

THIN PLATE BUCKLING MITIGATION AND REDUCTION CHALLENGES FOR NAVAL SHIPS

N.A.McPherson¹, A.M. Galloway² and W.McGhie¹

¹ BAE Systems Naval Ships, Glasgow, Scotland, UK.

²Dept. Of Mechanical and Aerospace Engineering, University of Strathclyde, Glasgow,
Scotland, UK.

Abstract

Thin plate buckling or distortion on ship structures is an ongoing issue for shipbuilders. It has been identified that a significant number of factors can be put in place based on prior knowledge and good practice. Additionally, research work aimed at reducing thin plate distortion has been relatively prolific, particularly in the area of simulation modelling. However, the uptake in the research findings by industry has been relatively low. A number of these findings are discussed and their application considered. For any further reductions in thin plate distortion to be generated there is a clear need for better interaction between the research institutes and the industry.

Key Words

Buckling; distortion; steel; rectification; FEM

Introduction

The ongoing drive to reduce weight in naval ships is solving one problem, but exacerbating another problem. That specific problem is perceived as being welding induced thin plate buckling. The term 'distortion' is more generically used, but in the case of thin plate the term buckling which is an out of plane effect is used. Traditionally this has been described as the 'hungry horse' phenomenon, where the ribs of a lean horse were perceived as stiffeners and the sagged areas between them was the plating.

The issue of thin plate distortion is not new, and it was particularly evident in naval vessels where lighter plating was the norm. However it could also be seen in some accommodation areas of commercial ships. In some commercial vessels the plating has been increased in the accommodation areas to avoid the issue of distortion. On bulk carriers, tankers etc the very slight extra weight has not been identified as an issue. In the naval vessels the buckling has created cosmetic issues for customers and has also generated significant rework associated with it. To some extent it was seen as being an integral or natural part of the process and the rework was included into the overall manhour requirement for the build. However, some shipbuilders were publicly quoting figures of between 25,000 and 30,000 manhours to heat straighten buckled areas. In addition, the figure would be a function of the vessel size and plating, and there was the need to generate some sort of normalised figure for heat straightening. Significantly, there was a publication¹ based on an US Navy destroyer programme, which stated that there was about 10 times as much additional rework associated with the complete process. Listed were such issues as reinstating paint damage, reinstating insulation that had to be removed, taking down and putting back equipment that was in the vicinity of the rectification process, changes to plan, etc.

Currently there is a significant database of prior knowledge²⁻⁵ about thin plate buckling. One of the underpinning facts is that the greater the heat involved in the process then the more the buckling will be. If this is taken as the basic building block some significant benefits can be obtained.

In addition to the buckling effects, there is the additional effect of residual stress on fatigue life⁶, but that will not form part of this current paper.

For a recent contract a distortion/buckling workshop was held and a Fishbone or Ishikawa diagram was developed. This is shown in Figure 1. The most striking effect of this is the potential complexity and possible interaction of the factors. The most populated sector is the one related to 'method', and many of the issues are relatively well known. For example – heat input; intermittent welds; joint design; weld sequences. Although these factors may be

well known it is quite often the case that their significance relative to one another is not known.

Heat Factors

The plate and bar burning processes that can be used are very varied, but the optimum within a facility could be

- Laser cutting for all thin plate (8mm and below)
- Dry plasma cutting for all bars.

These have both been shown to generate significant benefits in reducing early stage distortion⁷.

The next stage of the process is to minimise welding heat input, one of the issues raised in Figure 1. Ideally, yards would benefit from having a hybrid laser welding facility, but this carries a high capital cost when installed new, and can not always be retrofitted onto existing equipment or facilities. However, there are benefits as shown in Figure 2⁸. This figure shows a variety of welding equipment type along with the normal heat input generated during the welding process. Based on this the Cold Metal Transfer (CMT) could potentially have a place in distortion reduction, where a lower cost option was being considered.

The previous comments are equally applicable to seam and fillet welding processes.

For conventional seam welding it is beneficial to weld from two sides, to equalise heat input from each side and minimise angular distortion. Again, this is not always possible and the potential use of heat sinks around the seam weld can be employed, if available.

During panel construction a great deal of distortion occurs at the fillet welding stage. An example of distortion in the form of edge rippling is shown in Figure 3. Depending on yard configuration it may be standard to weld all the longitudinals from the plate centre out to the edge first, and then do any transverse connections.

Wherever possible, intermittent welding should be used if design considerations allow it.

Very simply, this move reduces the overall heat input by almost 50%. In addition a short dwell of the arc at the end of each length of intermittent weld will reduce the potential for

fatigue cracking from the small crater crack that can be produced. An example of the pore and crater crack is shown in Figure 4.

Fillet size is also a significant issue. The minimum allowable fillet size from a design viewpoint should be aimed for. For example reducing the fillet weld leg length from 4.5mm to 3.5mm reduces the weld volume by 40%. In turn this can be equated to a heat input reduction of 40%. By combining intermittent welding and reduced fillet size, very substantial decreases in heat input can be achieved. Further benefits can also be obtained in intermittent welding by placing the tack weld, using metal cored MIG wire, within the start or end area to be welded. Welding is then carried out up to the tack but not over it. This creates a further potential to reduce heat input by around 16%.

However, fillet leg length control is only one part of the fillet weld scenario. Over penetration of the weld as shown in Figure 5 has to be avoided. Some current work⁹ is on-going to optimise the welding parameters; travel speed, welding torch angles, electrode stick out and electrode aim point by a series of statistical process design and artificial neural network (ANN) projects. Related to this is the use of metal cored MIG welding wire which can be used at higher welding speeds and lower heat input. Very recent work¹⁰ has also shown that a decrease in shielding gas flow rate can increase the weld metal penetration. Not surprisingly this was coupled to an increase in distortion.

In addition to heat input, there is a need to ensure that heat is not concentrated into local areas, when welding bars on to panels. This is normally countered by developing weld sequences. There are basic rules for this such as welding from the centre of a panel towards the edges and if using two welders, ensure that they are welding in opposite directions. Areas of high bar concentration, such as that shown in Figure 6 require a sequence of welds to be defined, particularly in the area around the carling plates.

Once a panel or sub-assembly has been completed, it is important to retain its stability. It has been shown that this can be achieved by the use of ribbing bars which are basically temporary attachments. In addition it is beneficial to keep these in place for as long as

possible into the build process. For example when erecting bulkheads, there is a much higher incidence of ease of fit up when erecting bulkheads with ribbing bars.

Units can benefit from the initial panel being tied down onto a flat bed and restraining it there. For this to be effective it is essential not to weld any vertical connections within the panel prior to it being tied down. This gives the structure the ability to move slightly when being restrained. Thereafter the critical aspects of the structural build are to ensure that the structure is welded in such a way that any welding residual stress is kept to a minimum by adopting the correct weld sequencing. It has been shown that back stepping corner connections is highly beneficial in maintaining the structural geometry and also minimising other forms of distortion.

There was also a view expressed¹¹ that pulling down the panel against a significantly solid structure will help remove heat as the structure will act as a heat sink. For a variety of reasons this is debateable as a very high level of surface contact between the two surfaces has to be achieved to ensure effective heat transfer

Outfit issues

The fitting and welding of outfit items has basically been neglected as a contributing factor to thin plate distortion. Figure 7 is an area where a relatively high number of attachments are fully welded. In some cases the length of outfit welding can be similar to the structural welded length in a compartment. Additionally, there is an education process that needs to be put in place with all involved in the welding process – structural welders are relatively well aware of the issues surrounding distortion, but that is not always the case for welders engaged on fitting and welding outfit items.

Options are available which need to be more fully explored. The most obvious one is the potential benefit of using adhesive bonding for outfit items. Most of the issues surrounding fire resistance and toxicity have been resolved, but certain shock criteria still negate its use on specific contracts. Another possibility is to use a carrier plate to which a number of steel

outfit items are welded. The carrier plate can then be welded or bolted onto the structure. However, it has not always been possible to follow this through due to weight considerations. Despite what has been quoted here, it is quite clear that better control over outfit welding would give benefits in reducing distortion.

The Role of buckling rectification

At BAE Systems on the Type 45 destroyer contract, buckling rectification was not carried out until near the end of the block build. This eliminated the possibility of the process being carried out twice.

Heat straightening is an age old process within shipyards, and considered to be a 'black art'. Whether that latter comment is correct or not, there is a need to ensure that processes such as this are carried out in a controllable and reproducible manner.

Any rectification process has to be productive, reproducible, and cost effective. Induction heating has been in place in shipbuilding in a number of forms for many years. However, in recent years EFD have introduced a simple to operate induction heating system for rectifying thin plate distortion. There were some doubts about its effectiveness for use on 4mm thick plate but it has been found¹² to produce acceptable results at this thickness. The main factor in the use of the induction heating system is a 50% reduction in rectification time¹². The capital cost of the equipment can be recovered relatively quickly. Experience has shown that it can be used to produce totally flat decks, and when aiming for that, the rectification time increases and the overall benefits against traditional heat straightening techniques decrease. The 50% reduction quoted earlier is for the situation of taking the required flatness into tolerance.

There is a move currently underway to show that flame straightening can be carried out in a more efficient manner by using an oxy-acetylene gas instead of oxy-propane. The advantages are that oxy-acetylene is a more thermally efficient gas than oxy-propane; it is lighter than air and will not leak into low spaces where it could gather, and create significant hazard.

Overall outcome

By adopting the approaches described above (except induction heating) very significant improvements in distortion rework can be achieved. On the six ship Type 45 destroyer programme, a prediction was made of the heat straightening rework manhours based on other smaller contracts. In terms of actual performance this figure was reduced by between 75 and 80% on ships 2-6 onwards. A normalised manhour/tonne figure was used, and for the Type 45 the outcome was 5.5 manhours/tonne. The steel weight used to generate this figure was the weight of structural plate and bar used in the structure, and excluded items such as seats, castings etc.

The actions described that contributed to this effect could all be defined as being good practice, and very few of them were not patently obvious. These have been defined as being 'Management Issues' i.e. their application is now reliant on adherence to laid down practices. Any further reduction in rework level posed a number of challenges

- Introduce induction heating and reduce the rework to ~ 2.5manhours / tonne¹²
- Tackle the remaining issues which are root causes of distortion, and generate incremental benefits.

The case for the introduction of induction heating is straightforward¹².

However, there are still sound reasons to continue the investigations into distortion/buckling to more fully understand this phenomenon on thin plate. In the next section there is a good example of this in the area of tack welding.

The next steps

A vast amount of research work has been published on thin plate buckling, but there seems to be an issue in the application of the findings to industrial practice. Conversely there also seems to be a lack of acknowledgement by researchers on how significantly the known factors can reduce the buckling, and how they need to be under control to maximise the benefits of the new technology implementation.

It is quite clear that the application of techniques such as artificial neural networks (ANN)⁷, risk shared management (RSM)⁷ and finite element modelling (FEM)^{4, 13} can lead to a greater understanding of factors involved in distortion / buckling.

Plate and bar quality

One of the most significant and difficult factors involved in distortion is understanding and knowing the residual stress levels and distribution within the plates and bars prior to cutting and welding. From a practical viewpoint it is quite obvious that plates react differently to the effects of cutting. In some cases, edges lift as the residual stress relieves itself, and this is a completely random effect. As already mentioned higher heat input cutting processes create more distortion. In line with this is the need to use plates which have been produced to very tight flatness tolerance. Work at the University of Strathclyde¹³ has shown that pre-existing out of flatness acts as a site for more distortion. Inevitably the tighter flatness requirement creates an area of potential conflict as the additional cost of the tighter tolerance is passed on to the shipbuilder.

Plate and bar cutting

Finite element modelling studies¹³ have shown that there is no benefit of sequencing the plate cutting process when using laser cutting. As a result the most effective manner is a single periphery cut for all plates. Further FEM work has shown that to minimise distortion, cut outs should be avoided at an early stage. Some practical work on Type 45 showed that leaving the bridge windows uncut, until a very late phase in the build was highly beneficial in reducing distortion in that area (4mm thick).

Welding

A number of studies have been carried out related to the thin plate on the Type 45 contract and the 6.5mm thick decks on a current aircraft carrier build.

As stated earlier, when welding longitudinal bulb bars to panels, fillet welding was carried out from the centre of the panel towards the end, and starting the second side of the bar as the first side torch returns to the centre to repeat the operation in the opposite direction. This

situation was subsequently modelled and the benefits were shown to be of the order of a 50% decrease in average distortion against welding from one edge directly to the other edge. To some extent this is reverse engineering, but it did confirm that what was considered to be a logical and practical approach was in fact beneficial. When this work was repeated using 30% more heat input and the optimum sequence, the average distortion increased by 100%. However the most significant aspect was the 300% increase when welding from one end of the panel to the other. This latter piece of work served to emphasise the importance of controlling the heat input, by modelling the scenario and then implementing the findings.

Panel geometry

Panel breakers are used along the centreline of bulkheads as a method of potentially reducing buckling. Modelling showed that it had no effect when welding was carried out on all the downhand welds, but when the vertical connections were made, the panel initially distorted badly and then actually buckled. It is perhaps feasible to do the vertical connections at a later stage in the construction. This buckling is thought to be related to the magnitude and the direction of shrinkage of the vertical welds.

However it was established that welding from the centre of the panel out did reduce distortion as did leaving the last 500mm of the fillet weld on the bars loose.

Restraint

Restraining panels has been discussed for many years in shipbuilding. An FEM evaluation indicated the potential for a 30% reduction in distortion. However, when a practical evaluation was carried out there was no benefit against a base case. The issue is that not all restraint methods yield benefits in reducing distortion. It is very much an area where a great deal of clarification is required. This specific point has been reinforced by Schenk et al¹⁴, who found that the length of the clamping time also had an effect on the type of distortion and distortion amplitude a T bar would undergo.

This is one area where there is a need to attempt to develop more definitive directions for the practical application of restraint. In Michaleris'⁴ book, the use of physical restraint as a single distortion mitigation process is barely mentioned. It is difficult to totally understand the logic of developing various tensioning techniques, when the concept of simple restraint has not been fully understood.

Tack welding

Tack welding of a structure was evaluated using a practical approach, based on some tentative findings from some FEM work. A series of trials were carried out on 4mm thick plate, and the data shown below was established. This work was based on a flat starting point, and shows that on average

14.4% of the total distortion was related to initial plate condition

32.7% of the total distortion was due to the effect of tacking.

It was at this point the initial 'saddle' topography was developed in the plates and some movement of the corners took place.

This work was extended along with the FEM studies and it was established that using a small number of longer tacks was more beneficial than a large number of small tacks by about 12%. It was also established that the optimum total tack length should be about 14% of the total length being welded.

An additional finding was that it was beneficial to tack on the opposite side from that where the bulk of the welding was taking place.

Welding consumable

Currently there is significant interest in the use of higher strength welding consumables which generate compressive stresses within the weld area and reduce the detrimental weld tensile residual stresses in that area. An example of some early work¹⁵ is shown in Figure 8, where a higher strength 'bainitic' welding wire was used. Comparing the longitudinal stress data in this figure shows that the bainitic consumable created a significant decrease in the

tensile residual stress in the weld area, but not in the heat affected zone. In this area the stresses were unchanged.

Although this work is at an intermediate stage, it does appear to potentially hold benefits, and there is now evidence¹⁶ to show that a previous issue related to poor toughness has a possible solution. That specific work identified two welding consumables – one with basically a 13%Cr – 6% Ni composition, and the other with a 1% Cr - 12%Ni - 6%Mo composition. Whichever one would be selected is dependant on the particular situation, as both have been found to introduce compressive and longitudinal residual stress into the weld region. Although this specific work is not complete it has shown a basic consumable design is available, which will satisfy both the distortion and the toughness requirements.

3-D modelling of unit welding

As part of the preparatory work for the build of an aircraft carrier build programme, a series of simulations were carried out by The Welding Institute (TWI). Overall this was very extensive and acted to verify certain processes, and also to indicate potential outcomes on others. Some extensive work was done on a particular deck unit which contained significant proportions of 6 and 6.5mm thick plate. This was the thinnest plating on the carriers.

The base case was defined as being constructed from panels welded from one end to the other. The comparator was constructed of panels welded from the centre out.

Figure 9(a) and (b) show the two cases mentioned. Although the distortion cannot be quantified, a subjective judgement shows that it has been reduced in the centre out situation.

A comparison was made on the von Mises stress and showed a similar, but more obvious, trend.

Concluding comments

There is little doubt that the buckling of thin plate during the shipbuilding process is a complex situation.

However, there is a great deal of prior knowledge that has to be put in place before implementing the outcomes of new research or technology. Unless the basics are in place it is perfectly possible the full potential of new technologies will not be realised.

However, there is a joint responsibility between researchers and builders to work in a more integrated manner to develop beneficial technology or research that at least has the basis for industrialisation.

Acknowledgements

The authors wish to thank BAE Systems Naval Ships for permission to publish this paper. In addition, permission to use the data in Figure 9, was given by Dr. Jageth Mawella, MOD, and this is gratefully acknowledged.

References

1. Kirk, M., C. Conrady, A. DeBiccari and P. Michaleris, 1996, 'Prediction and prevention of excessive unfairness in *Arleigh Burke* (DDG-51)-class deckhouse fabrication', in 'Welding and Weld Automation', Ed. R. DeNale, Pub. The Minerals, Metals and Materials Society, pp67-84.
2. Feng, Z., '2005, Processes and Mechanisms of Welding Residual Stress and Distortion', Woodhead Publishing
3. Masubuchi, K., 1980, 'Analysis of Welded Structures, Pergamon Press.
4. Michaleris, P., 2011, 'Minimization of Welding Distortion and Buckling', Woodhead Publishing.
5. Radaj, D., 2003, 'Welding Residual Stresses and Distortion'. DVS Verlag.
6. Fricke, W., 2003, 'Fatigue analysis of welded joints: state of development', Marine Structures, Vol.16, 185-200.
7. McPherson, N.A., 2007, 'Thin plate distortion – the ongoing problem in shipbuilding', Journal of Ship Production, Vol.23, No.2, May, 94-117.

8. Colegrove, P., Ikeagu, Thistlethwaite, A., Williams, S., Nagy, T., Suder, W., Steuwer, A. and Pirling, T. 2009, 'Welding process impact on residual stress and distortion', Science and Technology of Welding and Joining, Vol.14, No.8, 717-725.
9. Cairns, J. 2012, Unpublished Work, University of Strathclyde.
11. Campbell, S.W. 2011, Unpublished Work, University of Strathclyde.
12. Perryman, I., 2007, Private Communication
13. Gray, T.G.F., Camilleri, D., and McPherson, N.A., 2013, 'Design support on minimising distortion of welded plate fabrications' To be published, Woodhead Publishing
14. Schenk, T., 2011, 'Modelling welding distortion – Influence of clamping and sequencing', PhD Thesis, TU Delft.
15. Davies, C.M., 2009, Imperial College, London, EPSRC Project EP/D060729/1
16. Moat, R.J., Stone, H.J., Shirzadi, A.A., Francis, J.A., Mark, A.F., Bhadeshia, H.K.D.H., Karlsson, L. and Withers, P.J., 2011, 'Design of weld fillers for mitigation of residual stresses in ferritic and austenitic steel welds', Science and Technology of Welding and Joining, Vol.16, No.3, 279-284.

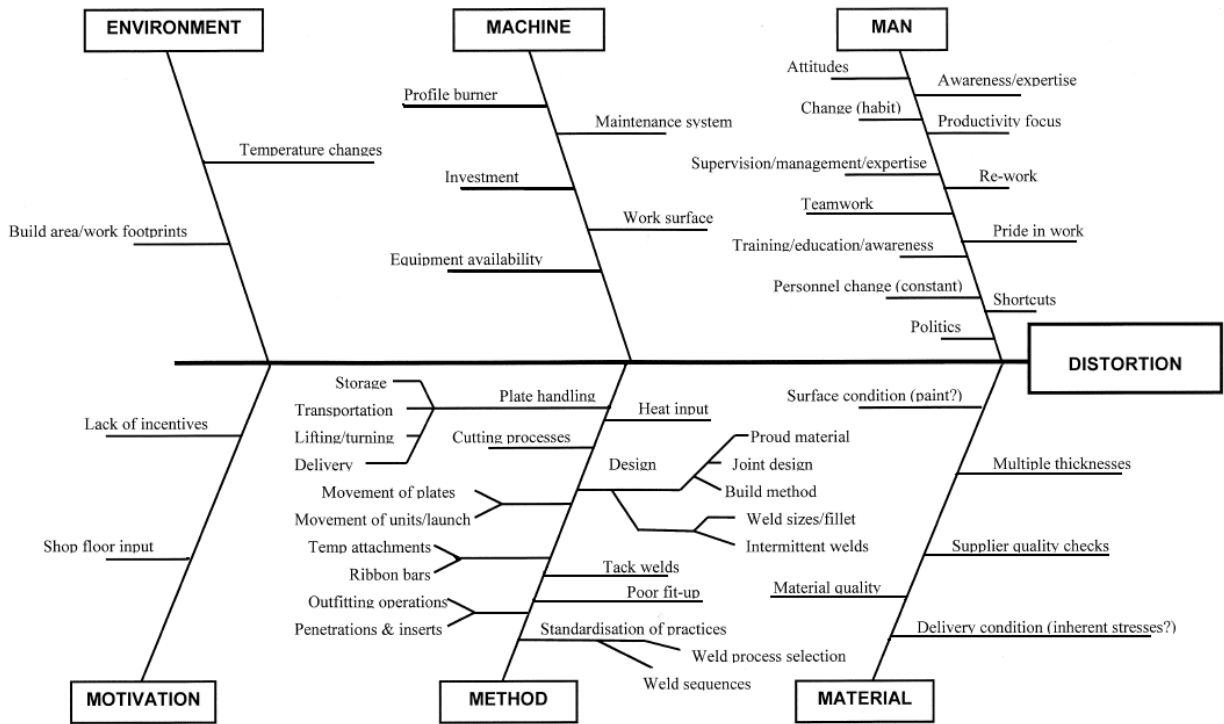


Figure 1 Ishikawa diagram on factors related to thin plate distortion

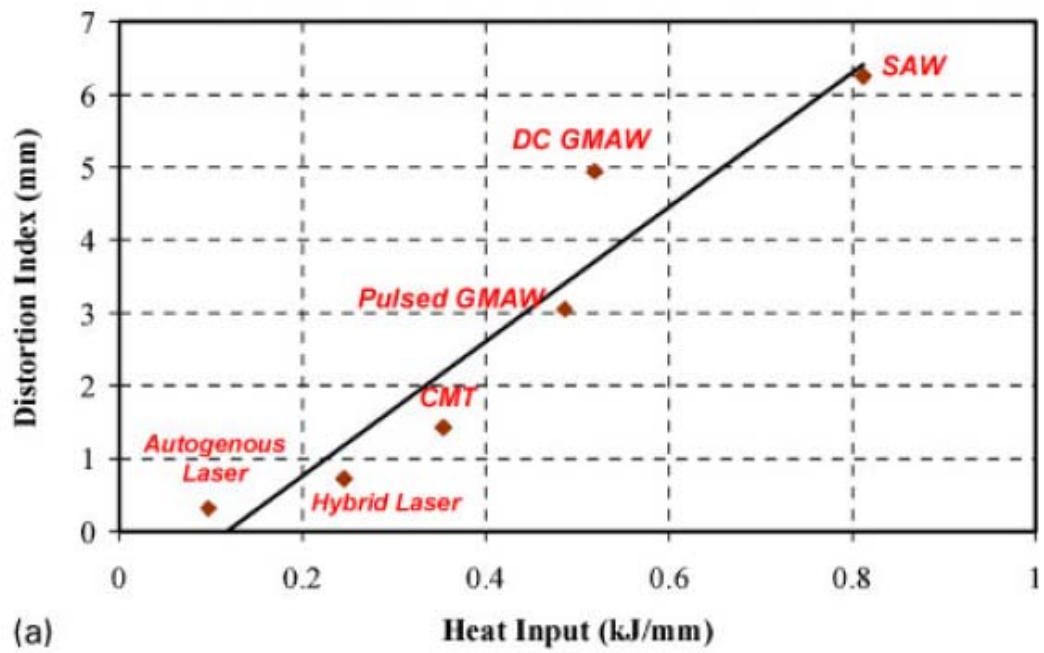


Figure 2 Distortion as a function of heat input from a number of welding processes (8)



Figure 3 Edge rippling on a panel as a result of distortion.

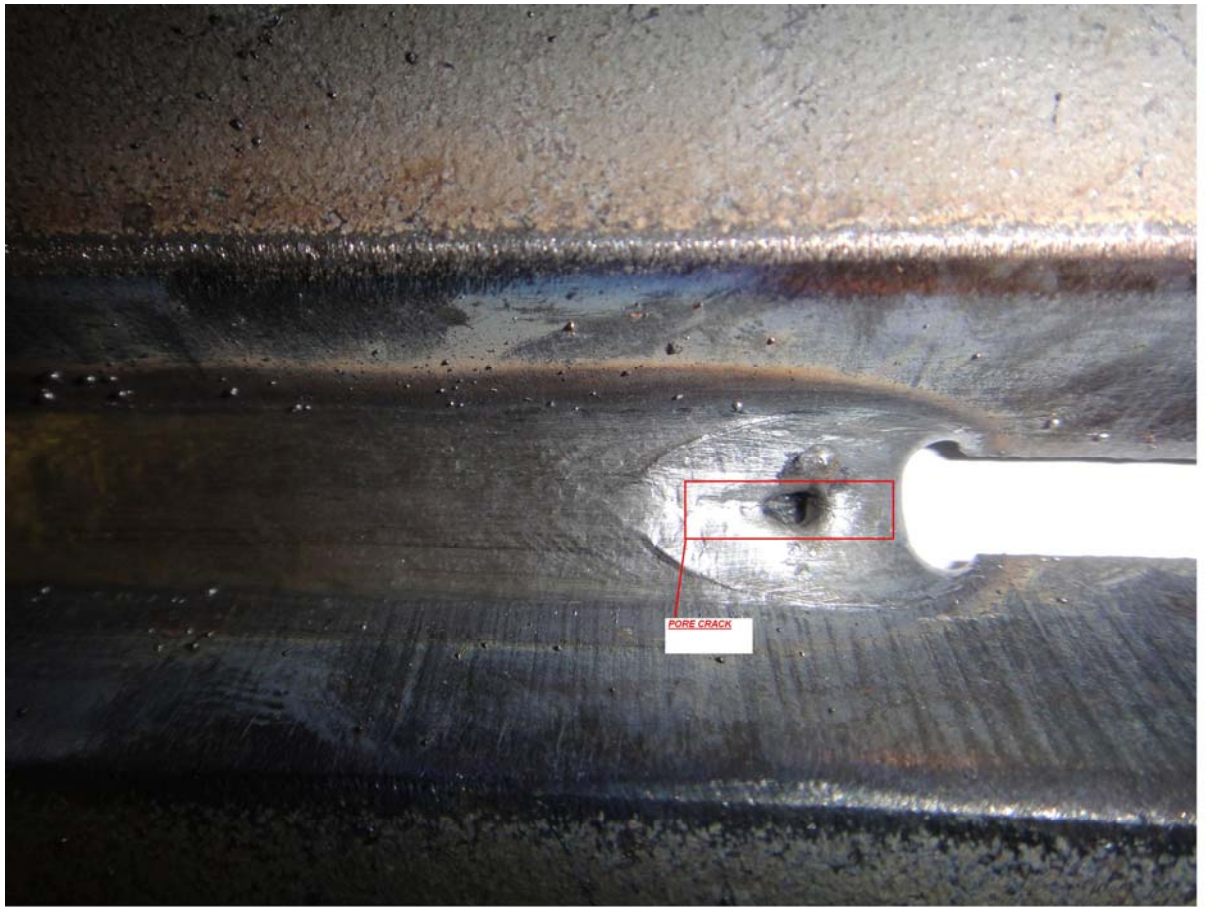


Figure 4 Pore and pore crack associated with weld end.

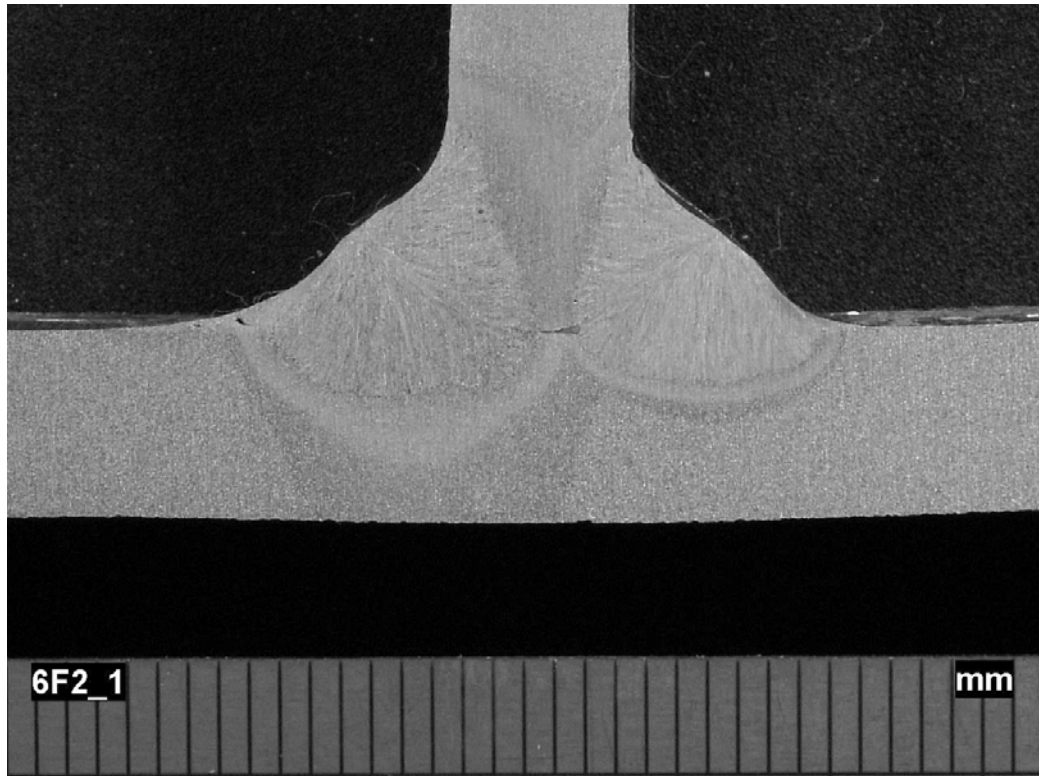


Figure 5 An example of a grossly over penetrated fillet weld.

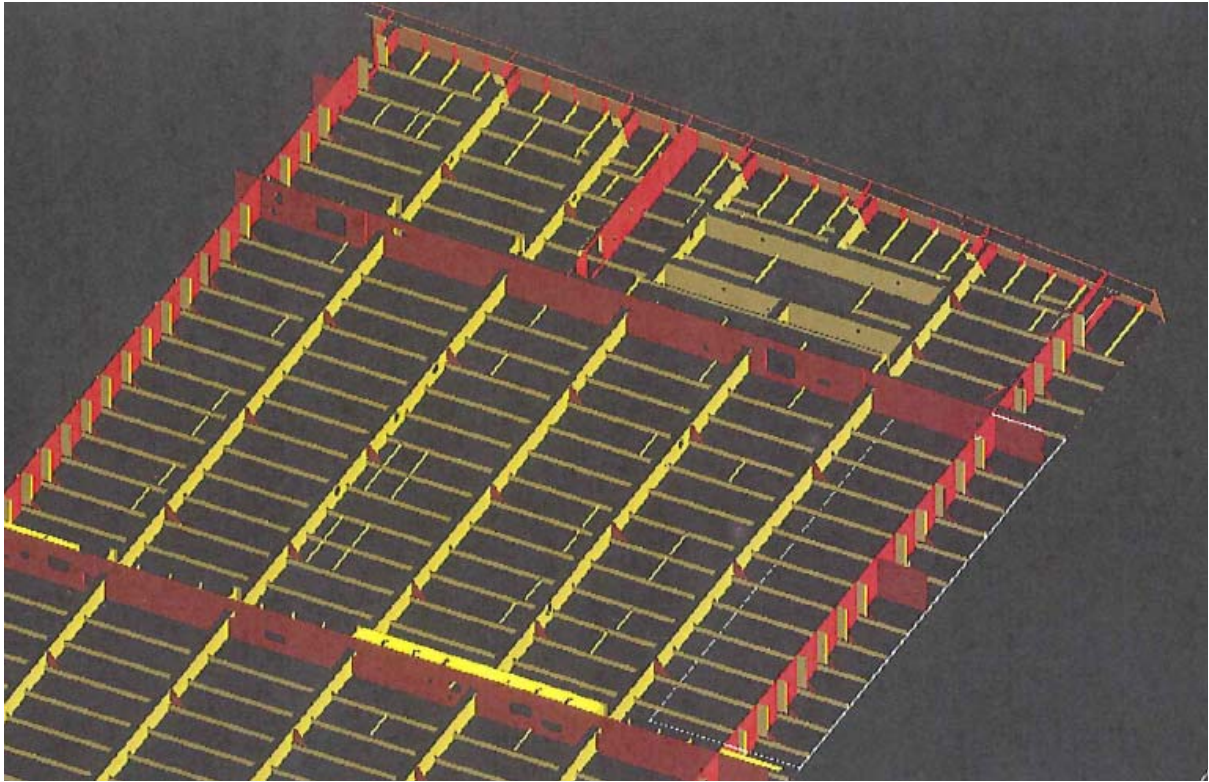


Figure 6 A deck panel which would require welding to be sequenced to minimise distortion, particularly where the carling plates are sited

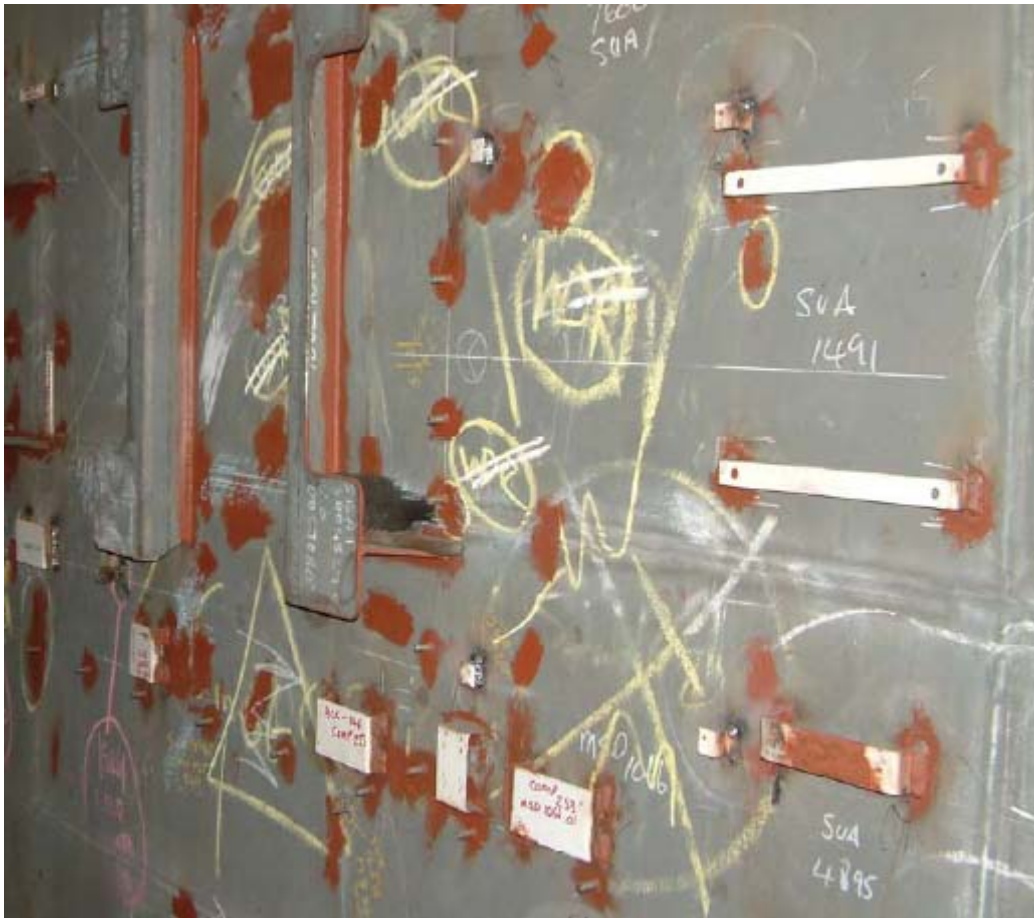


Figure 7 Example of a 4mm thick bulkhead with a high incidence of fully welded attachments.

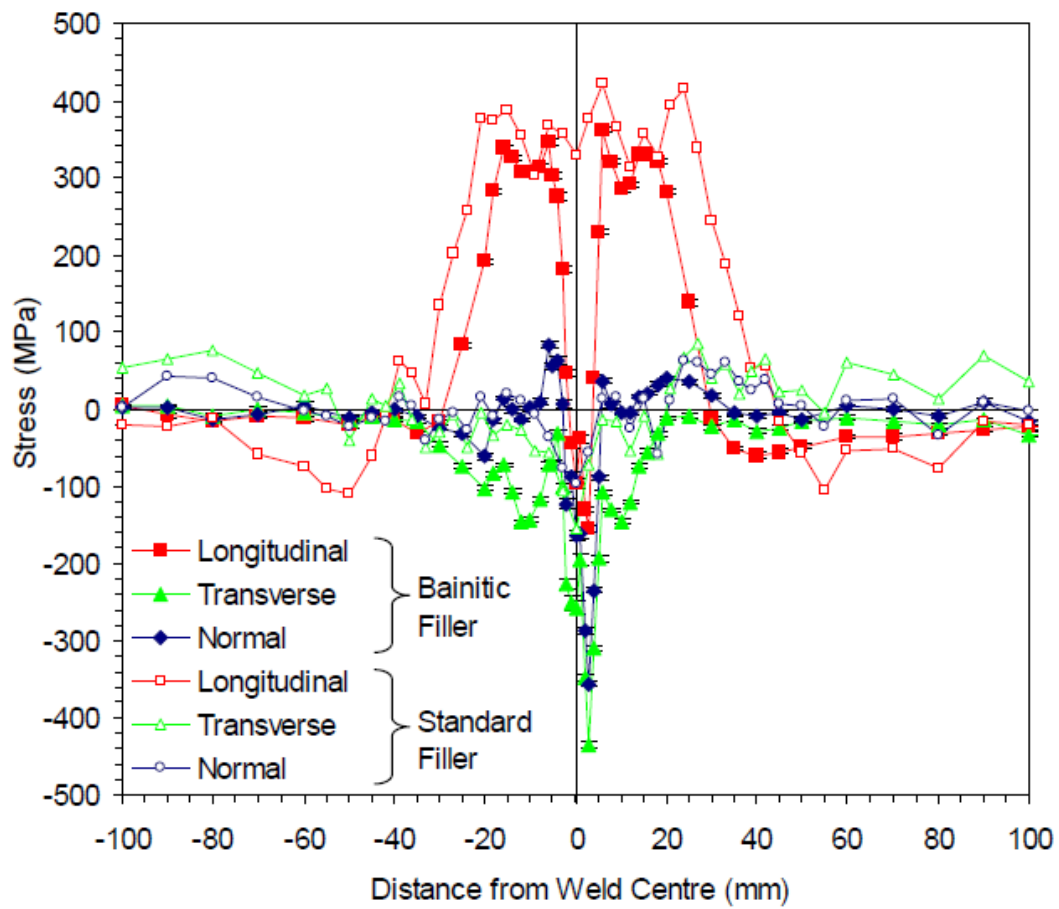


Figure 8 Comparison when using a bainitic welding wire and a standard welding wire. (15)

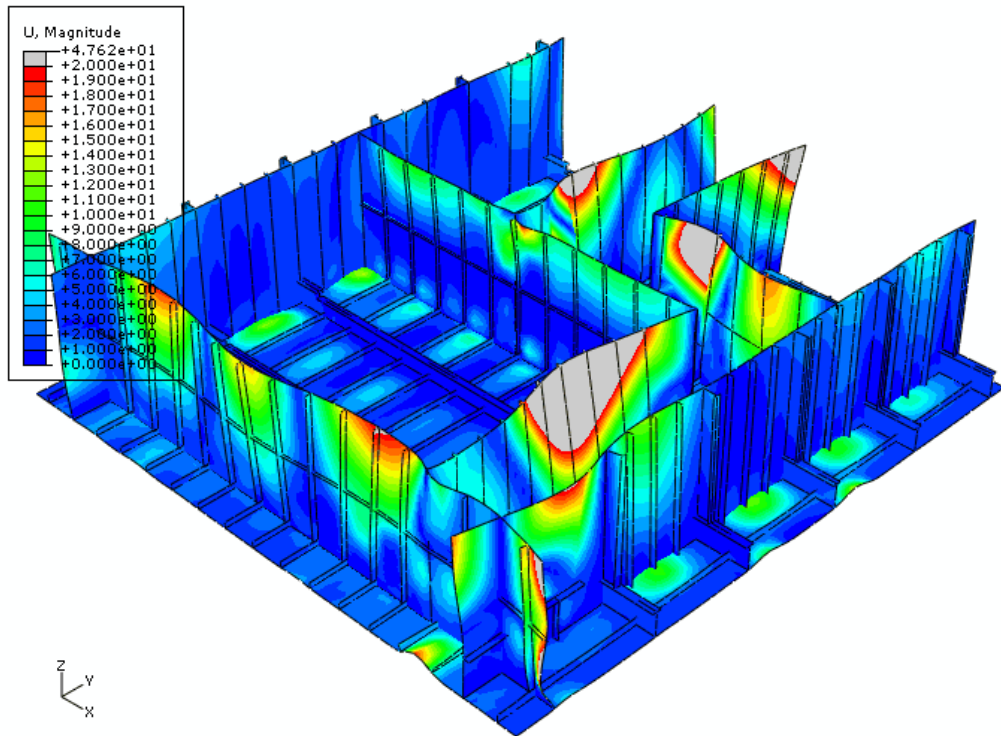


Figure 9(a) Distortion induced in a unit where the panels were welded end to end

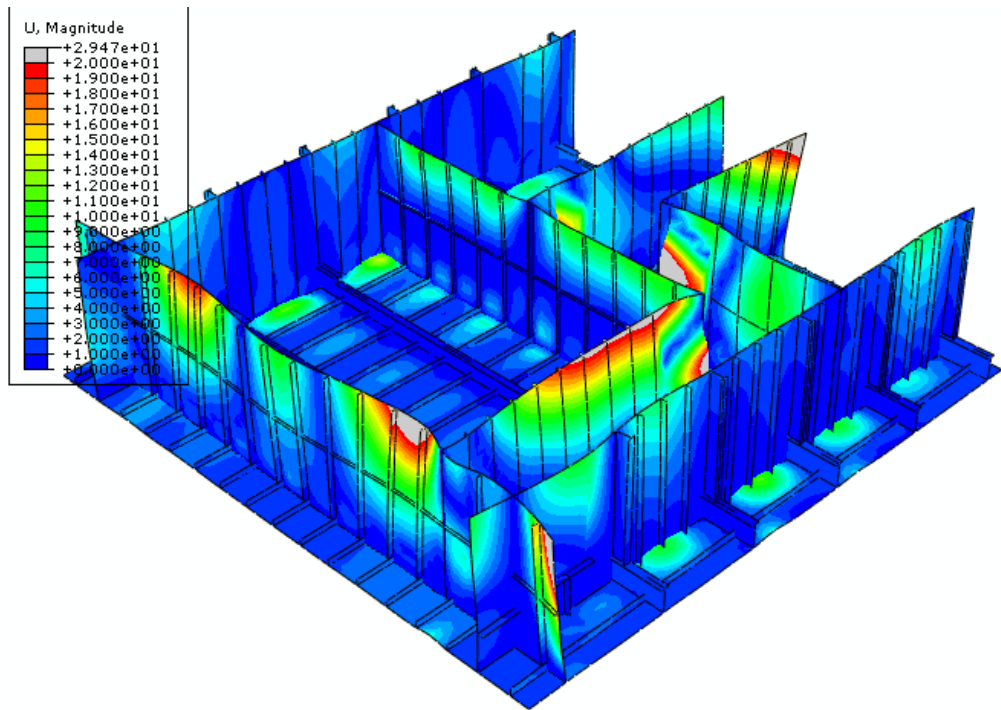


Figure 9(b) Distortion induced in the same unit when centre out welding was used at panel build. A visual comparison shows less severe distortion, than that in Figure 9(a)