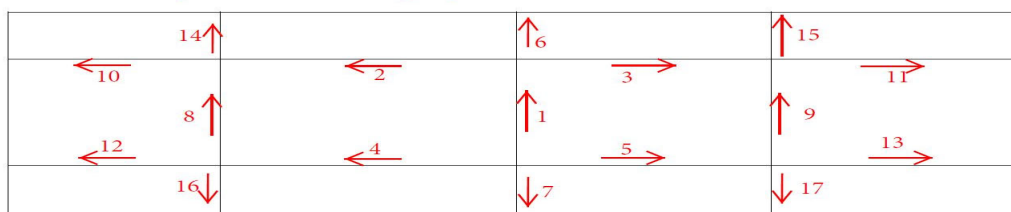


**Figure 2.11 Welding from the centre and going outwards**

#### 2.4.3 Over Welding

Over-welding is one of the most common avoidable causes of distortion in shipyard practice. More weld metal deposited in a joint means greater shrinkage forces and greater distortion.

- **Comply with specified fillet size:** Fillet weld leg lengths shall not exceed the design-specified size by more than 1 mm. An increase in fillet leg length increases deposited volume, increasing therefore both heat input and shrinkage force, with no structural benefit.
- **Increase of stitch weld length or fillet throat:** Intermittent weld lengths and throat sizes shall not be increased beyond specification as a substitution for improving fit-up. If fit-up is poor, the fit-up shall be corrected; the weld shall not be enlarged to bridge the gap.
- **Highly convex beads:** A highly convex weld bead concentrates residual stress and increases shrinkage without providing additional structural capacity. Bead profiles shall be smooth and consistent, as specified in the WPS.

#### 2.4.4 Use of Restraints, Clamps, Fixtures, and Strong-Backs

Mechanical restraints — clamps, jigs, fixtures, strong-backs, tack welds, and wedges — physically limit movement of components during welding and are an effective complement to sequence control.

- **Apply restraints systematically:** Restraints shall be positioned to resist the dominant distortion mode of the assembly, based on an assessment of the expected distortion direction. For panels

prone to angular distortion, strong-backs shall span the joint transversely; for bowing-prone assemblies, longitudinal bracing shall be applied.

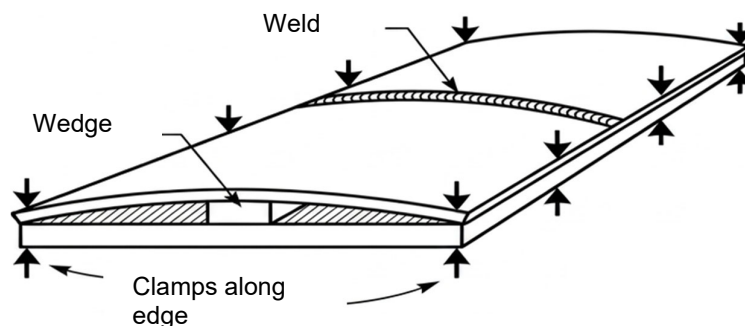


**Figure 2.12 Restraining Clamps**

- **Do not over-restrain:** Restraints shall limit harmful distortion modes while still allowing the structure to shrink in-plane. Complete immobilisation of a joint concentrates tensile residual stress toward the material's yield strength and can cause hot cracking at the weld or cold cracking in the heat-affected zone. The structure must be allowed some degree of in-plane elastic contraction.
- **Timing of release:** Restraints shall not be removed until the assembly has cooled to ambient temperature. Premature release before thermal equilibrium transfers locked-in thermal reaction forces into the structure, causing delayed distortion or crack initiation.
- **Tack welds (Not forming the part of the final weld):** Tack welds shall be of adequate size and length to maintain joint alignment during welding but shall not act as permanent restraints. Undersized tack welds that fracture during welding introduce sudden load redistribution and can cause local angular distortion.

## **2.5 Corrective Methods for Distorted Structure**

When distortion is detected and exceeds the fabrication tolerances defined in IACS Recommendation No. 47, corrective action is required before the component proceeds to the next construction stage. The following methods are available, listed in order of increasing invasiveness. The least invasive method that achieves compliance with tolerance shall always be attempted first.

### **2.5.1 Mechanical Straightening**

Cold mechanical straightening uses presses, jacks, or purpose-built fixtures to impose a force on the distorted structure opposite to the distortion direction, plastically correcting the deformed profile.

Mechanical straightening is appropriate for localised deformations where the distortion is accessible and the required correction force can be applied without overstressing the surrounding structure. Hydraulic correction is the preferred form for large structures where simple press tooling cannot reach. The total plastic strain imposed by mechanical straightening must remain within the limits permitted by the Classification Society, the strain-ageing test procedure per IACS UR W11 may be required where local cold forming exceeds 5%.

All mechanically straightened areas shall be visually inspected for surface cracking and subject to Magnetic Particle Inspection (MPI) or Dye Penetrant Inspection (DPI) before sign-off.

### **2.5.2 Flame Straightening (Thermal Straightening)**

Flame straightening — controlled localised heating by oxy-fuel or induction torch — is the most widely used corrective method in shipyard practice for structural distortion. The principle is the reverse of the welding distortion mechanism: carefully applied localised heat causes compressive plastic yielding in

## Best Practices – Distortions of Ship Hull during Construction – Causes and Preventive Measures August 2026

the heated zone; on cooling, the zone contracts and the surrounding elastic material provides restraint, pulling the distorted structure back toward its intended geometry.

- **Heating patterns:** The torch is applied in line, wedge, or point patterns depending on the type of distortion being corrected. Line heating is used for longitudinal bowing; wedge heating is effective for angular distortion and localised plate dishing. The operator's skill in applying the correct pattern, at the correct temperature, at the correct location, is critical to effectiveness.
- **Temperature monitoring:** Surface temperature shall be monitored continuously by a calibrated pyrometer during heating. The temperature probe shall be within 100 mm of the active heating zone and read by a dedicated observer (not the torch operator). Temperature monitoring is mandatory — it is not optional for structural steel components.
- **Maximum surface temperatures by steel grade:** The maximum heating temperature is governed by the material grade. Exceeding these limits destroys the steel microstructure (Table 2.2):

| Table 2.2 — Indicative Maximum Surface Temperature Limits for Thermal Straightening |                                                                          |                                                                |
|-------------------------------------------------------------------------------------|--------------------------------------------------------------------------|----------------------------------------------------------------|
| Steel Grade                                                                         | Maximum Surface Temperature                                              | Cooling Method                                                 |
| Normal-strength steel (A, B, D, E)                                                  | $\leq 900\text{ }^{\circ}\text{C}$                                       | Air or controlled water quench                                 |
| Higher-strength steel (AH32, DH36 etc.)                                             | $\leq 900\text{ }^{\circ}\text{C}$                                       | Air-cool to $500^{\circ}\text{C}$ ; water spray then permitted |
| TMCP high strength (AH36, DH36, EH36)                                               | $\leq 900\text{ }^{\circ}\text{C}$ (confirm with steelmaker)             | Air cool; pyrometer mandatory                                  |
| Extra high strength / heavy TMCP plate                                              | $\leq 700\text{--}850\text{ }^{\circ}\text{C}$ (do not exceed $A_{c1}$ ) | Air cool only; forced quench prohibited                        |

- **Repeated cycles:** Same location shall not be subjected to more than three thermal straightening cycles. Repeated heating causes cumulative grain coarsening. Where repeated straightening is necessary, the underlying production cause of recurring distortion shall be investigated and the process corrected before further cycles are attempted.
- **Post-straightening inspection:** All thermally straightened areas shall be inspected for cracks after correction and after cooling to ambient temperature. Magnetic Particle Inspection (MPI) or Dye Penetrant inspection (DPI) shall be applied to all straightened zones on high-strength and TMCP steels as a mandatory quality gate.

### 2.5.3 Peening

Peening is the process of mechanically working the surface of a completed weld bead by repeated blows from a pneumatic peening hammer or needle gun. The impact stretches and thins the weld bead, inducing compressive surface stress that partially counteracts the tensile residual stress generated by cooling contraction. In effect, peening relieves shrinkage forces by plastic deformation of the bead itself.

Peening is most effective on intermediate passes in multi-pass welds; it shall not be applied to the final cap pass (as this may hide surface defects) or to the root pass (as it can introduce cracking). Peening is a useful supplementary technique for controlling angular distortion in accessible multi-pass joints but

is not a primary distortion control method for large structural assemblies. Care must be taken not to over-peak to the point of causing surface fatigue damage.

#### 2.5.4 Stress Relieving by Controlled Heating

Post-weld thermal stress relieving — controlled heating of the weldment to a specified temperature, holding at temperature for a defined period, then controlled slow cooling — reduces residual stresses by allowing the material to creep and relax. This technique is used in special situations where residual stress must be controlled for fatigue life or service environment reasons.

#### 2.5.5 Cutting and Re-welding

Where distortion is severe, recurring, or involves material that has been metallurgically degraded by over-temperature thermal straightening, the affected plate or component shall be cut out and a new insert plate or replacement section fitted. This is the most invasive corrective method and incurs the highest cost and schedule impact, but it is the correct engineering response when all other corrective methods are inadequate or inadvisable.

Insert plates shall have a minimum dimension of 300 mm in any direction; butt joints of the insert plate shall be positioned at least 150 mm from any structural intersection. All insert plate butt welds shall be subject to 100% ultrasonic testing on completion, and a delayed cold-crack inspection shall be conducted not less than 48 hours after weld completion for high-strength steel insert plates.

#### 2.5.6 Localized Heat treatment

In specific situations where geometric correction combined with stress management is required (for example, at a heavily restrained erection joint), controlled localised post-weld heat treatment (PWHT) within prescribed temperature and soak-time parameters may be applied. This shall be executed strictly in accordance with a documented heat treatment procedure approved by the Classification Society and is not a standard corrective option for general hull fabrication.

### 2.6 Summary

The following summarises the key preventive and corrective actions from Sections 3–6. It is intended for use by production supervisors and welding engineers as a pre-weld, in-process, and post-weld quality reference.

#### *Before Welding*

- **Joint design:** Confirm minimum weld size is specified; prefer double-sided joint preparations for thick plate; weld line to pass through or close to neutral axis.
- **Fit-up:** Verify root gaps comply with IACS Rec. 47 tolerances; correct poor fit-up before welding, do not force fit-up the components without pre-forming, do not bridge gaps by over-welding.
- **Presetting:** Apply preset offset or back-arch opposite to expected distortion direction; verify preset angle against predicted distortion magnitude.
- **Weld plan:** Prepare and approve a written weld sequence plan for each block type; centre-out symmetrical sequence, with backstep for runs over 1 m.
- **Restraints:** Fit strong-backs, clamps, or fixtures to resist dominant distortion mode; do not over-constrain; verify all restraints are securely in place.
- **Process parameters:** Confirm welding machine is set to WPS parameters; verify process is appropriate for plate thickness.

#### *During Welding*

- **Sequence compliance:** Confirm sequence plan is being followed; do not deviate from approved sequence without production engineering approval.

**Best Practices – Distortions of Ship Hull during Construction –  
Causes and Preventive Measures  
August 2026**

---

- **No over-welding:** Use calibrated weld gauge to spot-check fillet sizes; leg lengths shall not exceed design specification by more than 1 mm.
- **Weld alternately:** Alternate sides for double-sided joints; do not complete all passes on one side before starting the other.
- **Restraint monitoring:** Do not release restraints or strong backs during welding or before ambient temperature is reached.

*After Welding*

- **Dimensional check:** Measure assembly dimensions at all mandatory quality milestones against IACS Rec. 47 tolerances; record results in block quality dossier.
- **If distortion exceeds Standard tolerance:** Initiate corrective action; attempt cold mechanical straightening first, thermal straightening second; document all corrective work.
- **Temperature control during flame straightening:** Pyrometer mandatory; do not exceed grade-specific maximum surface temperature; mandatory post-straightening NDE for HTS and TMCP grades.
- **Post-correction inspection:** Inspect all corrected areas for cracks (visual + MPI/DPI); obtain sign-off before covering work proceeds.

## **Section 3**

### **Mechanical and Load Induced Distortion**

Mechanical and load induced distortion arises from physical forces acting on hull plates and assemblies during fabrication, handling, assembly, and pre-erection storage. Unlike welding distortion, it is not thermally driven: it results from external physical forces, improper support configurations, forced constraints, and unplanned impacts that cause elastic or plastic deformation of the structural component.

#### **3.1 Mechanism and Root Cause**

The susceptibility of a hull plate or assembly to mechanical deformation depends on the ratio of the applied load to the structural stiffness of the component. Thin, lightly stiffened plates — which dominate modern optimised hull designs — have very low out-of-plane flexural stiffness. Even loads well within the structural design capacity of the completed hull can permanently deform an unstiffened plate during fabrication, when that plate is not yet part of the stiffened structure.

Two distinct mechanical responses can occur:

- **Elastic deformation:** The plate deforms elastically under the load and recovers to original position on removal of load. If, however, welding or other restraint is applied while the plate is in the elastically deformed state, the deformation becomes locked and residual stress is developed.
- **Plastic deformation:** The applied load exceeds the local yield strength of the plate, causing permanent shape change that does not recover on removal of the load. This is the more serious of the two responses, as it requires active corrective measures to rectify.

The critical factors that impact the severity of distortion are plate thickness, unsupported span between structural members, magnitude and distribution of the applied load, and the duration of loading.

#### **3.2 Assembly and Fabrication Operations**

##### **3.2.1 Forced Fit-Up and Assembly Restraints**

Forced fit-up is one of the most common sources of mechanically induced distortion in shipyard production. It occurs when a plate or sub-assembly does not naturally match its mating component and is forced into position using hydraulic jacks, wedges, or excessive tack welds. The forcing introduces elastic strain energy into the assembly; when weld heat is subsequently applied, this stored energy interacts with weld shrinkage, and the combined result is distortion that is larger and less predictable than for a freely fit joint.

- **Identify the cause:** When a component resists being placed into its design position, the source of misalignment shall be identified and corrected — by pre-forming, by adjusting the mating component, or by accepted green-material trimming — rather than forcing the component into place. Forced fit-up is not a permissible substitute for accurate fabrication.
- **Quantify the fit-up gap before welding:** Root gaps and hi-lo misalignment at all structural joints shall be measured and recorded before tacking. Joints outside IACS Rec. 47 tolerance shall be corrected before welding commences. Bridging an excessive gap by depositing additional weld metal increases both heat input and mechanical distortion simultaneously.
- **Release temporary restraints gradually:** Temporary clamps and fit-up restraints shall be released gradually and in a planned sequence after tacking, not removed suddenly. Sudden release causes the assembly to snap into a new equilibrium position, which may cause the tack welds to crack or the joint faces to shift out of alignment.

### 3.2.2 Cold Bending and Forming Operations

Cold bending, rolling, and pressing are routine operations in hull fabrication, used to form shell plates to the hull's curved geometry, to pre-bend deck plates, and to produce curved frames and brackets. Incorrectly controlled forming is a significant source of permanent plate distortion.

- **Use progressive, controlled passes:** Cold bending shall be performed in small, progressive increments rather than in a single large press stroke. A single excessive press stroke past the material's elastic limit produces a sharp localised crease rather than a smooth curve and creates a stress concentration that cannot be corrected without cutting and re-forming.
- **Calibrate spring-back for each plate:** Spring-back after release of the press varies with plate material, thickness, and pre-existing rolling residual stress. Trial bends on material from the same heat or batch shall be used to calibrate effective spring-back before production forming commences. Over-bending to compensate for spring-back shall be calculated, not estimated.
- **Apply symmetric forming forces:** Forming forces shall be applied symmetrically across the plate width. Uneven die or roller contact causes one edge to deform more than the other, producing taper, twist, or edge waviness that is difficult to correct after forming.
- **Temperature controls for line heating used in forming:** where line heating is used as a forming method (rather than as a corrective measure), the same surface temperature limits applicable to thermal straightening shall apply. Forming by line heating on TMCP grades above 900°C risks microstructural damage identical to that caused by uncontrolled thermal straightening.

### 3.2.3 Incorrect Support During Fabrication

A plate or sub-assembly placed on uneven, misaligned, or insufficiently spaced fabrication supports deforms under its own weight before any load is applied. Because hull plates are large and thin, even small support height differences can produce significant permanent deformation over the support span.

- **Supports under primary structural members:** Fabrication supports, jig stools, and trestles shall be positioned directly beneath primary structural members — web frames, longitudinal girders, and transverse bulkhead webs. Placing supports beneath unsupported plate fields concentrates load onto the plate between stiffeners, causing local dishing.
- **Level and co-planar support surface:** All support points shall be set to a co-planar level within  $\pm 3$  mm before any plate or sub-assembly is placed on them. Out-of-level supports impose an imposed twist equal to the height differential divided by the diagonal distance introducing additional stress.
- **Span limits between supports:** The maximum unsupported span between adjacent fabrication supports shall be determined by calculation for each plate thickness, based on limiting the self-weight deflection at mid-span to a fraction of the fabrication tolerance.

### 3.2.4 Weight of Attached Structures, Outfitting, and Resting Equipment

Premature installation of heavy outfitting — machinery, tanks, pipe runs, heavy brackets — before the supporting structure is complete, and the practice of resting heavy items directly on plate panels, are persistent sources of local plate deformation in shipyard practice.

- **Install heavy outfitting after structural completion:** Heavy machinery, equipment bases, and structural outfitting shall not be installed in a block until the primary structural floor and girder system to which they transfer load is fully welded, inspected, and dimensionally accepted. Installing heavy items on an incomplete block causes local bending between structural members and imposes concentrated loads on plating that is not yet stiffened.
- **No loads on unsupported plating:** Heavy equipment, materials, consumables, and staging shall not rest directly on shell or deck plating without an intervening spreader plate or timber bearer positioned over a structural member.

- **Temporary stiffeners and supports for early installation:** Where design requirements make it necessary to install heavy outfitting before the surrounding structure is complete, temporary structural supports shall be designed and fitted to transfer the outfitting load into primary structural members. Their removal sequence documented before the permanent structure is completed around them.

#### 3.2.5 Overloading by Workers, Materials, and Construction Equipment

In active production areas, hull panels and decks are frequently used as working platforms before they are part of the completed hull structure. The loads from workers, tool sets, equipment, and stored materials can locally exceed the capacity of unsupported thin plating.

- **Distribute construction loads over structural members:** Temporary loads from workers, staging, and portable construction equipment shall be distributed by bearers or staging frames so that load transfer occurs through stiffened areas, not directly onto unsupported plate fields.
- **Define and post load limits for working platforms:** For thin-plated decks and panels used as working platforms during construction, calculated load limits shall be posted and enforced. Storage of consumables, pipe runs, and other bulk materials in concentrated areas shall not be permitted without a load check against the local panel capacity.
- **Remove construction loads before dimensional inspection:** All temporary loads — stored materials, staging, equipment, personnel concentrations — shall be removed before dimensional inspection is conducted. Measuring deflected geometry under live construction load and recording it as the structural dimension produces false acceptance.

#### 3.3 Lifting and Handling Operations

Block and panel lifting is one of the highest-distortion-risk activities in the construction sequence. A sub-assembly that is dimensionally correct on the ground can be permanently deformed in a single lift if the rigging is incorrectly configured.

##### 3.3.1 Incorrect Lifting Methods — Sling Angles and Lifting Point Positions

- **Prepare a lifting plan for every block type:** A written lifting plan shall be prepared by a qualified production or structural engineer before the first lift of each block type. The plan shall state verified block weight and centre of gravity, padeye and sling positions, sling lengths and minimum angles, crane rating, and the expected stress state of the block during the lift. No lift shall proceed without an approved plan.
- **Minimum sling angle of 60°:** The sling angle measured from the horizontal shall not be less than 60° for any hull block lift. Sling angles below 60° introduce horizontal compressive components into the top structure of the block that can cause plate buckling. Where geometry prevents 60°, a spreader beam shall be used.
- **Position lifting lugs over primary structural members:** Padeyes and lifting lugs shall be located directly above transverse web frames, longitudinal girders, or bulkhead webs. Positioning above unsupported plate fields introduces concentrated peel loads at the lug attachment that cause local plate deformation and cracking risk at the lug weld.
- **Use spreader beams for large flexible panels:** Wide, lightly framed panels shall be lifted using multi-point spreader beam arrangements that distribute the lift force to multiple points along the panel's primary structural members. Single-hook or two-point lifting of large panels creates global bending that can cause permanent bow or twist.
- **Apply dynamic amplification factors:** Lifting load calculations shall apply a suitable dynamic amplification factor (DAF) to the static block weight for standard shipyard lifts. Static calculations alone are insufficient for flexible hull structures.

### 3.3.2 Block Turning and Rotation

Turn-over operations — rotating a block through 180° to weld the reverse side in the flat position — subject internal structure to loading conditions that may not occur in service and for which the block is not stiffened at the time of turning.

- **Fit internal temporary trussing before turning:** Before any turn-over, temporary internal pipe trussing or bracing shall be fitted to transfer inertial and gravitational loads into primary structural members during the period when the block passes through the inverted position. This is particularly critical for blocks with thin bulkheads, large openings, or asymmetric structure.
- **Use synchronised dual-hook cranes:** Where available, synchronised dual-hook cranes shall be used for turn-over, allowing controlled, gradual rotation rather than the sudden dynamic loading that occurs with single-hook flip-over. Rotation speed shall be controlled and specified in the lifting plan.
- **Inspect after every turn-over:** Following each turn-over operation, the block's dimensions and fairness shall be checked against production drawing requirements before further work proceeds. Distortion introduced during turn-over is most cost-effectively corrected before subsequent welding locks the deformation in.

### 3.3.3 Impact and Mechanical Damage

Impacts from crane hooks, spreader bars, transport vehicles, and dropped loads are a significant and frequently underreported source of plate deformation in active fabrication areas.

- **Establish and enforce exclusion zones:** Exclusion zones shall be marked around completed or primed panels and block surfaces where moving crane loads or transport equipment could make accidental contact. A minimum clearance of 500 mm shall be maintained between moving suspended loads and adjacent hull structures.
- **Mandatory damage reporting:** All impacts, dents, gouges, or mechanical deformation — however minor in appearance — shall be immediately reported, recorded with location and measured dimensions, and assessed by a qualified structural engineer before any covering work, outfitting, coating, or insulation is applied over the affected area.
- **Assess and correct before progression:** Damage that exceeds IACS Rec. 47 fairness limits (typically  $\pm 4$  mm plate fairness,  $\pm 6$  mm limit) shall be corrected by the appropriate method (cold pressing or thermal straightening) before the block proceeds to the next production stage. Concealing damage under subsequent outfitting is prohibited.

### 3.4 Support, Block Arrangement, and Keel Blocks

The arrangement and condition of keel blocks, cradles, and storage supports is a critical but often underappreciated distortion risk. A block supported on uneven keel blocks is, in effect, being forced into a twisted shape by its own deadweight before a single weld is made or any external load is applied.

- **Set keel blocks to uniform height:** Keel blocks shall be set to a uniform, verified height before block landing. Height uniformity shall be checked with a precision level or laser instrument across the full block footprint, and any block showing a height difference greater than 3 mm from the reference plane shall be adjusted before the block is landed.
- **Align keel blocks under load-bearing members:** Keel blocks and cradle support shall be positioned directly beneath primary internal structural members — floors, girders, transverse frames, and bulkhead webs. Keel blocks beneath unsupported plate fields between structural members act as concentrated loads on the outer shell plating and cause local dishing under deadweight.
- **Re-verify block support after movement:** Keel block and cradle heights shall be re-verified after every block movement, transport, turn-over, or extended storage period, and before any dimensional inspection is recorded. Ground settlement, vibration from nearby construction activity, and block transport can all alter support geometry.

- **Use adjustable hydraulic pin-jig platforms or SPMTs for precision work:** For blocks requiring precise dimensional control prior to erection, adjustable hydraulic pin-jig platforms or self-propelled modular transporters (SPMTs) should be used in preference to fixed keel blocks. These maintain a defined, level support geometry regardless of ground irregularities throughout the storage and pre-erection inspection period.
- **Define stacking load limits:** Where blocks are stacked vertically in the storage yard, the stacking load shall be verified against the structural capacity of the lower block at its current state of completion. Vertical load transfer shall occur only through primary structural members; stacking shall be documented on the storage record for each block.

### 3.5 Equipment

The condition and calibration of fabrication equipment directly affect the dimensional accuracy of cut and formed components. Inaccurate components require forced fit-up, generating the mechanical distortion described in Section 4.2.1.

- **Maintain and calibrate CNC cutting equipment:** CNC cutting tables and plasma/laser cutting machines shall be maintained and calibrated on a documented schedule. Worn drive mechanisms, misaligned guide rails, or uncalibrated torch height controllers produce dimensional inaccuracies in cut components that propagate directly into fit-up gaps and forced assembly at subsequent stages.
- **Inspect and rectify bending and rolling machines:** Bending rolls, press brakes, and plate straighteners shall be inspected for roll wear, bearing play, and roller alignment on a documented schedule. Worn or misaligned rolls produce inconsistent curvature — one edge of the plate is formed more than the other — generating taper and twist in formed shell plates that cannot be fully corrected by subsequent handling.
- **Inspect and replace damaged jigs and fixtures:** Fabrication jigs, fixtures, and fit-up frames shall be inspected for distortion, cracked welds, worn locking pins, and deteriorated reference surfaces before each use. A jig that has itself been deformed produces consistently distorted output; jigs showing loss of dimensional accuracy shall be withdrawn from service and repaired or replaced before production use.
- **Maintain hydraulic clamps and restraint equipment:** Hydraulic clamps and chain blocks used for fit-up and restraint shall be maintained to their rated holding force. Under-performing clamps that cannot maintain the required restraint force allow progressive creep during welding, compounding mechanical and thermal distortion simultaneously.
- **Calibrate marking and measurement tools:** Tape measures, straight edges, squares, and level instruments shall be calibrated on a schedule appropriate to their use frequency. A systematic measurement error — for example, a stretched tape or an uncalibrated square — produces consistent dimensional offset across all components cut or checked with that tool, resulting in systematic fit-up problems throughout the block.

### 3.6 Workmanship and Personnel

Mechanical distortion from handling, fitting, and assembly operations is strongly influenced by the skill and discipline of the workers performing those operations. Unlike welding, where WPS compliance provides a documented baseline, mechanical handling operations often have less formal procedural control and rely more heavily on individual judgement and training.

- **Train riggers and fitters in distortion-critical practices:** All riggers, fitters, platers, and machinery handlers involved in hull fabrication shall receive documented training in correct lifting point selection and sling angle requirements; support and keel block setting procedures; fit-up gap measurement and the prohibition on forced assembly; load limits for working on unsupported plating; and damage reporting obligations. Training shall be refreshed whenever working practices or equipment change.
- **Require engineering approval for non-standard handling:** Any handling or assembly operation that deviates from the approved lifting plan or fit-up procedure — including use of additional jacking,

unplanned turning, or improvised support arrangements — shall require written engineering approval before execution. Improvised mechanical solutions to fit-up or handling problems are a leading cause of distortion escalation.

- **Supervise high-risk operations:** Block turn-over operations, the first lift of a new block type, and landing of blocks on keel blocks in the dry dock shall be directly supervised by a qualified production engineer, not left entirely to the crane operator and rigging team. The engineer's role is to verify that the lifting plan is being followed and to halt the operation if conditions differ from those planned.
- **Enforce a no-improvisation rule for fit-up:** Fitters shall not improvise solutions to difficult fit-up situations — excessive jacking, burning off material without engineering approval, or using welding to fill gaps beyond permitted tolerance — without documented production engineering review. These improvisations routinely introduce distortion that propagates to the block assembly and erection stages.

### **3.7 Preventive Measures — Mechanical Distortion**

The following preventive measures draw together the requirements from Sections 4.1 through 4.6 into an actionable set of controls for production supervisors and production engineers.

#### **Lifting and Rigging**

- **Lifting plans:** Prepare and approve a written lifting plan for every new block type before the first lift; verify block weight, centre of gravity, padeye positions, sling angles (minimum 60°), and crane rating.
- **Spreader beams:** Use spreader beams for all wide, thin-plated, or flexible panels where a two-point sling configuration would load the block asymmetrically or at a sling angle below 60°.
- **Turn-over preparation:** Fit and verify internal temporary trussing before block turn-over; use synchronised dual-hook cranes where available; inspect dimensions after every turn-over before proceeding.

#### **Support and Keel Blocks**

- **Level setting:** Set all keel blocks, cradles, and fabrication supports to  $\pm 3$  mm co-planar level before landing any block; re-verify after every movement or extended storage period.
- **Position under primary structure:** Place all supports and keel blocks under primary structural load paths — floors, girders, frames, and bulkhead webs — never under unsupported plate fields.
- **Use hydraulic pin-jigs for precision blocks:** Use adjustable hydraulic pin-jig platforms or SPMTs for blocks requiring tight dimensional control through to erection.

#### **Fabrication and Fit-Up**

- **No forced fit-up:** Do not force components into alignment; identify and correct the cause of misalignment before proceeding.
- **Progressive forming:** Perform cold bending in controlled progressive passes; calibrate spring-back from trial bends before production forming; apply forming forces symmetrically.
- **Supports under fabrication:** Set fabrication supports co-planar within  $\pm 3$  mm; limit unsupported spans to 1.5 m for plates thinner than 8 mm; verify before starting work.

#### **Construction Loads**

- **No loads on bare plating:** Use timber bearers or spreader plates over structural members for all equipment, material, and staging loads on plate thinner than 10 mm.
- **Install outfitting after structural completion:** Heavy machinery and outfitting items shall not be installed until the primary structural floor to which they connect is fully welded and accepted.
- **Remove loads before inspection:** All temporary construction loads shall be removed before dimensional measurements are recorded.

**Best Practices – Distortions of Ship Hull during Construction –  
Causes and Preventive Measures  
August 2026**

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Damage Control

- **Mandatory reporting:** All mechanical damage — dents, gouges, or deformation from impacts — shall be reported immediately, recorded with location and measured size, and assessed before any covering work proceeds.
- **Correct before progression:** Damage exceeding IACS Rec. 47 fairness limits shall be corrected by cold pressing or thermal straightening before the block advances to the next production stage. Concealment is prohibited.

Equipment and Personnel

- **Maintain calibration:** Maintain cutting machines, bending rolls, jigs, clamps, and measurement tools on documented schedules; withdraw worn or damaged equipment from service until repaired.
- **Train and supervise:** Ensure all riggers, fitters, and handlers have documented training in distortion-critical operations; require engineering supervision for high-risk lifts, first lifts, and non-standard fit-up situations.

## **Section 4**

### **Environmental and Storage-Related Distortion**

Environmental conditions and storage practices are often overlooked but significant source of structural distortion in ship hull fabrication. Unlike welding distortion, which is introduced at a defined production event, environmental and storage-related distortion accumulates slowly and silently — through months of inadequate support, repeated daily temperature cycles, moisture infiltration, and progressive surface degradation. By the time the distortion is measured at a quality gate, its origin may be difficult to trace and the correction costly. The most effective strategy is prevention: implementing correct storage practice, monitoring plate condition during extended storage, and controlling the environmental conditions under which precision fabrication operations are carried out.

#### **4.1. Improper Storage**

Improper storage is one of the most common and most preventable causes of distortion in shipyard fabrication. A plate or sub-assembly placed on inadequate supports and left in that condition for an extended period will deform under its own self-weight to an extent that may be permanent and irreversible without active corrective measures.

##### **4.1.1 Inadequate or Uneven Supports During Long-Term Storage**

Hull steel plates are heavy and over a storage span of several weeks or months, even small unsupported lengths allow the plate to creep progressively into a deflected shape that was not present on delivery. The governing factors are the unsupported span between supports, the plate thickness (flexural stiffness scales with the cube of thickness), the duration of storage, and any asymmetry in the support arrangement.

**Uneven supports** are the more insidious problem. Where supports are nominally present but not co-planar — for example, where one leg of a storage rack has settled into soft ground, or where a plate is rested across an uneven floor with an obstruction under one edge — the plate is forced into a twisted or bowed configuration under its own weight. Because the load is static and continuous, the material gradually creeps from the elastic into the plastic range, and the distortion becomes permanent even if the plate is subsequently placed on even supports.

- **Support at primary structural locations only:** Plates shall be stored with supports positioned at structurally appropriate intervals and at points that align with the expected stiffened regions of the finished panel. Supports placed at arbitrary positions across a wide, flat plate cause local high-spot contact that is mechanically equivalent to a point load on thin plating.
- **Ensure co-planarity of all support points:** All storage supports — racks, timber bearers, cradle frames, or floor-mounted pads — shall be set to a co-planar level within  $\pm 3$  mm before any plate is placed on them. Ground settlement, floor irregularities, and worn rack components all cause support surfaces to diverge from level over time; the storage arrangement shall be re-checked after any ground disturbance or rack modification.
- **Never rest plates directly on uneven ground or floor:** Plates shall not be stored by resting one edge or one corner on the floor while the body is unsupported. This configuration applies the plate's full self-weight as a bending moment at the supported edge and produces severe permanent bow along the plate length. Even short-term storage in this position — less than 24 hours — can produce visible permanent deformation in plates thinner than 10 mm.
- **Horizontal storage is preferred over vertical for flat plates:** Flat plates shall be stored horizontally, face down on a level surface, whenever space permits. Vertical storage of flat plate sheets is permissible only with purpose-built A-frame or inclined rack systems that support the plate

along its full length; leaning a flat plate against a wall or another plate introduces continuous bending stress and is prohibited for plates intended for precision fabrication.

#### 4.1.2 Permanent Sag Under Self-Weight

Self-weight sag is the progressive, time-dependent deflection that occurs when a plate is stored across an unsupported span for an extended period. In its early stages sag is elastic — the plate returns to flat when properly supported. Beyond a critical combination of span, thickness, and duration, self-weight sag crosses into the plastic range and the deflection becomes permanent.

The risk is greatest for thin, wide plates (deckhouse panels, inner bottom plates, thin bulkhead plates) stored flat across wide spacing. A plate under its own weight generates a mid-span bending well within the elastic range for a normal-strength plate, so the plate will recover if properly supported within a reasonable time. However, if the same plate is stored at elevated temperature or is subjected to minor additional loads from adjacent stored material, the effective yield limit is reduced, and permanent deformation begins at lower stress levels.

- **Maximum permissible storage span for each plate thickness:** Production engineering shall establish and document maximum permissible storage spans for each plate thickness used in the build, based on limiting elastic mid-span deflection to no more than one-quarter of the applicable plate fairness tolerance (typically 1.0 mm) under self-weight loading. Plates of exceptional length or width shall be assessed individually.
- **Monitor sag during extended storage:** For plates stored for periods exceeding 30 days, the flatness of the plate shall be checked at monthly intervals using a straight-edge or laser level across the full plate length and width. Any increase in measured sag shall be reported and the storage arrangement corrected before the sag exceeds the elastic recovery limit.
- **Prioritise early use of thin-gauge plates:** Thin-gauge plates shall be scheduled for earliest possible use after delivery. Where storage of thin-gauge plate beyond 30 days is unavoidable, additional intermediate supports shall be introduced to reduce the effective span by at least 50%.

#### 4.2 Temperature Variation

Steel is a thermally responsive material: a 1°C temperature change produces a strain of approximately  $12 \times 10^{-6}$  in structural steel (coefficient of thermal expansion  $\approx 12 \times 10^{-6}/^{\circ}\text{C}$ ). When this expansion is non-uniform — different on the top and bottom faces, or between sun-exposed and shaded sections — the plate is forced to bow, twist, or buckle to accommodate the differential strain. Temperature variation is therefore a genuine and quantifiable distortion mechanism, not merely a background annoyance.

##### 4.2.1 Differential Heating — Sunlight, Nearby Hot Work

**Solar heating** is the most common form of differential heating in open-air and semi-covered shipyards. A large steel plate exposed to direct sunlight on its upper face can reach surface temperatures of 55–70°C on a clear summer day while the lower face, shaded by the ground or adjacent structure, remains at ambient temperature (25–35°C). This temperature differential of 20–40°C through the plate thickness produces a thermal bending moment that bows the plate with the heated (upper) face in compression — exactly the same mechanism as angular distortion in welding but driven by ambient heat rather than the arc.

The resulting deformation is generally temporary: the plate returns to flat when the temperature equalises. However, if the plate is measured, fitted, or tack-welded while in the thermally bowed condition, the elastic thermal strain is locked in as residual stress. When the plate subsequently cools, it does not return to flat because the tack welds prevent free contraction.

**Nearby hot work** — Torch cutting, grinding, flame straightening, preheating operations — creates sharply localised thermal gradients in adjacent plating that cause rapid, sometimes permanent, local

distortion. The most common occurrence is bow or angular distortion in a plate that is welded or cut within 500 mm of an already-completed weld line in a thin, lightly stiffened panel.

- **Shield large, exposed plates during precision operations:** Where precision fit-up, tack welding, or dimensional inspection is planned for plates exposed to direct sunlight, temporary shading (tarpaulins, shade cloth, or staging boards) shall be erected over the plate at least 2 hours before the operation commences and maintained throughout. The 2-hour lead time is necessary to allow the thermal gradient to equalise, not merely for the surface temperature to reduce.
- **Establish a 500 mm exclusion zone around active hot work:** No precision fit-up, marking, cutting, or dimensional inspection of plate shall be conducted within 500 mm of any active torch cutting, grinding, or flame heating operation. Within this zone, the thermal gradient makes all measurements unreliable and any fit-up or tack welding risks locking in thermally induced strain.
- **Measure and record plate surface temperature before precision operations:** Before any marking, cutting, fit-up, or dimensional inspection of plates that have been exposed to direct sunlight or nearby heat sources, the surface temperature shall be measured at not less than four representative points across the plate (corners and centre). If any point differs from the nominal ambient temperature by more than 5°C, the operation shall be deferred until thermal equilibration is achieved.

#### 4.2.2 Thermal Equilibration Requirements Before Precision Operations

A plate moved from a cold store, cold transport, or shaded area into a warm fabrication shop — or from indoors to a hot outdoor yard — carries a transient thermal gradient that can persist for several hours, depending on plate thickness and the temperature differential. During this period, the plate is in a continuously changing dimensional state: it is physically impossible to mark, cut, or fit it accurately to its nominal design dimensions.

This is a frequently overlooked source of systematic dimensional error in hull fabrication. A plate delivered to the CNC cutting table directly from cold storage in winter, without adequate warm-up time, will be cut to dimensions that are correct for the cold plate but will be 1–3 mm undersize when the plate reaches shop temperature — because the thermal expansion from cold to ambient occurs after cutting, not before.

- **Allow a minimum 2-hour thermal soak before precision cutting:** Plates shall be placed in the fabrication shop environment for a minimum of 2 hours — and preferably 4 hours for plates thicker than 20 mm — before CNC cutting commences. This thermal soak period allows the plate to reach thermal equilibrium with the cutting hall environment, ensuring that the nominal cut dimensions correspond to the plate's ambient-temperature dimensions.
- **Allow 4 hours for fit-up and dimensional inspection after temperature change:** Plates or sub-assemblies that have been moved from a significantly different temperature environment (greater than 10°C difference) shall be allowed to equilibrate for a minimum of 4 hours before final fit-up, tack welding, or formal dimensional inspection. This applies equally to plates moved from outdoor storage in cold weather into a heated assembly hall, and to plates moved from air-conditioned storage into a hot summer yard.
- **Conduct dimensional baseline measurements at a defined reference temperature:** All master dimensional measurements — block dimensions, erection joint profiles, and accept/reject dimensional records — shall be taken at a defined reference temperature, nominally 20°C. Where measurement must be conducted outside this temperature range, the measured dimensions shall be corrected by the applicable thermal expansion coefficient ( $12 \times 10^{-6}/^{\circ}\text{C}$  for structural steel) before comparison with nominal design dimensions. The actual plate temperature at the time of measurement shall be recorded on the dimensional inspection certificate.

#### 4.2.3 Seasonal and Day-Night Temperature Cycling in Open Yards

Blocks and sub-assemblies stored in open yards are subjected to continuous thermal cycling: daytime heating and night-time cooling, summer and winter seasonal cycles, and rapid changes associated with rain showers on sun-heated surfaces. Each thermal cycle produces a small increment of plastic deformation in any part of the assembly that is constrained from free expansion — by its own self-weight on supports, by tack welds, or by attached temporary stiffeners.

Over a storage period of several months, this accumulated plastic strain can produce measurable distortion that was not present at the end of fabrication. This is particularly relevant for blocks stored in open yards awaiting erection: a block that passed all dimensional checks on leaving the panel shop may arrive at the drydock out of tolerance, not because of any single event, but because of continuous low-level thermal cycling during outdoor storage.

- **Limit outdoor storage duration for dimensionally critical blocks:** Blocks or sub-assemblies that have been dimensionally accepted for erection shall not be stored outdoors for periods exceeding 60 days before erection, unless re-measured and re-accepted. For blocks containing thin-gauge plate (below 8 mm) or large unsupported spans, the outdoor storage limit shall be reduced to 30 days.
- **Cover blocks during outdoor storage where practicable:** Blocks stored outdoors shall be covered with tarpaulins or shade cloth to reduce direct solar heating differentials. Coverage also reduces rain-induced thermal shock from cold rainwater striking hot sun-heated steel surfaces, which introduces localised high-rate thermal stresses in the plate surface.
- **Re-survey blocks before transport to erection berth:** All blocks shall be dimensionally re-surveyed within 48 hours of transport to the erection berth, regardless of the date of their initial dimensional acceptance. Any deviation from acceptance dimensions discovered at this stage shall be corrected before erection commences, while the block is still accessible on the ground.

#### 4.3 Environmental Degradation

Beyond the immediate distortion mechanisms of inadequate support and thermal cycling, prolonged environmental exposure degrades the surface condition and, in severe cases, the bulk mechanical properties of steel plates and sub-assemblies. This degradation acts as a second-order contributor to distortion: it does not itself cause geometric deformation, but it makes subsequent fabrication operations — welding, cutting, forming — more likely to produce distortion and less likely to achieve the required dimensional accuracy.

##### 4.3.1 Corrosion Effects on Surface Condition and Plate Properties

Structural steel is inherently susceptible to atmospheric corrosion. Mill scale, the thin oxide layer produced during hot rolling, provides limited short-term protection but lifts and spalls within weeks in humid or marine environments, exposing the base steel. Surface rust begins at exposed areas and progresses inward at rates that depend on humidity, temperature, and the presence of chlorides (common in coastal shipyard environments).

Corrosion affects distortion in three distinct ways:

- **Surface pitting creates non-uniform plate thickness:** Localised corrosion pitting reduces plate thickness unevenly across the plate surface. A plate with non-uniform thickness has non-uniform flexural stiffness: the thinner, pitted regions will deflect more under a given load — welding or self-weight — than the un-corroded regions. This produces local distortion patterns that do not correspond to any of the standard welding or mechanical distortion modes and are correspondingly difficult to predict or correct.
- **Corroded surfaces impair welding quality and increase heat input:** Welding on corroded, scaled, or heavily rusted surfaces requires higher heat input to achieve adequate fusion and penetration. The increased heat input directly amplifies all forms of thermal distortion. Corrosion

products also introduce hydrogen into the weld metal and heat-affected zone, increasing the risk of hydrogen-induced cold cracking — particularly in high-strength and TMCP plate grades.

- **Heavy corrosion can compromise plate mechanical properties:** Where corrosion has progressed beyond surface pitting to general thickness loss of more than 10% of the nominal plate thickness, the plate's structural capacity is formally reduced. Such plates shall be assessed against applicable classification society rules before use and re-surveyed with ultrasonic thickness measurement across a representative grid before approval for incorporation into the structure.

**Remove surface contamination before welding and cutting:** All welding and thermal cutting surfaces shall be cleaned of rust, mill scale, moisture, and contamination to bright metal condition in a band not less than 25 mm on each side of the intended weld or cut line, in accordance with the requirements of the applicable Welding Procedure Specification (WPS). This is not merely a workmanship requirement: it is a direct distortion-control measure, since it reduces the additional heat input required to achieve fusion through contaminated surfaces.

#### 4.3.2 Moisture and Its Effect on Welding Quality and Distortion

Moisture is the most pervasive environmental contaminant affecting welding operations in shipyard environments. It is present not only as visible surface water from rain or condensation, but as absorbed moisture in hygroscopic coatings, primer films, and weld flux, and as atmospheric humidity that condenses on cold steel surfaces when temperature drops below the dew point.

- **Never weld on visibly wet surfaces:** Welding shall not commence on any surface showing visible moisture — water droplets, condensation film, or frost. Wet surfaces shall be dried by low-temperature heating (warm air blast or gentle flame heating to approximately 50°C) before welding commences. The presence of moisture on the weld surface is not merely a quality defect: the steam generated in the arc increases hydrogen content in the weld metal, elevates heat input, and produces spatter patterns that contaminate adjacent surfaces and increase the risk of arc-strikes causing local hard spots.
- **Preheat to above the dew point in humid conditions:** When the ambient relative humidity exceeds 80%, or when the steel surface temperature is within 5°C of the ambient dew point, a minimum preheat of 50°C shall be applied to the weld area — in addition to any preheat required by the WPS for the steel grade and thickness — before welding commences. This preheat shall be maintained throughout the welding operation; in outdoor or semi-open conditions, preheating shall be suspended and re-applied if the surface temperature drops below 50°C due to wind or rain.
- **Store and condition low-hydrogen consumables correctly:** All low-hydrogen welding consumables (covered electrodes, flux, and flux-cored wire) shall be stored in heated, humidity-controlled conditions in accordance with the consumable manufacturer's requirements and shall be issued from dry storage immediately before use. Reconditioned electrodes shall only be used in accordance with the applicable WPS and shall not be reconditioned more than once. The use of damp or unconditioned low-hydrogen consumables on high-strength or TMCP plate is strictly prohibited: it eliminates the protective function of the low-hydrogen specification and renders the weld susceptible to cold cracking regardless of all other precautions.
- **Apply temporary weatherproofing to joints awaiting welding:** Structural joints that have been fitted and tacked but are awaiting final welding shall be protected from rain, condensation, and direct sea spray by temporary covers (tape, plastic sheeting, or purpose-made joint protectors) where the delay between fitting and welding exceeds 8 hours, or where the joint will be exposed to overnight weather. This prevents the joint root gap from filling with water, which must then be boiled off at the start of welding — introducing localised steam pressure and additional hydrogen.

#### **4.4 Preventive Measures — Environmental and Storage**

The following preventive measures consolidate the requirements of Sections 4.1 through 4.3 into a set of actionable controls for production supervisors, quality engineers, and storage yard management. They are organised by activity rather than by distortion mechanism.

##### **4.4.1 Plate Storage Requirements — Level Supports, Blocking, Duration Limits**

- **Establish a dedicated plate storage area with level, hard-standing ground:** The plate storage area shall be on hard-standing ground (concrete or compacted gravel) that is surveyed level within  $\pm 10$  mm across the full storage footprint and is drained to prevent standing water. Plates shall not be stored on soft or uneven ground even for short periods; ground settlement under the weight of stored steel displaces support points and introduces progressive distortion.
- **Set storage racks and bearers co-planar to  $\pm 3$  mm:** All storage racks, bearer frames, and ground-level timber support systems shall be set and verified before plates are placed on them. The co-planarity shall be verified with a laser level or precision spirit level, not by visual inspection. A rack that appears level but has one support 5 mm low imposes a twist of 0.05% of the plate diagonal on any plate resting on it — sufficient to exceed IACS Rec. 47 plate fairness limits for plates above approximately 2 m width.
- **Duration limits and re-inspection requirements:** Plain steel plates without primer shall be scheduled for use within 30 days of delivery to prevent significant surface rust formation. Primed or shop-coated plates may be stored for up to 90 days before re-inspection. Plates stored beyond these periods shall be re-measured for flatness and re-inspected for surface condition before release to production. Any plate found to exceed IACS Rec. 47 flatness limits shall be corrected before use.
- **Segregate plates by grade and thickness:** Plates shall be stored segregated by grade and thickness, with clear identification marking at each stack. Mixed-grade stacks create risk of grade substitution at production draw-down — a non-TMCP plate substituted for a TMCP-specified location will behave differently under forming, welding, and thermal straightening, producing unexpected distortion. Each plate shall retain its mill certificate identification through fabrication.

##### **4.4.2 Temperature Controls for Precision Fit-Up and Measurement**

- **Define and observe a reference temperature for all dimensional work:** All dimensional measurements, fit-up operations, and marking out for precision cutting shall be performed at a plate surface temperature within  $\pm 5^{\circ}\text{C}$  of the defined reference temperature (nominally  $20^{\circ}\text{C}$ ). Operations performed outside this range shall record the actual plate temperature and apply the appropriate thermal correction to all measured dimensions before acceptance or rejection decisions are made.
- **Do not conduct formal dimensional acceptance in direct sunlight:** Formal dimensional acceptance measurements of panels, blocks, and erection joint profiles shall not be conducted on surfaces in direct sunlight. Where covered measurement space is not available, measurements shall be deferred to early morning or late afternoon in summer conditions or conducted under temporary shading. Record the shade temperature and plate temperature at the time of each measurement set.
- **Account for temperature in erection-joint pre-survey:** The virtual trial assembly and pre-erection dimensional survey (CAD-to-scan comparison) shall record the ambient and plate temperatures at the time of scanning. Where the erection will be conducted at a significantly different temperature from the survey temperature, the expected thermal differential change in block dimensions shall be calculated and communicated to the erection team before block landing.

##### **4.4.3 Plate Condition Monitoring During Extended Storage**

- **Implement a formal storage register for all hull steel:** A storage register shall be maintained for all hull steel plates and fabricated sub-assemblies, recording for each item: mill certificate reference, plate grade and thickness, date of delivery, storage location, date of any condition

**Best Practices – Distortions of Ship Hull during Construction –  
Causes and Preventive Measures  
August 2026**

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inspection, condition rating, and date of release to production. The register shall be reviewed at monthly intervals and plates approaching their storage duration limit shall be flagged for priority use or re-inspection.

- **Periodical flatness check for stored plates:** A flatness check using a 2 m straight-edge or laser level shall be conducted on all plates that have been in storage for more days. The measured crown height under the straight edge shall be recorded.
- **Protect fabricated sub-assemblies and blocks in storage:** Fabricated sub-assemblies and completed blocks awaiting erection shall be protected from the ingress of rainwater into hollow sections, tank boundaries, and double-bottom void spaces. Accumulated water in enclosed spaces exerts hydrostatic load on plating, creating sustained mechanical loading over the storage period. Drain holes shall be provided at the lowest point of all enclosed spaces before a block enters outdoor storage and blanked off before water pressure testing and on erection.

## Section 5

### Material-Related Distortion

The material from which a hull is built carries its own contribution to distortion risk, independent of the welding and handling operations applied to it. Residual stresses locked into plate at the rolling mill, material defects in the form of thickness variations, laminations, and non-uniform mechanical properties — these characteristics are present before fabrication begins and can cause or amplify distortion at every subsequent production stage if they are not identified, screened, and managed at the procurement and incoming inspection stage. This section addresses the physical mechanisms by which material characteristics drive distortion, the specific defect types most significant in hull fabrication, and the preventive measures that control them from procurement through to final fabrication.

#### 5.1 Residual Stresses from Plate Rolling

All hot-rolled structural steel plate carries residual stresses from the rolling process. These are internal self-equilibrating stress fields that exist in the plate at ambient temperature without any external load applied. They are present on delivery, invisible on visual inspection, and cannot be detected without specialised measurement. Yet they directly influence the plate's behaviour under every subsequent fabrication operation — cutting, forming, welding, and constraint — and are a significant and systematically underestimated contributor to hull distortion in shipyard practice.

##### 5.1.1 Mechanism

Hot rolling reduces a steel slab to a specified plate thickness by passing it through a series of rotating rollers under progressively increasing pressure. The process is inherently non-uniform in two respects that give rise to residual stress:

**Non-uniform cooling through thickness.** The plate surface cools significantly faster than the plate core as it exits the final rolling pass. The cooler, contracting surface attempts to shorten, but the hot and comparatively plastic core resists contraction. When the core finally cools, it attempts to contract in turn, but the now-rigid surface resists it. The result is a characteristic through-thickness residual stress pattern: compressive stress at the plate surface, tensile stress at the core.

**Non-uniform deformation across the plate width.** The central region of the plate is compressed more freely by the rollers than the plate edges, which are laterally unconstrained. Edge elongation is therefore less than central elongation. To maintain geometric compatibility, residual stresses develop across the width: **tensile stress at the plate edges, compressive stress in the centre**. In wide, thin plates this transverse residual stress field can also be significant, typically 40–80 N/mm<sup>2</sup> in each direction for normal-strength grades.

**TMCP plates** — produced by controlled rolling followed by accelerated cooling — have tightly managed thermal gradients during processing and generally exhibit lower residual stress levels than conventionally rolled plate of equivalent nominal thickness. However, any deviation from the intended cooling curve, or substitution of a non-TMCP plate in a TMCP-specified location, can introduce substantially higher residual stresses than the design assumes.

- **Through-thickness gradient leading to angular distortion:** A plate with high surface compressive / core tensile residual stress is effectively pre-loaded in a configuration that mimics the residual stress field produced by single-sided welding. When the plate is heated asymmetrically during welding or cutting, the pre-existing stress field adds directly to the weld-induced field, producing angular distortion that exceeds what the heat input alone would predict. This is a principal reason why measured angular distortion sometimes exceeds analytical predictions based on heat input alone.

- **Transverse edge-tension / centre-compression leading to buckling:** The compressive residual stress in the central width of a rolled plate reduces the effective critical buckling stress of that region. When welding adds further compressive residual stress in the plate-centre panel fields, the combined compressive field reaches the critical buckling threshold at a lower total weld heat input than would be required for a nominally stress-free plate. This explains why large, thin deckhouse panels sometimes buckle at fillet-weld heat inputs that appear to be well within acceptable limits.

#### 5.1.2 Release Triggers — Cutting, Machining, Constraint, Welding

Rolling residual stresses are self-equilibrating across the full plate cross-section. Any operation that removes material, applies new stress, or constrains the plate in a way that prevents free movement will disturb this equilibrium and cause the plate to deform as it seeks a new equilibrium state. The principal triggers encountered in hull fabrication are:

##### ***Thermal cutting — plasma, oxy-fuel, laser***

Cutting removes a strip of material along the cut line, eliminating the stresses carried by that material. The removed material's stress contribution can no longer be balanced by the rest of the plate, so the remaining plate deforms to re-equilibrate. The deformation occurs immediately on cutting and cannot be corrected by re-cutting the same line. Additionally, the heat of the cutting process introduces new thermal residual stresses along the cut edge, which superimpose on and interact with the pre-existing rolling residual stresses. The combined effect is most pronounced in long, narrow strips cut from a wide plate — for example, stiffener flats, longitudinal web plates, or bar stock for frames — where the high ratio of cut-edge length to remaining cross-section amplifies both the rolling stress release and the thermal cutting effect.

##### ***Machining and edge preparation***

Milling, grinding, and edge bevelling for weld joint preparation remove material from one or both plate surfaces or edges. Because the rolling residual stress field is not uniform through the thickness or across the width, removing material at one surface disturbs the through-thickness stress balance in the same way as asymmetric thermal cutting. The plate may bow transversely (curling toward the machined face) or develop longitudinal camber. This effect is particularly significant in heavy plates destined for precision-machined structural seats, machinery foundations, and azimuth thruster seatings, where the tolerance on flatness after machining may be tighter than the deformation produced by stress release during the machining operation itself.

##### ***Mechanical constraint during fit-up and tack welding***

When a plate carrying rolling residual stresses is forced into alignment with a mating component — clamped against a jig, jacked into a curved form, or drawn flat by tack welds — the mechanical constraint acts on the residual stress field as an additional applied load. The plate is now in a state of combined rolling residual stress plus mechanically applied constraint stress. When the constraint is removed (tacks released, clamps opened), the stored elastic energy from both source releases simultaneously. The resulting deformation is the sum of what the rolling stress alone would have produced and what the mechanical forcing alone would have produced — but because the two stress fields interact non-linearly through the material's elastic-plastic constitutive response, the combined release deformation is often larger and differently directed than the simple sum would suggest.

##### ***Welding heat cycle***

The welding arc deposits a highly localised heat pulse that temporarily abolishes rolling residual stresses in the heat-affected zone while simultaneously creating a new, weld-induced residual stress field on cooling. The net residual stress state in the welded plate is therefore the superposition of: (a) the unrelieved rolling residual stresses in the regions of the plate remote from the weld, (b) a modified rolling residual stress field in the partially heated regions at the boundary of the HAZ, and (c) the new

weld-induced residual stress field in the HAZ and weld metal. This complex superposition is the reason why the final residual stress state after welding on a plate with significant rolling residual stresses is systematically more severe — and produces greater distortion — than analytical models that assume a zero-stress starting condition would predict.

#### 5.1.3 Distortion Modes Resulting from Stress Release

Depending on which residual stress component is released, and by which trigger, rolling stress release produces characteristic distortion patterns that can be used diagnostically to identify plate rolling stresses as the cause rather than welding or mechanical handling:

- **Longitudinal bow (camber or reverse camber) on cut strips:** A long, narrow strip cut from the centre of a wide plate releases the central compressive residual stress and acquires a longitudinal bow, curving toward the original plate surface that was in compression. The strip appears flat before cutting and bows immediately on completion of the cut. The magnitude of the bow increases with strip length and decreases with strip width. This is the most observed symptom of significant rolling residual stress in shipyard practice and is frequently misattributed to thermal distortion from the cutting process.
- **Transverse bow in wide plates after edge trimming:** Trimming one or both edges of a wide plate to final dimensions releases the tensile edge stresses, allowing the plate to bow transversely — curving across its width. The direction of the bow (which face is convex) depends on the sign of the through-thickness stress gradient at the trimmed edge and can be either face. Transverse bow in a freshly trimmed plate that was flat before trimming is diagnostic of significant rolling edge-tension residual stress.
- **Twist on asymmetrically cut plates:** Plates cut to trapezoidal or asymmetric plan shapes release rolling residual stresses unevenly along the cut edges, producing torsional deformation — diagonal twist — that is rarely present before cutting. A trapezoidal plate that lies flat on the cutting table but develops visible diagonal lift at one corner on removal from the table is exhibiting rolling residual stress release through torsion.
- **Unexpected angular distortion amplitude after welding:** When measured angular distortion at a fillet weld is consistently and significantly greater than the value predicted by the Satoh-Terasaki relationship for the actual heat input and plate thickness, the discrepancy is a strong indicator that rolling residual stresses in the plate are adding to the weld-induced angular distortion field. This diagnostic should trigger a review of the plate procurement specification and incoming inspection records for the batch.

## 5.2 Material Defects

Beyond the residual stress field that is an inherent feature of the rolling process, structural steel plate can contain localised defects — thickness variations, laminations, inclusions, and regions of non-uniform mechanical properties — that cause distortion by creating local differences in stiffness, strength, or thermal response during fabrication. Unlike rolling residual stresses, which are present in all hot-rolled plate to some degree, material defects are governed by steel quality, mill practice, and the applicable supply standard, and can be controlled through specification and incoming inspection.

### 5.2.1 Thickness Variations and Laminations

**Thickness variations** occur when the rolling process does not reduce the slab uniformly across the plate width or along its length. The principal forms are:

**Wedge:** Systematic taper across the plate width, with one longitudinal edge consistently thicker than the other. Wedge is typically measured as the thickness difference between opposite edges at the same longitudinal position. Even within specification, wedge creates a plate with non-uniform flexural stiffness across its width: the thicker edge has (thickness)<sup>3</sup> greater stiffness than the thinner edge, causing the plate to bow asymmetrically under the same applied load or heat input.

**Local thickness excesses and deficiencies** occur due to surface scale inclusions, roller wear patterns, and material flow variations. They create stiffness anomalies that cause local buckling to occur preferentially at thin spots under welding compressive residual stress, rather than as a smooth pattern across the panel.

**Laminations** are planar separations within the plate parallel to the rolling surface, arising from gas pockets, segregation bands, or non-metallic inclusions in the original slab that are rolled into thin, planar discontinuities by the rolling process. Laminations affect distortion in two ways: they create a plane of reduced shear transfer through the plate thickness (reducing the effective flexural stiffness of the full-thickness section), and they create planes of stress concentration that can propagate as cracks under the repeated thermal cycling of welding, particularly when welding is performed transversely to the lamination plane (as in T-butt joints and one-sided fillet welds to thin plates).

- **Specify lamination testing for components susceptible to through-thickness loading:** Plates intended for T-butt weld connections subjected to through-thickness tensile stress — including transverse butt straps, pad plates, bracket heels, and structural seats — shall be specified to include ultrasonic lamination testing per EN 10160 or equivalent. The minimum acceptance class shall be S1/E1 (lowest allowable inclusion content) for critical structural connections.
- **Reject plates with systematic wedge exceeding supply standard limits:** At incoming inspection, plate width and thickness measurements shall be taken at both longitudinal edges and at mid-width, at not less than three positions along the plate length. Any plate exhibiting edge-to-edge thickness variation exceeding the supply standard limit or exhibiting a systematic wedge pattern (consistently thicker on one edge), shall be rejected or downgraded to non-structural applications.

#### 5.2.2 Inclusions and Non-Uniform Mechanical Properties

**Non-metallic inclusions** — oxide, sulphide, and silicate particles from the steelmaking process — are present in all structural steel but are controlled in quantity and morphology by modern steelmaking practice. When inclusions are present in excess, are poorly distributed, or are in elongated string form (sulphide stringers), they affect fabrication behaviour in three ways:

First, they act as stress concentrators under mechanical and thermal loading. Under the thermal cycle of welding, inclusions at the plate surface or within the HAZ create local plastic strain concentrations that add to the weld residual stress field and increase the local angular distortion relative to an inclusion-free plate. Second, sulphide stringers parallel to the plate surface create preferential planes of weakness across which HAZ hydrogen cracking can propagate, potentially as delamination along the stringer plane rather than as a classical cold crack. Third, large inclusions discovered during machining or surface preparation — appearing as pits, voids, or dark spots — require local repair welding that introduces additional heat input and associated localised distortion.

**Non-uniform mechanical properties** are most encountered as:

**Banded microstructure:** alternating bands of ferrite and pearlite parallel to the rolling direction, present to varying degrees in all hot-rolled carbon-manganese steels. Severely banded plate exhibits different yield strength and hardness in alternate layers, causing non-uniform deformation during cold forming and non-uniform HAZ response during welding. The practical effect is inconsistent spring-back during cold pressing and localised hardness peaks in the HAZ that increase cold cracking susceptibility.

**Segregation at plate centreline:** concentration of carbon, manganese, sulphur, and phosphorus at the original slab centreline, which is the last region to solidify. In plates of medium to heavy thickness, centreline segregation can produce a region with significantly elevated carbon equivalent, lower toughness, and higher susceptibility to hydrogen cracking compared with the plate surface. When welding through-thickness (in T-butt connections or through-deck penetrations), the weld HAZ intersects this centreline segregation zone and is correspondingly at higher cracking risk.

- **Specify sulphur content limits for through-thickness-loaded components:** Plates intended for connections in which significant through-thickness tensile stress will be induced — pad plates, transverse stiffener connections, and one-sided bracket attachments — shall be specified with maximum sulphur content of 0.008% (Z-quality, per EN 10164) to minimise sulphide stringer content and laminar tearing risk. Standard structural steel grades permit up to 0.030% sulphur; the Z-quality limitation reduces through-thickness ductility reduction by approximately 60%.
- **Specify Charpy V-notch toughness at the service temperature:** The procurement specification shall require documented Charpy V-notch toughness testing at the minimum anticipated service temperature for the vessel operating area. Grade D and E plates (and their higher-strength equivalents DH/EH) have tighter toughness requirements than A/B/AH grades; substitution of A-grade for D-grade in exposed structural locations in cold-service vessels is a material specification error with both structural and fabrication distortion implications.
- **Reject plates with surface-breaking inclusions in weld areas:** All surfaces in the planned weld area shall be visually inspected before fit-up. Visible surface inclusions (pits, voids, scale pockets) within 50 mm of an intended weld line shall be assessed by Magnetic Particle Inspection. Inclusions within the planned weld joint preparation shall be ground out, and the resulting depression evaluated against IACS Rec. 47 root gap and groove geometry limits before welding commences.

#### 5.2.3 Identification and Screening at Incoming Inspection

The purpose of incoming inspection is to screen incoming plate for material defects that could cause distortion, cracking, or structural inadequacy during subsequent fabrication, before the material enters the production stream. Defective material identified at incoming inspection costs only its replacement value; the same material incorporated into a fabricated block before the defect is discovered costs the replacement value plus all the fabrication labour applied to it, plus the distortion and rework costs associated with any welding already performed on the defective plate. Incoming inspection is therefore one of the highest-leverage quality investment activities available to the shipyard.

- **Check the mill certificate against the procurement specification for every heat:** The mill certificate (material test report) for each plate shall be reviewed against the procurement specification before the plate is admitted to the yard. The review shall confirm steel grade and specification (including standard reference); heat/cast number matching the plate identification marking; chemical composition (particularly carbon equivalent  $C_{eq}$  and sulphur content); mechanical properties (yield strength, tensile strength, elongation, Charpy impact values at specified temperature); delivery condition (as-rolled, normalised, TMCP); and any supplementary test results required by the specification. Plates without a matching, specification-compliant mill certificate shall not be admitted to the yard.
- **Verify plate identification marking against the mill certificate:** Each plate shall carry legible identification marking (heat/cast number, grade, thickness, and standard) applied by the steel mill. The marking on every plate shall be physically checked against the corresponding mill certificate before the plate is stacked. Un-marked plates, plates with illegible markings, or plates whose markings do not match any mill certificate in the delivery documentation shall be quarantined pending resolution with the steel supplier.
- **Measure thickness at incoming inspection:** A sample of not less than 10% of plates in each delivery, and 100% of plates thinner than 8 mm, shall be thickness-measured by a calibrated ultrasonic thickness gauge at not less than six points (four corners and two mid-edge positions) at incoming inspection. Any plate showing thickness outside the specified tolerance range or showing edge-to-edge variation exceeding the supply standard limit for the applicable tolerance class, shall be rejected or downgraded.
- **Assess flatness at incoming inspection for distortion-sensitive plates:** Plates thinner than 10 mm, plates of exceptional width-to-thickness ratio ( $\text{width} > 80 \times \text{thickness}$ ), and plates specified for precision-machined connections shall be checked for flatness using a 2 m straight-edge at incoming inspection. Any plate showing a crown under the straight-edge greater than 3 mm shall

be assessed for the cause (rolling residual stress, transit damage, or storage distortion) before acceptance. Plates showing permanent bow greater than 5 mm under a 2 m straight edge shall be returned to the supplier or pre-straightened before production use.

- **Perform ultrasonic scanning for laminations on specified components:** Plates for which lamination testing has been specified in the procurement document (Section 5.3.1) shall be scanned by ultrasonic testing per EN 10160 or equivalent at incoming inspection, unless the mill certificate includes a compliant lamination test report issued by the steel manufacturer. Any plate failing the specified lamination acceptance class shall be rejected for the intended application.

### **5.3 Preventive Measures — Material**

Preventive measures for material-related distortion operate at four stages: procurement specification, incoming inspection (covered in Section 5.2.3 above), pre-production preparation, and controlled treatment of known high-risk components before fabrication begins. The earlier in the production sequence that a material-related distortion risk is identified and addressed, the lower the cost of control.

#### **5.3.1 Procurement Specification — Normalised or Stress-Relieved Plate**

The delivery condition of structural steel plate is one of the most important and most frequently overlooked material parameters in shipyard procurement. The same nominal steel grade can be supplied in several delivery conditions that differ significantly in their residual stress content and in the uniformity of their mechanical properties:

**As-rolled (AR):** The plate is rolled to final dimensions and allowed to cool in air without further thermal treatment. Rolling residual stresses are retained at their maximum level. Mechanical properties may be somewhat variable due to uncontrolled cooling rates. As-rolled plate is the most economical delivery condition and is appropriate for most structural applications in hull fabrication where the tolerances on distortion are achievable by standard production practice.

**Normalised (N):** The plate is reheated after rolling to a temperature in the range 880–950°C (above the austenitizing temperature) and then allowed to cool in still air. Normalising eliminates rolling residual stresses and produces a uniform, fine-grained microstructure with consistent mechanical properties throughout the plate thickness. Normalised plate is significantly less likely to distort during cutting, forming, and welding than as-rolled plate of the same grade and thickness.

**TMCP (Thermo-Mechanical Control Process):** The rolling schedule and cooling rate are precisely controlled to produce high yield strength with low carbon equivalent, good toughness, and relatively low residual stress, without post-rolling heat treatment. TMCP plate generally has lower rolling residual stresses than conventionally rolled plate of the same thickness and higher strength. However, TMCP plates are metallurgically sensitive to reheating and have strict temperature limits for forming, repair welding, and thermal straightening that must be observed throughout fabrication.

**Stress-relieved (SR):** The plate is subjected to a full Post-Weld Heat Treatment (PWHT) cycle before delivery. This is the most effective treatment for residual stress removal and is appropriate for precision-machined components, heavily restrained joints, and applications where subsequent machining operations would release significant residual stress if the plate were not pre-treated

**Specify normalised delivery condition for thin-gauge and precision-critical components:** The procurement specification shall require normalised (N) delivery for plates thinner than 8 mm destined for deckhouse structures, precision bulkheads, and panels with tight flatness requirements after welding; for plates requiring extensive edge machining or CNC profiling to complex curves; and for plates specified for structural seats, bearing pads, and other precision-machined connection interfaces. The normalised specification shall reference the applicable delivery condition letter per the relevant standard

- **Require TMCP traceability and prohibit grade substitution:** Where TMCP plate is specified, the procurement order shall explicitly state the TMCP requirement with reference to the applicable standard, and shall state that as-rolled, normalised, or conventionally quenched-and-tempered plate of nominally equivalent yield strength is not an acceptable substitute. Mill certificates for TMCP plates shall identify the TMCP delivery condition explicitly. Any plate delivered without this identification shall be treated as non-TMCP for the purposes of heat treatment limits throughout fabrication.
- **Specify stress-relieved delivery for precision-machined structural components:** Components that will be subject to extensive material removal by machining after plate delivery — including rudder stocks, shaft brackets, propeller boss plates, thruster seatings, and engine bed plates — shall be specified with stress-relieved delivery condition where distortion during machining is a quality risk. The specification shall state the soak temperature and minimum soak duration required and shall require certification of compliance on the mill certificate.

#### 5.3.2 Incoming Inspection and Mill Certificate Review

Full requirements for incoming inspection are set out in Section 5.2.3. The following additional requirements apply specifically to managing material-related distortion risk through the procurement and inspection interface:

- **Establish a material approval list for each vessel build:** Before production commences, a Material Approval List (MAL) shall be prepared specifying: the approved steel standards and grades for each structural zone; the required delivery condition (AR, N, TMCP, SR); any supplementary testing requirements (Charpy temperature, lamination class, sulphur limit); and the thickness tolerance class. The MAL shall be agreed with the Classification Society Surveyor and used as the primary reference document for all procurement and incoming inspection decisions.
- **Implement a formal first-article material review for new steel sources:** When a new steel mill or steel stockist is used for the first time on a build, a first-article material review shall be conducted before full production quantities are admitted to the yard. The review shall include independent chemical analysis verification; mechanical property testing from randomly selected plates; and a trial cutting and welding programme on a representative thin-gauge plate to assess actual distortion behaviour under production conditions. Results shall be documented and used to calibrate shrinkage allowances and forming parameters for that specific material source.
- **Quarantine and segregate rejected plates:** Plates rejected at incoming inspection shall be physically quarantined in a designated area, marked with a distinctive rejection indicator, and removed from the production yard or storage area. Rejected plates shall not be permitted to re-enter the production queue without specific engineering review and either supplier replacement or a formal concession documenting the basis for acceptance at a reduced specification.

#### 5.3.3 Pre-Straightening Before Precision Cutting

A plate that exhibits visible bow, camber, or twist on delivery — whether from rolling residual stress release during handling, from inadequate storage support, or from residual stress release on edge trimming at the mill — cannot be reliably cut to precision dimensions while in that condition. Attempting to cut a bowed or twisted plate on a CNC cutting table results in components whose plan dimensions are correct, but whose cut surfaces are not perpendicular to the true plate plane, generating systematic root gap errors and bevel angle errors at subsequent fit-up.

- **Cold pressing for plates with bow or camber:** Plates exhibiting flatness deviations greater than 3 mm under a 2 m straight-edge shall be cold-pressed to flat on a plate straightening machine before placement on the cutting table. Cold pressing shall be performed in progressive passes with displacement controlled to remain within the elastic range of the plate material at each pass, with the final flat condition verified by straight-edge before the plate is released to cutting. The cold pressing operation and result shall be recorded in the material processing record for the plate.

- **Thermal stress relieving for plates with high rolling residual stress:** Where cold pressing corrects the visible flatness but the plate repeatedly returns to a bowed or twisted condition after pressing (indicating high rolling residual stress rather than plastic deformation), controlled thermal stress relief, and slow furnace cooling — shall be applied before precision cutting. Thermal stress relief at this temperature does not materially alter the mechanical properties of as-rolled normal-strength plate; for TMCP grades, the TMCP grade-specific maximum temperature limit shall be observed and steelmaker approval sought if this limit is below 550°C.
- **Do not attempt to cut plates with twist greater than 5 mm diagonal:** Plates exhibiting diagonal twist (one corner lifted relative to the plane of the other three) greater than 5 mm at incoming inspection shall not be placed directly onto the cutting table. The twist means that at least two corners of the plate are not in contact with the table surface, and the plate will deflect under the cut-piece self-weight as the cut progresses, producing cut edges that are not planar. Such plates shall be pre-straightened by cold pressing or thermal stress relief before cutting commences.

#### 5.3.4 Controlled Thermal Stress Relief for Critical Components

For components where residual stress in the base material poses a definitive risk to dimensional accuracy during subsequent machining or welding operations, and where normalised delivery alone is insufficient, controlled thermal stress relief applied after initial fabrication but before final machining is the most effective preventive measure. This is a process-stage intervention, distinct from the delivery-condition specification in Section 5.3.1 and is applied as a defined production step in the fabrication plan.

- **Identify components requiring post-fabrication stress relief in the production plan:** The production engineering plan shall identify, for each vessel build, the specific fabricated components that will receive controlled thermal stress relief before final machining. The criteria for inclusion are: components requiring flatness tolerance below 1.0 mm after machining; components where extensive material removal is planned; components where the welding sequence produces a heavily restrained, high-residual-stress assembly before machining; and components where previous build experience has demonstrated unacceptable distortion during machining of un-stress-relieved fabrications.
- **Execute stress relief in accordance with a documented heat treatment procedure:** Thermal stress relief shall be executed in accordance with a written heat treatment procedure approved by the Classification Society. The procedure shall specify furnace loading configuration and maximum component temperature differential during heating; target soak; heating and cooling rates; minimum soak duration; and the temperature monitoring instrumentation and calibration requirements.
- **TMCP grade temperature limits must govern:** For components fabricated from TMCP plate, the maximum stress relief temperature shall not exceed the steelmaker's specified limit for the grade. The steelmaker's technical advisory shall be obtained in writing before any thermal stress relief is applied to a TMCP plate component, and the agreed temperature limit shall be incorporated into the heat treatment procedure and made available to the Classification Society Surveyor.
- **Verify effectiveness by measurement before release to machining:** Following thermal stress relief and cooling, the component shall be dimensionally re-measured and its flatness and straightness verified against the pre-machining dimensional tolerance before it is released to the machining operation. A component that remains outside the pre-machining flatness tolerance after stress relief shall be assessed by the production engineer before machining commences, since machining a component that is still significantly distorted will produce a finished surface that is geometrically correct at the time of measurement but will deform when the residual stress in the un-machined portion continues to release during subsequent heating or constraint in assembly.
- **Conduct mandatory NDE after stress relief on high-strength and TMCP components:** All TMCP and high-strength plate components that have undergone thermal stress relief shall be subject to a post-treatment NDE inspection consisting of visual examination and Magnetic Particle Inspection (MPI) of all weld areas, conducted after the component has cooled to ambient

temperature. Thermal stress relief can make pre-existing sub-threshold weld defects visible by redistributing the residual stress field around them and can also initiate stress-corrosion cracking in regions where external contamination (chlorides, sulphates) was present on the surface during heating.

## **Section 6**

### **Workmanship, Equipment Condition, and Process Automation**

Sections 3 to 5 addressed the physical mechanisms by which distortion is generated — thermal contraction at the weld, mechanical loading during handling and assembly, environmental and storage effects, and the residual stress carried in the material itself. Each of those mechanisms is modulated by three production variables that cut across all of them: the competence and discipline of the personnel performing the work, the condition and calibration of the equipment they use, and the degree to which the operation is mechanised rather than performed by hand. These three variables do not introduce distortion modes of their own. What they determine is the magnitude of the distortion produced by every mechanism already described, and — more significantly for production control — its repeatability.

The distinction between magnitude and repeatability is central to this section. A correctly specified welding procedure executed with an uncalibrated power source by an inadequately trained welder produces distortion more than the design prediction, and the excess is not consistent from joint to joint or from block to block. Systematic distortion of known magnitude can be compensated at the design stage by pre-setting, added shrinkage allowance, or planned fairing. Scattered distortion of unpredictable magnitude cannot be compensated by any of these means and must instead be absorbed by rework at the accuracy control gates. Controlling workmanship, equipment condition, and automation is therefore not a general quality aspiration but a specific and necessary precondition for the distortion control measures set out in Sections 3 to 5 to be effective in practice.

#### **6.1 Workmanship and Operator Competence**

Welding distortion is deterministic in its physics. For a given joint geometry, plate thickness, restraint condition, and heat input, the resulting angular and longitudinal distortion is predictable within reasonable bounds. What varies in manual fabrication is not the physical relationship but the inputs to it — and those inputs are set, moment by moment, by the person holding the torch, the fitter setting the gap, and the rigger positioning the block. Operator competence is therefore best understood not as a general standard of care but as the mechanism that controls the variance of the input parameters to an otherwise predictable process.

##### **6.1.1 Mechanism — Operator Variability as Dimensional Scatter**

Arc energy per unit length of weld is the product of welding current and arc voltage divided by travel speed. A change in any one of these parameters changes the total energy deposited into the joint, and with it the volume of material driven through the thermal expansion and contraction cycle that generates shrinkage force. In mechanised welding all three parameters are held by the equipment; in manual welding all three are set by the operator in real time and are subject to variation from technique, fatigue, welding position, access restriction, and visibility.

- **Mean distortion can be compensated; scatter cannot:** Where distortion is systematic and repeatable, it can be neutralised at source by pre-setting the joint, by applying a documented shrinkage allowance at the cutting stage, or by planned counter-welding. All of these techniques require the distortion to be predictable in both magnitude and direction. Operator-induced variance destroys that predictability and, in doing so, disables the entire preventive toolkit described in Section 3.
- **Scatter accumulates across the block:** A single fillet run welded outside its intended parameter band produces a local deviation that may be within tolerance in isolation. A panel containing many such runs, each deviating randomly, accumulates a dimensional error at the panel boundary that is frequently outside tolerance and cannot be traced to any single defective weld.

- **Competence is joint-specific, not general:** A welder fully competent in downhand fillet welding may produce substantially greater heat input variation in vertical-up or overhead position on the same joint detail. Qualification and competence assessment shall therefore be specific to the position, process, and joint configuration encountered in production, not established once in the most favourable position.

#### 6.1.2 Excessive and Inconsistent Heat Input

Excessive heat input is identified in Section 3.2 as the most frequently cited root cause of weld induced distortion. In manual welding, the specific operator behaviours that produce it are well established and are readily observable during production supervision.

**Slow travel speed.** The most common cause of excessive heat input in manual welding is travel speed below the value validated by the welding procedure. It arises from an operator concentrating on bead appearance or on ensuring fusion at the root, and it is frequently self-reinforcing: a slow-travelled bead is wide and convex, which the operator may interpret as evidence of good deposition rather than excess energy.

**Weaving beyond the qualified amplitude.** Weave width directly controls the width of the heated zone either side of the joint centreline. Weaving beyond the amplitude qualified in the Welding Procedure Specification widens the region undergoing thermal expansion and contraction and increases both angular distortion and the transverse shrinkage of the joint, without any corresponding gain in strength.

**Habitual fillet oversizing.** Depositing a fillet larger than the specified leg length is a practice, since an oversized fillet passes every conventional visual and dimensional weld inspection. Shrinkage force at a fillet joint increase approximately with the square of the leg length.

**Verify travel speed during production, not only at qualification:** Welding supervisors shall periodically time actual production runs against the length welded and compare the resulting travel speed with the WPS range. This check requires no instrumentation and is the single most effective in-process control on manual heat input.

- **Measure deposited fillet size at the panel:** Fillet leg length shall be checked with a weld gauge on a documented sampling basis across production panels, with results recorded against the welder identification. Persistent oversizing by an individual welder is a training issue that will not correct itself, because the practice produces no visible defect.
- **Enforce interpass temperature limits:** The maximum interpass temperature stated in the WPS controls the accumulation of heat in multi-pass joints. Where interpass temperature is exceeded, each successive pass is deposited into a body of material that is already thermally expanded, and the total contraction on final cooling is correspondingly greater. Interpass temperature shall be verified by contact thermometer or temperature-indicating crayon before each pass on thickness-critical and distortion-critical joints.

#### 6.1.3 Departure from the Planned Welding Sequence

The balanced welding sequences described in Section 3.6 — centre-outward progression, alternation between opposite faces, backstep segmentation, and skip deposition — are effective only if they are followed as documented. Sequence deviation is one of the most consequential workmanship failures because it is silent: the completed weld is sound, passes all non-destructive examination, and gives no indication that it was deposited in the wrong order. The distortion appears later, at the dimensional gate, by which time the sequence in which the joints were welded is no longer recoverable.

The dominant driver of sequence deviation is access. A weld plan written at the production engineering desk assumes an ideal working sequence; the welder on the panel line encounters staging, temporary bracing, adjacent trades, and services that make the specified next joint physically awkward and an

unspecified joint immediately convenient. Absent a supervised sequence discipline, the convenient joint is welded first.

- **Issue the sequence as a marked drawing, not as a text instruction:** The weld sequence shall be issued to the shop floor as a drawing on which each joint or joint segment is numbered in welding order. A sequence expressed only as narrative text in a procedure is not usable at the panel and is not followed in practice.
- **Require sign-off at defined sequence stages:** For distortion-critical assemblies, welding shall be released in stages, with each stage signed off by the supervisor before the next is authorised. This converts sequence compliance from an unverifiable individual behaviour into a documented production hold point.
- **Prohibit completion of one side of a double-sided joint:** Where a joint is to be welded from both sides, no more than the number of consecutive passes stated in the WPS shall be deposited on one face before alternating. Completing one face entirely before turning the assembly produces the maximum achievable angular distortion for that joint and is not recoverable by subsequent welding on the second face.
- **Prohibit unidirectional continuous welding of long fillets:** Continuous fillet runs exceeding approximately 1000 mm shall be deposited in backstep or skip sequence as specified in the weld plan.

#### 6.1.4 Tack Welding, Fit-Up, and Restraint Practice

Tack welds and fit-up quality are the responsibility of the fitter rather than the welder and are frequently subject to less procedural control than the production welding that follows. This is a significant control gap, because the geometry established by the fitter is the geometry that the welding sequence must then hold.

- **Specify tack size, spacing, and quality as a procedure:** Tack welds shall be deposited to a documented specification covering minimum length, throat size, and maximum spacing appropriate to the plate thickness and joint type. Undersized or excessively spaced tacks permit progressive joint opening and closing during welding, allowing angular rotation of the joint that the sequence was designed to prevent.
- **Tack welds shall be sound and shall be inspected:** Cracked or partially fused tacks provide no restraint and additionally act as defect initiation sites that are subsequently welded over. Tacks shall be visually inspected before production welding commences, and cracked tacks removed and replaced rather than welded over.
- **Tacking shall not be used to close an out-of-tolerance gap:** Where the root gap exceeds the range permitted by the WPS, the fit-up shall be corrected by re-cutting, re-positioning, or approved buttering — not by forcing the joint closed with heavy tacks. Forcing a joint closed by tacking locks a mechanical pre-load into the assembly which is released as distortion when the tacks are consumed by the production weld.
- **Restraint removal timing shall be specified:** Strong-backs, clamps, and fixtures shall not be removed until the assembly has cooled to a defined temperature stated in the production procedure. Premature restraint removal, commonly driven by pressure to release fixtures for the next assembly, permits the residual thermal contraction still occurring in the joint to express itself as free distortion.

#### 6.1.5 Repair and Rework Cycles as a Cumulative Heat Source

Every weld repair is a complete additional thermal cycle applied to a joint that has already undergone its full shrinkage. Excavation by arc-air gouging or grinding removes the deposited metal but does not remove the residual stress field established in the surrounding parent material; the subsequent re-weld then superimposes a second contraction cycle on that pre-stressed condition. Arc-air gouging in

particular is a high heat input operation in its own right, frequently exceeding the heat input of the original weld it is removing.

The distortion consequence of repair is therefore not equal to the distortion of the original weld but is additive to it, and it is applied at a single location rather than distributed across the structure as the original balanced sequence intended. A joint repaired twice has been subjected to three unbalanced contraction cycles at one point on the assembly. This is a principal reason why localised out-of-flatness and local angular kinks are so frequently found to coincide with repair locations when accuracy control data is reviewed against the repair register.

- **Maintain a repair register keyed to location:** All weld repairs shall be recorded against the specific joint and station, not merely against the block. Without location-keyed records, the correlation between repeat repair and local distortion cannot be identified and the underlying cause is not addressed.
- **Limit repeat repairs at a single location:** No location shall be subjected to more than two repair cycles without written engineering assessment. Where a third repair is contemplated, the assessment shall address the accumulated distortion and residual stress condition of the surrounding structure, not solely the acceptability of the weld itself.
- **Investigate the cause before authorising repeat repair:** A joint requiring repeated repair indicates a defect in fit-up, access, procedure selection, consumable condition, or welder capability. Repeating the repair without correcting the cause guarantees a further repair cycle and further distortion. The production cause shall be identified and corrected before the repair is authorised.
- **Re-measure the assembly after repair:** Dimensional measurements taken before a repair campaign are invalid afterwards. Any assembly subjected to significant repair welding shall be re-measured against its dimensional gate before release to the next production stage.
- **Apply balanced technique to the repair itself:** Repair welds shall be deposited using the same backstep, skip, and balancing principles required of production welds, and shall be included in the weld sequence documentation. Repair welding is routinely performed as an unplanned, unidirectional, continuous operation, which maximises its distortion contribution.

## **6.2 Equipment Condition and Calibration**

Fabrication equipment determines whether the parameters specified in a procedure are actually delivered at the workpiece. A welding procedure qualified at a defined current and voltage is only meaningful if the power source delivers those values; a cutting programme is only accurate if the machine tracks the programmed path. Equipment degradation is progressive and largely invisible: the machine continues to operate, produces output that appears normal, and delivers parameters that have drifted steadily away from the values assumed by the procedure. Section 3.9 addresses the condition of cutting, forming, jigging, and measurement equipment as it affects component accuracy and fit-up. This section addresses the equipment that directly controls heat input.

### **6.2.1 Welding Power Sources and Wire Feed Systems**

Welding power source output drifts with age, with contamination of internal components, and with damage to output cables and connections. The consequence is that the current and voltage indicated at the machine no longer correspond to the current and voltage delivered at the arc. Because the welder sets the machine to the WPS values and has no independent means of verifying them, an uncalibrated power source produces systematic, undetected departure from the qualified procedure across every weld made with that machine.

**Return circuit resistance.** A frequently overlooked contributor is the welding return path. Corroded return clamps, undersized or damaged return cables, and returns connected through incidental structure rather than directly to the workpiece all add resistance to the welding circuit. The result is a voltage drop between the machine terminals and the arc, so that the arc voltage — and therefore the

actual heat input — differs from the set value. Return path faults also produce arc instability, which the welder compensates for by slowing travel speed, compounding the heat input error.

**Wire feed consistency.** In GMAW and FCAW, deposition rate is governed by wire feed speed. Worn drive rolls, incorrect roll pressure, a contaminated or kinked liner, and a worn contact tip all cause intermittent wire feed slip. The resulting variation in deposition produces uneven bead size along the joint, which translates directly into uneven shrinkage force and local angular variation along a weld that appears, on visual inspection, to be continuous and acceptable.

- **Calibrate power source output against certified instruments:** Welding power sources shall have their output current and voltage verified against calibrated reference instruments on a documented schedule, and after any repair to the machine. Verification shall be recorded and the machine tagged with its calibration status and due date. Machines outside their calibration interval shall be withdrawn from use on procedure-controlled welding.
- **Verify parameters at the arc, not at the dial:** For distortion-critical joints, actual welding parameters shall be verified using an in-line welding parameter monitor or clamp meter at the workpiece during production, rather than relying on the machine's own indication. The difference between set and delivered parameters is the quantity of interest, and it cannot be established from the machine display alone.
- **Inspect and maintain the return circuit:** Return cables, clamps, and connection points shall be inspected on the same schedule as the power source. Return connections shall be made directly to the workpiece or to a dedicated return bar, and shall not be routed through jigs, staging, temporary structure, or dock structure.
- **Establish consumable replacement schedules:** Contact tips, liners, drive rolls, and gas diffusers shall be replaced on a usage-based schedule rather than on failure. Waiting for visible feed failure means accepting a period of progressively degrading deposition consistency before the fault becomes apparent.
- **Control shielding gas supply and flow:** Shielding gas flow rate and mixture shall be verified at the torch on a documented schedule. Inadequate or contaminated shielding produces porosity and poor bead profile, which drives the repair cycles addressed in Section 6.1.5.

#### 6.2.2 Thermal Cutting Equipment and Consumables

Thermal cutting introduces both dimensional error and a thermally distorted cut edge. Both effects are strongly dependent on the condition of the cutting consumables and the mechanical accuracy of the cutting machine. Because cutting is the first operation in the fabrication chain, its errors are inherited by every subsequent stage and are ultimately absorbed by forced fit-up and additional weld metal at assembly.

**Consumable condition and kerf geometry.** A worn plasma nozzle or electrode produces a constricted, unstable arc with a widened and tapered kerf. The immediate consequence is dimensional: the cut part is undersized or out of square, and the resulting fit-up gap must be bridged by additional weld metal with the shrinkage consequences described in Section 3.7. The secondary consequence is thermal: the widened heat-affected zone at the cut edge carries a higher residual stress field, and the strip of parent material adjacent to the cut contracts more on cooling, producing edge camber in narrow cut components such as face plates, brackets, and stiffener webs.

**Bevel cutting accuracy.** Bevel heads used for weld preparation depend on accurate angular positioning and on consistent standoff. Angular drift in a bevel head produces a groove angle differing from that assumed by the WPS, which changes the deposited weld volume required to fill the joint and therefore the shrinkage delivered. A groove angle two degrees wider than specified across a long butt joint represents a measurable increase in transverse shrinkage over the length of the seam.

- **Track consumable life and replace on schedule:** Plasma electrodes and nozzles, and oxy-fuel cutting tips, shall be replaced according to documented pierce-count or arc-hours criteria rather

than on deterioration of cut appearance. By the time cut quality is visibly degraded, dimensional accuracy has already been compromised across an unknown quantity of cut parts.

- **Sample cut quality dimensionally at defined intervals:** Cut edge squareness, kerf width, and part dimensions shall be measured on a sampling basis at the start of each shift and after each consumable change. Verification by visual inspection of cut appearance alone is not sufficient to detect the onset of dimensional drift.
- **Calibrate torch height control:** Automatic torch height controllers shall be calibrated on a documented schedule. Standoff drift alters kerf geometry and bevel angle progressively and is not detectable by the operator during cutting.
- **Verify gantry and rail alignment:** Cutting table rails, gantry squareness, and drive backlash shall be checked on a documented schedule. A gantry out of square produces parts that are dimensionally correct in each axis but not orthogonal, which manifests at assembly as a fit-up problem of unclear origin and is commonly resolved by forcing.
- **Programme and verify cutting compensation values:** Kerf compensation and shrinkage allowance values held in the cutting programme shall be reviewed against measured production data at defined intervals. Allowance values inherited from a previous vessel, plate supplier, or cutting process are a common and untraced source of systematic dimensional error.

#### 6.2.3 Forming, Restraint, Straightening, and Measurement Equipment

The condition of bending rolls, press brakes, jigs, fixtures, hydraulic clamps, and measurement tools, and its effect on component accuracy and forced fit-up, is addressed in Section 3.9. Two categories of equipment specific to distortion control merit additional attention.

- **Control the equipment used for thermal straightening:** Oxy-fuel torches, induction heating units, and temperature measurement instruments used for flame and induction straightening shall be maintained and calibrated as process equipment, not treated as general workshop tooling. Thermal straightening is a controlled heat treatment operation with defined maximum temperature limits, particularly on higher-strength and TMCP grades as set out in Section 5.3.4. An uncalibrated temperature-indicating instrument permits those limits to be exceeded without detection, damaging material properties while correcting geometry.
- **Re-certify jig and fixture reference surfaces:** The reference surfaces of fabrication jigs, panel line beds, and fit-up frames shall be surveyed for flatness and level on a documented schedule, and after any structural modification or relocation. A jig bed that has itself deflected produces consistently distorted output across every unit built on it — a systematic error which, precisely because it is consistent, is frequently attributed to the welding process rather than to the fixture.

### 6.3 Process Automation and Mechanization

Automation reduces distortion. The reason is not that an automated arc is inherently cooler or that automated deposition is metallurgically superior, but that automation removes the variance in the parameters that drive distortion. A mechanised carriage holds travel speed constant along the entire run; a robotic system executes the programmed sequence in the programmed order regardless of access convenience; a panel line deposits the same fillet size on the fiftieth stiffener as on the first. The distortion that results is not zero, but it is consistent — and consistent distortion is amenable to the compensation techniques described in Section 3.5 in a way that scattered distortion is not.

#### 6.3.1 Variance Reduction as the Mechanism of Benefit

The comparison set out in Table 6.1 is between characteristics of the process, not between the quality of the resulting welds. A skilled manual welder produces welds of excellent metallurgical quality; the point at issue is the reproducibility of the thermal input that accompanies them. It is worth noting that the productivity advantage of mechanisation carries a distortion benefit in its own right: higher travel speeds deposit a given weld size with less total energy transmitted into the surrounding plate, which is the effect quantified in the heat input comparison in Section 3.5.

**Table 6.1 Process characteristics affecting distortion — automated and manual welding compared**

| <b>Characteristic</b>       | <b>Automated / mechanised process</b>                                                       | <b>Manual process</b>                                                                       |
|-----------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| Heat input consistency      | Held to the WPS nominal by the drive and control system for the full length of the run.     | Varies with operator technique, fatigue, access, and welding position.                      |
| Travel speed                | Constant, set by the carriage or manipulator drive.                                         | Operator-dependent; varies along the run and between nominally identical runs.              |
| Weld bead and fillet size   | Uniform along the joint; deposited to the programmed size.                                  | Variable; habitual oversizing is common and passes visual inspection.                       |
| Welding sequence            | Pre-programmed and executed in the programmed order.                                        | Depends on operator adherence to the weld plan; access convenience drives deviation.        |
| Repeatability between units | High — the same distortion is produced on each unit.                                        | Low — distortion differs between nominally identical units.                                 |
| Distortion magnitude        | Lower, and predictable in magnitude and direction.                                          | Higher, and scattered in both magnitude and direction.                                      |
| Amenability to compensation | High — systematic distortion can be neutralised by pre-setting and shrinkage allowance.     | Low — scattered distortion cannot be reliably pre-set and must be faired individually.      |
| Exposure to human error     | Confined to programming, setup, and maintenance — but errors are systematic across the run. | Present at every weld — but errors are random and partially self-cancelling.                |
| Deposition rate             | High; the associated higher travel speed reduces total energy input to the plate.           | Lower; longer arc time transmits more heat into the surrounding structure.                  |
| Applicability               | Restricted to accessible, regular, repetitive geometry.                                     | Unrestricted — required at erection joints, closing seams, confined spaces, and all repair. |

#### 6.3.2 Automated and Mechanised Processes in Hull Fabrication

Mechanisation in hull construction is not a binary choice between fully robotic and fully manual operation. A graded range of options exists, and the intermediate levels deliver a substantial proportion of the variance reduction benefit at a fraction of the capital cost of full robotic installation.

- **One-side welding panel lines:** Flux-copper-backing and refractory-backing one-side welding systems join panel butt seams in a single pass from one side. Because the joint is completed in one thermal cycle with a symmetric backing arrangement, angular distortion is substantially lower than for a comparable manually welded double-sided joint, and it is highly repeatable across the panel.

- **Gantry and portal robotic fillet welding:** Robotic gantry systems welding stiffener-to-plate fillets on the panel line hold fillet leg size, travel speed, and welding sequence to programmed values across the entire panel. This eliminates the habitual fillet oversizing described in Section 6.1.2 and the sequence deviation described in Section 6.1.3 simultaneously, and these two effects together account for a large proportion of achievable panel distortion reduction.
- **Submerged arc welding for long seams:** SAW delivers high deposition rate and constant parameters on long butt seams and is the standard process for panel butts in heavy plate. Its high heat input requires careful application: as stated in Section 3.5, SAW carries significant distortion risk on thin plating and shall be selected against plate thickness rather than applied by default across all seams.
- **Tractor and carriage-mounted fillet welding:** Self-propelled welding carriages running on the workpiece or on a track provide constant travel speed and constant torch attitude at low capital cost and can be deployed at assembly stages where a fixed gantry cannot reach. This is the most accessible route to travel speed control for yards without panel line automation, and it addresses the single largest source of manual heat input variance.
- **CNC thermal and profile cutting:** CNC plasma, oxy-fuel, and laser cutting deliver repeatable part geometry with programmable kerf and shrinkage compensation, provided the machine is maintained and calibrated in accordance with Section 6.2.2. Cutting accuracy governs fit-up gap, and fit-up gap governs the weld volume that must be deposited at assembly.
- **Mechanised and robotic line heating for plate forming:** Automated line heating systems for curved shell plate formation control heating path, torch speed, and cooling application to programmed values, replacing an operation that is otherwise among the most experience-dependent in the shipyard. Repeatability of formed plate geometry reduces the fit-up correction required at the curved shell assembly stage.

#### 6.3.3 Manual Processes

Manual welding remains necessary throughout hull construction and cannot be eliminated. Erection joints between blocks, closing seams, welding in confined compartments and double bottoms, overhead and vertical positions, complex intersecting connections, and all repair welding are performed manually and will continue to be. The objective is therefore not to eliminate manual welding but to recognise it as the higher-variance process and to apply compensating controls proportionate to that variance.

- **Weight supervision toward manual operations:** Supervisory attention, in-process parameter verification, and dimensional checking shall be concentrated on manually welded joints, particularly at erection where restraint is highest and correction is most difficult and costly. Automated operations require verification at setup and at defined intervals; manual operations require continuous supervision.
- **Apply the strictest sequence discipline where restraint is highest:** Erection joints are welded into a structure that is already assembled and therefore highly restrained. Sequence deviation at this stage produces reaction stresses that cannot be relieved by free movement of the components and drives both distortion and, in restrained heavy sections, cracking risk. Erection weld sequence shall be issued as a marked drawing with mandatory sign-off at each stage.
- **Restrict extended manual welding in adverse positions:** Welding in overhead position, in confined spaces, and in poor ventilation produces the greatest heat input variance because operator control is most compromised. Working periods in these conditions shall be limited, and joints in these positions shall be prioritised for mechanisation where any mechanised option exists.
- **Match welder qualification to the actual joint condition:** Welders assigned to distortion-critical manual joints shall hold qualification in the specific process, position, and joint configuration of that joint, and shall have demonstrated parameter consistency, not solely weld soundness, during qualification.

#### 6.3.4 Automation

Mechanisation transfers the point at which human decisions influence distortion; it does not eliminate it. In manual welding, operator error is distributed and random — each weld is slightly different, and errors partially average out across a large assembly. In automated welding, human error is concentrated in programming, setup, and maintenance, and it is systematic: a programming error in fillet size, travel speed, or sequence is reproduced identically on every joint the machine welds, on every panel, until it is detected. The distortion produced is uniform, substantial, and present across the entire production run.

- **Require first-article dimensional verification for every new programme:** The first unit produced by any new or modified welding or cutting programme shall be subject to full dimensional verification against its accuracy control gate before further units are released. This is the sole control that catches systematic programming error before it propagates through a production batch.
- **Qualify and control programme changes:** Welding and cutting programmes shall be held under revision control, with changes authorised by production engineering and recorded. Undocumented parameter adjustment made at the machine by an operator to address a local problem is a common source of systematic distortion that is exceptionally difficult to trace after the fact.
- **Qualify programmers and maintenance technicians:** The competence requirement in a mechanised shipyard shifts to the personnel who programme, set up, and maintain the equipment. These roles shall carry documented qualification and training requirements equivalent in rigour to those applied to welders.
- **Do not operate automated equipment outside calibration:** An automated system executing a correct programme with an uncalibrated power source or a drifted torch height controller delivers incorrect parameters with perfect consistency. The consistency of automation amplifies the consequence of calibration failure rather than mitigating it, and automated equipment outside its calibration interval shall be withdrawn from production.

### 6.5 Preventive Measures — Workmanship, Equipment Condition, and Automation

The following preventive measures consolidate the requirements of Sections 6.1 to 6.4 into an actionable set of controls for production management, welding engineering, and quality assurance.

#### 6.5.1 Personnel Qualification, Training, and Supervision

- **Qualify welders to the actual production condition:** Welder qualification shall cover the process, position, joint configuration, and material grade encountered in production. Qualification testing shall assess parameter consistency and compliance with the specified sequence, in addition to weld soundness.
- **Provide documented distortion-awareness training:** Welders, fitters, platers, and supervisors shall receive documented training covering the relationship between heat input and distortion, the purpose of the specified welding sequence, the consequences of fillet oversizing, and the requirement for accurate fit-up. Personnel who understand why a sequence is specified comply with it; personnel who regard it as arbitrary do not.
- **Assign distortion-critical work to demonstrated competence:** Thin-plated structures, erection closing joints, machinery seatings, and any joint identified as distortion-critical in the production plan shall be assigned only to personnel with demonstrated competence on that class of work, recorded in the competence register.
- **Provide continuous supervision of manual welding at critical stages:** Welding supervisors shall be present during welding of distortion-critical joints, with specific responsibility for verifying travel speed, weave amplitude, fillet size, interpass temperature, and sequence compliance. Supervision at these stages is a technical verification function, not an attendance function.

- **Maintain performance feedback to individuals:** Accuracy control measurements and fillet size sampling results shall be fed back to the individual welders and fitters concerned. Distortion outcomes are not visible at the point of work; without deliberate feedback, no individual can correct a practice that produces no immediately observable defect.

#### 6.5.2 Equipment Calibration and Maintenance Regime

- **Maintain a documented calibration register:** Welding power sources, wire feed units, cutting machines, torch height controllers, bevel heads, hydraulic clamps, thermal straightening and temperature measurement instruments, and dimensional measurement tools shall be recorded in a calibration register with defined intervals, calibration status labelling, and a defined procedure for withdrawal from service when out of interval.
- **Verify delivered parameters at the workpiece:** Welding parameters shall be verified at the arc using calibrated instruments or in-line monitoring on a documented sampling basis for procedure-controlled welding, and after any power source maintenance or relocation.
- **Schedule consumable replacement by usage:** Contact tips, liners, drive rolls, plasma electrodes and nozzles, and cutting tips shall be replaced according to documented usage criteria rather than on failure or on visible degradation of output.
- **Survey jigs, fixtures, and beds periodically:** Reference surfaces of panel line beds, jigs, fixtures, and fit-up frames shall be surveyed for level and flatness on a documented schedule, and after modification, relocation, or any impact event.
- **Report and act on equipment defects:** Operators shall be required to report equipment faults, and a defined route shall exist for withdrawing defective equipment from service without production authorisation delay. Where reporting a fault is slower than working around it, faults are worked around and the resulting distortion is attributed elsewhere.

#### 6.5.3 Automation Strategy and Verification

- **Prioritise mechanisation by distortion sensitivity:** Investment in mechanisation shall be directed first at operations with the greatest product of distortion sensitivity and weld length — panel line stiffener fillets and panel butt seams on thin-plated structures typically rank highest — rather than distributed evenly across the yard.
- **Adopt intermediate mechanisation where full automation is not viable:** Self-propelled welding carriages and track-mounted systems deliver constant travel speed at low capital cost and shall be deployed at assembly and erection stages where fixed automation cannot reach.
- **Verify the first article of every programme:** The first unit produced under any new or revised welding or cutting programme shall receive full dimensional verification before further production is released.
- **Hold programmes under revision control:** Welding and cutting programmes shall be version-controlled, with all changes authorised by production engineering and recorded. Undocumented adjustment at the machine shall be prohibited.
- **Establish and maintain compensation values from measured data:** Where mechanisation has rendered distortion systematic and repeatable, the resulting distortion shall be measured, recorded, and converted into pre-setting and shrinkage allowance values applied at the cutting stage. Realising this benefit is the principal return on mechanisation, and it requires an accuracy control feedback loop that is deliberately established; it does not arise automatically from the installation of the equipment.
- **Review distortion data against personnel, equipment, and process records:** Accuracy control data shall be reviewed periodically against the welder identification, equipment used, repair register, and process employed for each unit. This correlation is the only reliable means of distinguishing workmanship-driven, equipment-driven, and procedure-driven distortion, and of directing corrective effort to the actual cause.

## Section 7

# Summary and Conclusion

Distortion is one of the principal dimensional control challenges encountered during ship hull construction. It arises from a range of interconnected factors acting throughout fabrication, assembly, block construction, storage, transportation, and erection. If not adequately controlled, distortion can affect dimensional accuracy, assembly fit-up, production efficiency, and ultimately the quality of the completed hull.

The principal sources of distortion encountered during shipbuilding include:

**Welding-induced distortion**, resulting from non-uniform heating, cooling, shrinkage, and residual stress development.

**Mechanical and load-induced distortion**, arising from forming operations, forced fit-up, handling, lifting, transportation, inadequate support arrangements, and construction loads.

**Environmental and storage-related distortion**, caused by self-weight sagging, thermal cycling, uneven solar heating, prolonged storage, and inadequate support conditions.

**Material-related distortion**, associated with rolling-induced residual stresses, thickness variations, laminations, and other material imperfections.

**Process and workmanship-related distortion**, arising from poor fit-up, improper welding sequences, inadequate dimensional control, equipment deficiencies, and inconsistent execution of approved procedures.

While the mechanisms differ, most distortion develops through the interaction of residual stresses, thermal effects, external loading, and the relatively low out-of-plane stiffness of thin ship hull plating. Small deformations introduced during individual construction activities can become locked into the structure and accumulate as work progresses from plate fabrication to panel assembly, block construction, and final erection.

The control measures presented in this report are intended to address distortion at its source and throughout the construction process. Their effectiveness depends upon timely implementation, adherence to approved procedures, and continuous verification of dimensional accuracy. In general, preventive measures are more effective and economical than corrective actions, reducing rework, preserving material properties, and improving production efficiency.

### 7.1 Control of Distortion

The controls set out in this report are most effective, when applied as early in the production chain as possible. Correcting distortion after it has formed is always more expensive, and more damaging to the material, than preventing it from arising.

- **Design and planning:** Joint design, weld-metal minimisation, support and lifting plans, and pre-setting remove distortion potential before any steel is cut.
- **Screen the material:** Procurement specification and incoming inspection keep high-residual-stress and defective plate out of precision applications.
- **Control the process:** Heat input, welding sequence, progressive forming, and fit-up discipline keep the structure within its elastic range throughout fabrication.
- **Assure execution:** trained personnel, calibrated equipment, and mechanisation of distortion-sensitive operations convert the planned controls into consistent results.

- **Verify, then correct only as a last resort:** Dimensional verification against IACS Rec. 47 identifies deviation early, while it is still cheap to correct; mechanical and thermal straightening are the final option, not a routine production stage.

## **7.2 Concluding Remarks**

Distortion is an inherent aspect of ship hull construction that cannot be eliminated entirely, but it can be effectively managed through a systematic and coordinated approach to design, fabrication, assembly, handling, storage, and dimensional control. Dimensional integrity is therefore achieved not by any one intervention but by applying the layered controls consistently across the whole build sequence — from procurement and design, through material screening, welding, forming, handling, and storage, to final verification. Thus, the final geometric accuracy of a hull is determined not by any single operation, but by the cumulative effect of decisions and practices applied throughout the construction cycle.

The success of any distortion control programme depends on effective execution. Qualified personnel, calibrated equipment, documented procedures, and regular dimensional verification provide the foundation for consistent results. Working together, the design, production, and quality functions play a key role in maintaining dimensional accuracy and minimizing the need for corrective work. Ultimately, the most economical and technically sound approach is to prevent distortion wherever possible, detect deviations early when they occur, and reserve corrective measures for situations where preventive controls have proven insufficient.