A risk-based method for minimizing welding distortion in steel ship production

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Abstract: The paper presents a novel approach, entitled responsibility-sharing management (RSM) which can be used to assist in effective management of welding distortion in ship production that takes into account scientific methods, procedures and management issues. The paper begins by outlining the nature of welding distortion, its impact on steel ship production and traditional methods of dealing with it before suggesting the alternative way forwards. The principles of the RSM approach are then explained and the key features of its six elements are examined. An illustrative example is used to demonstrate the effective use of this approach in a shipyard.

The main conclusions are the following. Firstly, since welding distortion has a significant impact on ship production, there is, therefore, a need for a fresh systematic approach for dealing with this problem which could address not only technical aspects but also management, operation and human factors. Secondly, it is essential to encourage the development of a positive culture in the management of ship production and this is particularly relevant in efforts to minimize welding distortion.

Keywords: welding distortion, shipbuilding, steel production, management system, risk-based methodology, responsibility sharing

1 INTRODUCTION

Today’s shipyards are significantly pressurized by international competition for increasing production efficiency and each shipyard is forced to establish continuous improvement and cost-saving methods in production. If ships can be produced cost effectively and completed on time with the customer’s quality requirements satisfied, more orders will be won and the future of the shipyard becomes more secure.

In the highly competitive shipbuilding industry the main aim is to produce a ship meeting the specification of the owner/client on time, with the required quality and within budget, while providing an acceptable level of profit to the shipbuilder. This goal is very challenging as shipbuilding is a process involving many activities, and problems at any stage of ship production cycle can cause delays. One of the main problems is welding distortion of steel structures. Welding distortion leads to dimensional inaccuracies and misalignment of structural members, which can result in corrective tasks or rework when tolerance limits are exceeded and can also affect joining processes during ship construction. This, in turn, increases the cost of production and leads to delays. Any attempts to minimize the distortion problem offer significant benefits in the way of improving steel ship production.

Many research studies have been carried out and plenty has been written on welding distortion and efforts to minimize it. Much of the current failure to tackle the distortion problems effectively arises from over-specialization and over-compartmentalization, with the ‘expert’ knowing ‘more and more about less and less …’. Attention in most cases is being paid only to technical matters of the problem. There is, therefore, a need for a broader and holistic fresh approach, which could cover not only technical activities but also management, operational and human aspects of ship production. It is necessary to examine the problem from multiple perspectives, to generalize existing knowledge, to bring together fragmentary research findings and to endeavour to put it on a more rational basis. This paper identifies distortion as one of key problems in the ship production process and generates suggestions for improvement of the process via minimizing welding distortion, taking a wider view on all aspects of that problem.

The paper begins with the brief review of information related to welding distortion and present methods of dealing with it. The novel approach, called responsibility-
2 CRITICAL REVIEW ON WELDING DISTORTION

2.1 The nature of welding distortion

The definition of distortion given in the *Oxford Dictionary* states that it is ‘the action or an act of distorting or twisting out of shape (permanently or temporarily)’. Also, the distorted condition is ‘a condition of the body ... in which it is twisted out of its natural shape’.

Distortion is a problem that exists in all industrial metalworking processes that employ heat and has been a serious problem for engineers since the early 1930s. With the introduction of welding in shipbuilding, it became necessary to control the dimensional changes of metal plates, stiffeners and assemblies that occur during welding process. The magnitude of distortion is controlled in practice within specified tolerances, not only for aesthetic purposes but also to maintain structural integrity in service.

The complex strain that develops during welding leads to internal forces that cause complex metal movement during welding and final distortion.

There are three fundamental dimensional changes that occur during the welding process and in the ways in which distortion can appear (Fig. 1) are principally:

(a) transverse shrinkage perpendicular to the weld line,
(b) longitudinal shrinkage parallel to the weld line and
(c) angular distortion around the weld line.

The severity of each of these will depend upon many factors. Depending on the configuration and dimensions of the structure it is possible to classify the basic types of distortion [2], such as transverse and longitudinal shrinkage, rotational, angular, longitudinal bending, torsional and buckling distortion. The problem here is that in real structure, especially in the case of a complex structure, which has various types of joint, all these types of distortion are combined.

Much research into the causes of welding distortion in steel structures has been carried out over recent years. For example, Masubuchi [2] provided details of his research study, summarizing the major factors as follows:

1. The welding process non-uniform heat input causes distortion in the fabricated structure.
2. Built-in residual stresses, which were created during the manufacturing processes, are released and cause metal deformation.

2.2 Impact on steel ship production

The most significant shipbuilding problem commonly encountered is the difficulty in joining blocks during hull erection due to inaccuracies in the overall block dimensions and the misalignment of structural members due to weld distortion, resulting in much rework at the erection stage. This excessive erection-site rework includes tasks such as the following: extensive realignment of butts, seams, and internal structural members with dogs, clips, wedges, hydraulic jacks, etc., the cutting free, realigning and rewelding of previously assembled parts; gas cutting for the adjustment of erection joints, the removal of dogs, clips, yokes and lugs; the restoration of surface finish. Excessive distortion in decks and bulkheads may also cause serious delay in subsequent fitting-out operations.

For example, an analysis performed by the Navy Joining Center [3] has identified the cost impact of distortion due to welding. It was estimated that the total cost impact on the DDG-51 *Arleigh Burke* class *Aegis* destroyer is between US$2.4 million and US$3.4 million per ship. This cost includes labour for straightening and other effects associated with increased fitting time, replacement of materials and interruption of other trades.

2.3 Traditional methods of dealing with welding distortion

Shipbuilders and other constructors have done much to improve control of distortion in welded construction and
to develop methods of removing distortion, but there are quite wide variations in practices employed and their effectiveness. Many influential factors are involved, but it is difficult to evaluate each in routine production.

A number of studies have examined various components of this problem:

(a) residual stress due to welding [2, 4–7];
(b) post-welded in-plane and out-of-plane deformation [2, 6, 8–12];
(c) influence of out-of-plane deformation on ship structures behaviour [9, 13–15].

Generally the post-welded distortion can be estimated by measurements or by theoretical and semiempirical analyses. These lead to several approaches to dealing with this problem:

(a) post-welded plate deflection measurements of laboratory tests [2, 8, 16];
(b) post-welded plate deflection measurements of actual shipbuilding plates [6, 9, 10, 12];
(c) development of semiempirical formulae to estimate the post-welded plate distortion for a given welding situation [17, 18];
(d) development of numerical modelling for estimating the post-welded distortion [19–21].

Using modern computers and computational techniques, such as the finite element method, a renewed effort has been made in recent years to study residual stresses and distortion. Therefore, it is now possible using computer programs to simulate the transient thermal stresses and movement during welding as well as the residual stresses and distortion that remain after welding is completed.

The results of these researches, together with obvious results of experience in production, make it possible to draw many conclusions as to the most effective practices.

From quite a broad survey of methods used and results achieved in various shipyards, it has been possible to formulate a number of general principles that can be applied in the control and correction of distortion. In most cases the results of this practical experience can be explained on the basis of known physical properties of steel and its behavior under changes in temperature.

2.3.1 Control of distortion

The methods of distortion control in welding have been well summarized in several publications [22–24] as follows.

Prevention by design of welded structures. At the design stage, welding distortion can often be prevented, or at least reduced, by considering:

(a) weld placement closer to the neutral axis of a fabrication;
(b) the effect of stiffener spacing and plate thickness;
(c) reducing the size and amount of welding to the minimum required for strength, elastic stability and balanced design;
(d) elimination of welds by forming the plate or using rolled or extruded section;
(e) joint-type design, which balances the thermal stress through the plate thickness;
(f) use of new alternative construction materials (e.g. SPS).

Techniques based on assembly procedures and pre-welding conditions. These are:

(a) minimization of residual stresses and initial distortion in delivered materials;
(b) presetting method (which is mainly employed in subassemblies);
(c) restrained method entailing:
   (i) use of strongbacks, jigs and fixtures,
   (ii) back-to-back assembly,
   (iii) tack welding and
   (iv) stiffening.

Techniques based on welding procedure. These involve:

(a) the selection of a welding process, which exhibits less distortion (e.g. laser welding);
(b) increasing the deposition rate and welding efficiency, as the weld can be deposited with the minimum number of runs and in the shortest possible time to minimize the heat input (e.g. using multiple wire welding, a flux or metal cored wire consumables, hot wire welding);
(c) the selection of the type of electrode that gives the lowest heat input per unit length of weld;
(d) using a sequence of runs balanced about the neutral axis of the joint;
(e) using a balanced welding sequence, such as back-step and skip welding techniques, for heat dispersion;
(f) using different types of general welding sequence of fabrications (e.g. the so-called ‘egg-box’ construction);
(g) modifying the thermal pattern of the weldment (forced cooling, side heating, etc.).

2.3.2 Correction of distortion

It is not always possible to control distortion within acceptable limits, especially with a new fabrication. In such circumstances, it is usually possible to remove distortion by producing adequate plastic deformation on the distorted member or section. The required amount of plastic deformation can be obtained by thermal or mechanical methods.

Mechanical method. Distorted members can be straightened with a press or jacks. When welded parts are small enough to be handled to straightening rolls or
The distorted area is straightened by thermal method. The distorted area is straightened by heating spots or lines to 600–650 °C and quenching. This procedure will cause the material to upset during heating and then shrinkage stresses will tend to straighten the plate or beam. There are various ways in which such local heating can be applied to remove distortion \[25, 26\], but it is only by experience that the best method can be selected for any particular job. In all cases the greatest danger is in overshrinking the area being heated, as this may cause even worse distortion.

2.4 Alternative way forward

The literature survey of the present methods of dealing with welding distortion and efforts in minimizing it during metal fabrication processes shows that there is a tendency to concentrate attention mainly at technical levels or, in other words, there is a ‘technological fix’ for the problem. Consequently, the causal explanations of welding distortion problem in general, and in ship production in particular, is limited by mathematically related representations of physical processes, involved in the production process, but the root of the problem goes much deeper. The generalization depends on a selection of relationships which are isolated from practice. Undoubtedly, such a representation is particularly well suited to analysis of optimal conditions and theoretical limits of physical processes in a technical system which carefully separates physical processes involved during welding from the complexity of the real world of ship production. Distortion phenomena in the environment of systems such as ship production organization cannot be considered as practically isolated and, therefore, described by classical engineering analysis. In this case the problem of minimizing welding distortion should be analysed and solved by a different method based on a wider causal representation, considering all aspects of shipbuilding system.

As the sixteenth-century proverb says: ‘Do not meet troubles halfway’. The causes of distortion problem are not always a matter of the effect of weld. The cause may lie partly in design, in many construction operations, and management. Therefore, control must be exercised all along the line of production operations, to minimize distortion successfully. To match the multifaceted nature of the environment of steel ship production while improving the situation of distortion problem, there is a need to consider various perspectives of a given problem, and they are as follows.

2.4.1 Engineering

In this context, engineering includes design and construction. These have an important part in the reduction of distortion, particularly in the early stages of design, where decisions have a considerable effect on the welding distortion problem in ship structures. There is much that the designer can do to facilitate distortion control, and some matters of design have already been discussed in Section 2.3. Of course, it is not generally possible to select a material on the basis of its liability to distort, or structural arrangements such as increasing the thickness of plate and reducing the spacing of stiffeners only from buckling elimination viewpoint. Strength, weight and economic considerations are generally the overriding factors. However, engineering alone cannot provide all the answers in distortion problem.

2.4.2 Operational factors

This level is concern with the performing of relevant actions (assembling, welding, etc.) under different conditions in order to produce a ship structure. This requires the devising of correct procedures followed by adequate personnel training. There is also a need to obtain and utilize feedback from experience. In most cases the root causes of distortion problem in the shipyard’s production process do not arise because these operational methods of distortion mitigation are ineffective, but because there is a lack of clear understanding by people regarding what, when, where and how to apply them.

Good design and satisfactory production operations are not, however, sufficient; they can have their full effect only when they form part of a planned policy for the control of distortion.

2.4.3 Managerial aspects

Attributing distortion problem to the inadequate design and to the action of the shop-floor workers is a mistaken oversimplification of that problem. In most cases, the worker error is only one attribute of the whole management system of a shipyard. It is the individual attitude to the distortion problem of some people, namely top management, that serves as the foundation for the shipyard culture which in turn influences the individual attitude of others. It is a management task to determine the goals and the set of standards, to plan the acquisition and utilization of resources, to organize and coordinate people, to incorporate control procedures and continuously to improve performance. It is the management of an organization that determines the policy, makes the decisions and develops a production culture within the organization. It is the management that has to be committed to productivity and to devote resources to the achievement of the desired level of productivity. Management is the most important aspect for improving the productivity of the entire shipbuilding system by focusing attention on individual areas, such as minimizing of distortion, where improvements offer significant benefits.
2.4.4 Human factors

Furthermore, the previous three aspects are closely associated with so-called ‘human elements’ or ‘human factors’ that deal with human behaviour and human interaction with hardware, software, the working environment and the culture of an activity. Human factors can be identified as a dominant factor in the distortion problem, occurring in all parts including design, operation and management. The study of ‘human factors’ and significance of its consideration has been discussed in detail elsewhere and well summarized in references [27] and [28]. Knowledge of why human errors occur is a basis for control of human actions. Rasmussen [29] made the observation that ‘human errors only made sense when they were classified in terms of mental operations being utilised in the task’, and as a result he distinguished three levels of human performance: skill, rule and knowledge based. Rasmussen’s view was that ‘the skill-based level represents the continuous real-time control of activities, the rule-based level reflects the adaptive choice among preplanned decision rules and the knowledge-based level reflects intelligent self-organization of behaviour’. Understanding these performance levels helps to classify the varieties of errors and violations, and to direct efforts in order to reduce them.

Clearly, the best solution for achieving the improvement in productivity through minimizing welding distortion will depend on a balance of management, engineering and operation, which also takes human factors into account. Taking into consideration the fact that dealing with weld distortion involves not only technical activities but also management and operation, a successful approach needs to be able to tackle this problem from a variety of perspectives. In fact, as was already mentioned, existing approaches tend to concentrate attention mainly on the technical and specialist levels, with little or no attention being paid to the management, operational and human aspects. There is, therefore, a need for a broader and more holistic fresh approach.

3 RSM FOR WELDING DISTORTION

In order to provide the framework that takes a broad view with multiple perspectives defined above, takes many relevant aspects into account and concentrates on interactions between the different parts of the welding distortion problem, a systems-based methodology was adopted. The novel approach, RSM, developed by Kuo and Cojeen [30] has been applied in this project as the most appropriate tool for dealing with welding distortion.

3.1 Basic concept

RSM was developed as an extension of the safety case concept. The safety case approach, in turn, has been derived from the application of the principles of system-based methodology and has been used in nuclear, chemical and offshore industries to study the safety of systems. That approach has been generalized by Kuo [27] for use in any study and its principles are applicable to many situations.

Essentially, the safety case concept is based on seeking the answers to five fundamental questions about any system or activity, process or project. These questions and the tasks, which have to be done in order to provide answers to those questions, are as shown in Table 1.

These questions and answers are equally applicable to steel ship production activity except that the hazard is defined here as something that can lead to undesired outcomes in the process of meeting an objective (here, to produce accurately dimensioned component with required quality, on time and within budget) and associated with welding distortion. Risk can be assessed with the acceptable data and its reduction can also be determined as a reduction of welding distortion. Emergency preparedness becomes a contingency method of removing distortion where it occurs, while safety management can be the production management system.

Recently, to update the goal-setting approach a new RSM approach was presented by Kuo and Cojeen [30]. Figure 2 illustrates the model of RSM approach showing its elements and their relationship. The RSM approach has a number of attractive features, and as can be seen from Fig. 2, the RSM model contains all the important elements of typical management system as well as the element of shared responsibility of stakeholders on the

<table>
<thead>
<tr>
<th>Number</th>
<th>Questions</th>
<th>Answers and scientific terms</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>What aspects of this system can go wrong?</td>
<td>Systematically identify potential hazards (hazard identification)</td>
</tr>
<tr>
<td>2</td>
<td>What are the chances and effects of their going wrong?</td>
<td>Assess the risk levels of the identified hazards (risk assessment)</td>
</tr>
<tr>
<td>3</td>
<td>How could these chances and effects be reduced?</td>
<td>Reduce the risk levels of selected hazards (risk reduction)</td>
</tr>
<tr>
<td>4</td>
<td>What should be done if an accident occurs?</td>
<td>Be prepared to respond to emergencies (emergency preparedness)</td>
</tr>
<tr>
<td>5</td>
<td>How can the system be managed to ensure safety?</td>
<td>Devise a system to manage and control the risk levels of the hazards (safety management system)</td>
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way of achieving the defined goals. The key elements are described in the next section.

3.2 The key elements of RSM

The RSM approach consists of six key elements that can be described briefly as follows:

**Element 1: define.** The purpose of that first element is to define the objectives, goals and policies. In other words, what needs to be done should be determined.

**Element 2: organize.** In order to ensure that the objective can be achieved, goals are met and policies are fulfilled, the second element involves organizing physical, human and financial resources, as well as allocating responsibility among relevant stakeholders, developing a communication mechanisms and other tasks.

**Element 3: collaborate.** The objective here is to ensure that all stakeholders will work together through the four steps of this element. The four steps are as follows:

- **Step 3.1. Identify** hazards in the system, activity or project by using appropriate techniques.
- **Step 3.2. Assess** risk level of identified hazards using qualitative and quantitative methods with the aim of establishing their significance, and group them into three regions: intolerable, tolerable and negligible.
- **Step 3.3. Reduce** risk levels of hazards in the intolerable region through a combination of management, engineering and operational methods, and if cost effective reduce those in the tolerable region.
- **Step 3.4. Prepare** for the possible occurrence of emergency scenarios and have contingency plans available.

**Element 4: implement.** Once the most appropriate decisions and recommendations for changes have been accepted as the output from the previous element, implementation of them should take place so as to ensure that the policies are satisfied.

**Element 5: measure.** In order to assess the overall level of implementation and effectiveness of the system, the performance-measuring element is needed. It has been said often that it is not possible to manage what cannot be measured. The performance can be measured by a variety of inspections, assessments and audits.

**Element 6: review.** In order to ensure that the system is achieving the desired results the review element should be instituted. It analyses the practical experience gained and lessons learnt, uncovering potential problem areas and indicating necessary improvements and corrective actions to be taken, and then feeds back information into element 1 so that goals and policies can be refined, thereby improving the system continuously.

4 ILLUSTRATIVE EXAMPLE OF RSM USE

The illustrative example of practical implementation of the RSM approach in the ‘real world’ of ship production has been selected to demonstrate how RSM could be helpful in achieving reduction of welding distortion in ship production by means of collaboration between all stakeholders. This example is concerned with the use of the RSM approach in the shipyard assembly workshop with the aim of improving situation of distortion problem during fabrication of the typical unit.

4.1 Practical implementation of RSM

**Element 1: define.** The general objective is stated as: ‘To achieve the overall improvement of steel production by minimizing distortion’. The situation of fabrication of a typical unit is considered as a case study. The desired outcome is to produce an accurately dimensioned unit with the required quality, on time and within budget.

**Element 2: organize.** To ensure that the defined goal can be realized, a number of tasks are outlined such as:

- (a) ensuring appropriate facilities to be used;
- (b) allocating resources and effort;
- (c) assigning responsibilities to individuals;
- (d) devising effective communication mechanism;
- (e) adopting standards and procedures.

**Element 3: collaborate.** At this stage the appropriate stakeholders, e.g. representatives from design department, production workshops, classification societies...
and ship owners, are worked together through the four steps of this element:

**Step 3.1: identify.** Using brainstorming techniques and considering different stages of the production process, the following typical examples of hazards are identified:

(a) initial distortion of plate/stiffener;  
(b) unevenness of temperature distribution in prefabrication processes;  
(c) increased size of the root gap;  
(d) incorrect welding parameters;  
(e) unbalanced welding sequence;  
(f) large amount of deposited metal;  
(g) failure to apply distortion mitigation technique;  
(h) lack of independent checking;  
(i) inadequate communication;  
(j) lack of feedback for corrective actions.

**Step 3.2: assess.** The risk level of each hazard is assessed by simultaneous examination of the consequence and likelihood of the occurrence using qualitative methods and experience of the group. The hazards are placed in the appropriate risk region, i.e. intolerable, tolerable or negligible. As a result, the following risk levels for the identified hazards are derived:

- **Intolerable level:** (e), (f), (g), (i)  
- **Tolerable level:** (a), (c), (d), (h), (j)  
- **Negligible level:** (b)

The assessment of the hazards with an intolerable risk level is also made using quantitative methods such as fault tree analysis and involving judgement, based on experience and available data.

**Step 3.3: reduce.** A number of methods are suggested to reduce the risk levels of those hazards in the intolerable risk region by addressing both consequences and probability of their occurrence using a combination of management, engineering and operational methods, also taking human factors into account. For example, the risk level of hazard (e) namely unbalanced welding sequence, can be reduced by increasing the rigidity of the structure (engineering), using restraint methods (operational), providing education and training to change attitude (management).

**Step 3.4: prepare.** To be prepared for ‘emergency’ occurrences, attention was given to a contingency plan which involves outlining the procedures to be followed and the remedial actions that would be necessary in different circumstances.

**Element 4: implement.** Following the process of making decision on actions in order to meet the objective, performed in the previous element, implementation of chosen decision and the ways of minimizing resistance in implementing the changes are considered.

**Element 5: measure.** The first task here is to establish what is to be measured and how the measurement is to be taken. Aspects to be measured could include the following:

(a) the time taken to complete the task;  
(b) the amount of lost time and its causes;  
(c) cost of remedy to reach desired quality.

Independent parties or people who are not directly involved should be used for the appraisal.

**Element 6: review.** The information generated by the previous element is then analysed in order to produce information required so that an evaluation can be made of the effectiveness of the performed actions. The results obtained then should be reviewed, comparing with the expected results, benchmarking with performance of other organizations or with ‘world class players’. Review of the experience gained, identifying any discrepancies and analysing strengths and weaknesses of the action, should be performed as well. The lessons learnt could be fed back to enhance any aspect of the other five elements.

Owing to a number of merits, with a robust management system and sharing responsibility of stakeholders, the practical implementation of the RSM approach to the distortion problem could considerably change the current problems faced in the shipyard, and moving through these six elements several times develops an effective ongoing improvement process in order ‘to engineer a bridgeable gap between “what is” and “what might be”’.

5 DISCUSSION

A number of issues deserve brief discussion, and they are considered under separate headings as follows.

5.1 Taking a broader view

The study began with a critical review of the information on problems related to welding distortion and methods of dealing with it, which are currently available for steel ship production. This revealed that the existing methods have made significant contributions to the acquiring of knowledge on the physical phenomena of welding distortion and attempts to minimize it, but the majority of those methods are biased towards the technical field and cover rather small and scattered parts of the whole spectrum of distortion problem.

Based on the available information related to subject of distortion an impression was created that the problem...
could be solved by methods based upon the mathematically representations of physical processes involved. There was the danger of finishing with taking too narrow a view of the problem situation, so recognizing only part of the problem.

To help to overcome this ‘perceptual block’ the RSM approach based on the safety case concept which reflects the underlying holistic methodology and other sound principles of systems-based methodology was adopted. To build an understanding of the whole distortion problem through knowledge of only a technical part is no longer valid. ‘It is not possible to analyse effectively the whole by looking at the parts separately’ [31]. From this point an attempt was made to bring together fragmentary research findings in a comprehensive view on technical as well as management and operation aspects and human factors. In practice it was ‘an outlook to see better, a network to understand better and a platform to act better’.

In order to understand the complexity of distortion problem and to generate solutions necessary for the solving of it effectively another way of thinking is needed. The systems concept and a systemic way of thinking can be applied to such a complex system as ship production. It expands the focus and concentrates on the function and behaviour of that system considering all elements: not only technical aspects but also management, operation and human factors, together with their relationships as a whole.

5.2 The need to focus on key factors

The holistic approach adopted helps to generate various perspectives on the problem in question, providing a wide view on it and producing a large number of findings and recommendations, but it is necessary to narrow the focus to specific issues capable of solving the problem effectively. The Pareto principle, or the ‘80 : 20 law’, states that a few causes are likely to account for most of the effect and, in many activities, 80 per cent of the potential value can be achieved from 20 per cent of effort; the remaining 80 per cent of effort can be spent for relatively little return. The activity aided in minimizing welding distortion in steel ship production is not an exception. The study provides a good understanding of where effort should be directed in order to tackle the distortion problem. Techniques used through four steps of the ‘collaborate’ element of the RSM approach allow the decision maker to determine whether or not the risk of identified hazards are unacceptably high and thus warrant remedial action, to select appropriate actions or alternatives that will reduce the risk to the tolerable level and to assign priorities to actions needed, thus increasing the likelihood that effort will have high a payoff. As a result, management, human as well as technical factors were identified as the dominant and most influencing factors contributing to the distortion problem in ship production. It is beliefs, attitudes and values that individuals from the top management to the shop floor worker possess that must ultimately be changed in order to solve the basic problems in the course of minimizing welding distortion.

6 CONCLUSIONS

The following main conclusions of this paper can be drawn:

1. Since welding distortion has a significant adverse impact on ship production, there is, therefore, a need for a fresh systematic approach for dealing with this problem which could address not only technical aspects but also management, operation and human factors.

2. It is essential to encourage the development of a positive culture in the management of ship production and this is particular relevant in efforts to minimize welding distortion.

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