INVESTIGATIONS AND SOLUTIONS FOR SUPERSTRUCTURE FATIGUE CRACKING IN UK ROYAL NAVAL VESSELS

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ABSTRACT

The Royal Navy (RN) fleet has a history of problems with localised fatigue induced cracking at the intersection of superstructure blocks with 1 deck. This cracking is believed to be exacerbated by poor alignment of the superstructure blocks with the under-deck support structure and the concentration of weld material in the area.

A number of studies have been undertaken investigating the problem with the overall aim of finding methods of alleviating the problem on existing vessels and preventing the problem on future vessels.

This paper seeks to review and consolidate the work undertaken to date, including reporting on the survey of the forgings fitted to HMS ST ALBANS.

INTRODUCTION

In general, studies undertaken to investigate the issue of fatigue cracking in way of superstructures have concentrated on the Type 23 (T23) frigate fleet which have proved to be particularly susceptible. Since the first of class, HMS NORFOLK, was launched in 1987 there have been numerous design changes introduced on successive ships in an attempt to alleviate the problem. In 2000, the T23 frigate HMS ST ALBANS introduced a pair of forgings at build at the intersection of the forward corners of the hangar superstructure block and 1 deck. In August 2007 the forgings were surveyed to assess the success of this latest trial.

SUPERSTRUCTURE MISALIGNMENT

Superstructures can constitute a severe discontinuity in the ship hull girder. This problem is not confined to the Naval industry and thus, the importance of structural continuity and alignment with supporting structure is well documented[1]. Vertical bending of the hull girder induces a strain in the upper deck which, as a result of the connection, is matched by an equal strain in the bottom of the superstructure sides. The resulting disparity in strain between the top and bottom of the superstructure block causes it to bend in the opposite direction to the hull girder. As a consequence high vertical loads develop, particularly at the block ends, forcing the superstructure curvature to match that of the hull girder.

The superstructure end bulkheads must be designed to bear these loads as must the under deck structure. When the superstructure and hull are brought together, any misalignment causes the high loads to be transmitted through the deck plating rather than directly to the supporting structure designed to bear them.

The high vertical loads will exist whatever the extent of the superstructure but increase with greater length to a maximum when the top of the superstructure becomes effective as part of the hull beam.

TYPE 23 FRIGATES

The studies reviewed in support of this paper date back to 1994 and, as such, are predominantly tasks associated with the T23 frigate fleet. However, the earliest report does identify previous work investigating hull-deckhouse interaction on LEANDER class frigates and investigation of in-service fatigue cracking occurring on TYPE 21 frigates.

The T23 frigate has a blocked deckhouse configuration, consisting of three separate blocks. This was, in part, intended to alleviate the known weaknesses induced by long deckhouses described above. Whilst the vertical loads are reduced by having shorter deckhouses, there are now three areas of concern rather than one.

The investigation of possible fatigue induced cracking on T23 frigates dates back to the design stage of the first of class, HMS NORFOLK. One study cites that the importance of fatigue design was well known and thus Finite Element (FE) calculations were carried out for the T23 01 structure as designed and subsequently built. The results identified that the failure of 1 deck through fatigue cracking would occur early in the ships life at the forward end of the hangar block.

This result initiated the first alteration to the design in an attempt to combat the problem. A prototype 20mm thick gusset plate was added to HMS NORFOLK, along with enhancement of the supporting 1 deck girder. This was just the start and throughout the development of the T23 frigate various investigations were carried out and a number of different solutions trialled on successive ships with varying degrees of success.

FE ANALYSIS

FE modelling has been used extensively at different stages to investigate the problem. Many different techniques have been employed including whole ship global modelling as well as refined local modelling.

As noted earlier the first FE modelling was employed at the design stage. Following the inclusion at build of the prototype gusset plate on HMS NORFOLK, the arrangement was re-analysed and the cracking that has since occurred in service was correctly predicted.

Simultaneously a more thorough investigation was underway examining a number of alternative methods of alleviating the problem. These included:

- Reducing deckhouse side plating thickness;

- Increasing deck plating thickness;
- Adding additional supporting bulkheads;
- Varying the gusset thickness and shape.

The investigation concluded that the optimum arrangement considered was a 6mm curved gusset (soft nosed bracket) supported by a girder under 1 deck. The arrangement was consequently fitted to ships 02 and 04 to 06, in addition to lighter deckhouse side plating.

In 1994 a study was completed which was aimed at determining the fatigue loading response of almost the entire T23 06 hull and superstructure to MoD design standards. In particular the report of the study sought to enable a sound basis for structural safety certification concerning low cycle fatigue fracture of the hull.

The investigation confirmed that the hull superstructure interface was still a primary area of concern with particularly high stresses in the gusset plate at the forward end of the aft hangar block. Despite the high stresses in the gusset plate, adjacent deck stresses were relatively low implying little transference of the stresses via the gusset plate. An experimental case was also run with the gusset plate stiffener removed. This resulted in a small increase in deck stresses but a significant reduction in the gusset plate stresses.

It was concluded that further investigation in this area would be beneficial and thus a number of alternative structural arrangements were analysed including:

- The original model;
- The original model with gusset plate removed;
- Increasing the size of longitudinal stiffeners in 1 deck;
- Increasing the size of longitudinals and the deep beam under hangar forward end;
- Replacing the aft of the hangar block with GRP (Glass Reinforced Plastic);
- Replacing all of the hangar block with GRP;
- Removing the gusset plate and adding a partial bulkhead under the forward end of hangar;
- Retaining the gusset plate and adding a partial bulkhead under the forward end of hangar;
- Connecting the hangar block to the midship superstructure block;

- Adding a deep frame to the sides and roof of the hangar block above the bulkhead at frame 115;

- Adding a deep frame to the sides and roof of the hangar block above the bulkhead at frame 115 and isolating the forward end of the hangar block from 1 deck with a 10” GRP expansion joint.

The methods used calculated design stresses and fatigue life predictions for each of the scenarios outlined above. The report concluded that the three most effective structural alterations were as follows:

- Increasing the size of longitudinals in 1 deck;

- Replacing the hangar block with GRP;

- Connecting the hangar block to superstructure block 3 thus forming a continuous structure.

The results demonstrated that the fatigue life of the gusset plate is severely limited and as such it may be preferable to adopt a design without a gusset plate rather than frequent replacement of the cracked gusset plate.

This study was extended to consider four further specific arrangements:

- Increase in section size of longitudinals;

- Increase in deck plate thickness;

- Increase in section size and plate thickness;

- Increase in section size, plate thickness and removal of gusset plate at forward end of hangar superstructure block.

Increasing both the longitudinal section size and the plate thickness independently was found to give a significant increase in fatigue life of the main strength deck. However, none of the proposed alterations gave a significant improvement in the fatigue life of the gusset plate in comparison to that of the ship. Thus the best option was demonstrated to incorporate increasing longitudinal section size, increasing plate thickness and removing the gusset plate altogether.

It was proposed that future work should concentrate on design of the gusset plate and its attachment to the deck and hangar and further improvements to the joint detail.

The final FE analysis undertaken to date was completed in April 2006. The study investigated the relationship between fatigue life and misalignment of superstructure and supporting structure. It also investigated the following three options for minimising stress concentrations at the forward end of the hangar block:

- 20mm thick deck insert;

- 12mm thick doubler plate;
- Above deck forged insert.

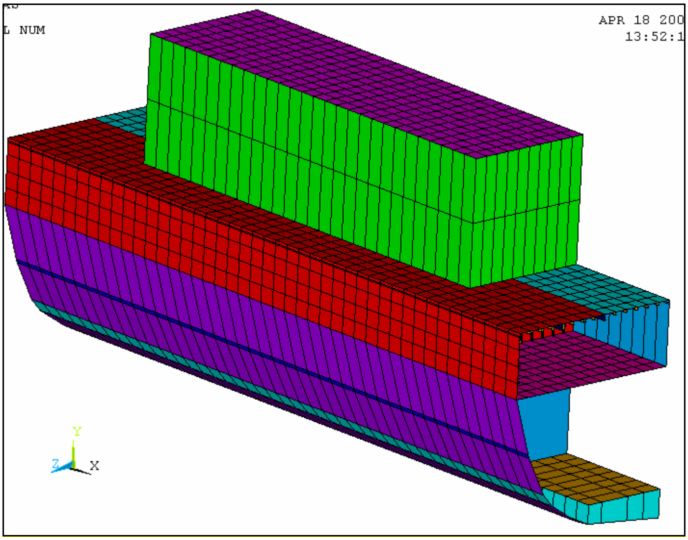

FIG.1 - GLOBAL MODEL (AREA PLOT)

The report concludes the following:

- That even minor misalignment of the superstructure with supporting structure significantly increases stress levels and hence reduces fatigue life;
- That every effort should be made to achieve a high degree of accuracy of alignment at build;
- That where a ship's superstructure is arranged in discreet blocks, careful consideration should be given to the detail design of the end connections.

The study found that the forged insert piece would virtually eliminate fatigue cracking in this area. The use of a deck insert or doubler plate was not found to be sufficiently effective to consider progressing further.

FEASIBILITY OF MODIFICATIONS

FE calculations are very useful for investigating many different design alterations for their effectiveness with regard to alleviating the problem. The models tend to be simplified to some degree and only include those aspects of the design that contribute to the ships structural strength. Once a potential solution has been identified, the feasibility of the solution needs to be investigated with respect to the impact of the alterations on ship arrangements and installation.

In August 1994 Yarrow Shipbuilders were consulted to investigate the feasibility of a number of the structural modifications proposed for the T23 frigates. Following the investigation it was decided to increase the scantlings of the 1 deck longitudinals to 300mm deep fabricated deep girders where possible and the remainder to 10" long stalk tee bars with the exception of those in the main passageway which would remain as 5" long stalk tee bars.

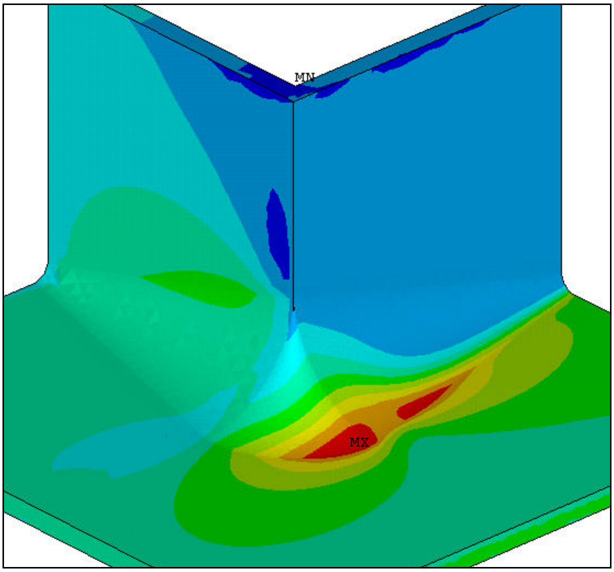

FIG.2 - VON MISES STRESS PLOT ABOVE DECK FORGED INSERT

The feasibility of increasing 1 deck plating thickness was also investigated. An earlier report considers which areas of deck it would be most beneficial to increase in thickness.

SOLUTION IMPLEMENTATION

It has already been mentioned that since the launch of HMS NORFOLK a number of different alterations have been made to the arrangement. One of these changes was a flat bar stiffener fitted to the gusset plate on T23 02, HMS ARGYLL, to assist in preventing cracking of the gusset plates. The flat bar extended diagonally across the gusset plate from the hangar to the deck plate (FIG.3). Following time at sea, survey identified that although no cracking had occurred in the gusset, fracture was evident along the gusset/deck plate weld seam.

In June 1995 a report was written summarising the investigation work to date and proposing a number of structural changes for the final batch of ships to be ordered. The changes proposed included increasing the scantlings of longitudinal stiffeners beneath 1 deck and increasing plate thickness. The report notes that the changes are still insufficient to raise the fatigue life of all hot spots to a full ship life so consideration should be given to opportunities for repair by replacement as appropriate. It was recommended that the changes are only considered for the latest batch so further investigation ought to be done to remedy fatigue life issues on in-service ships.

FIG.3 - T23 HANGAR BLOCK GUSSET PLATE

These structural changes were later endorsed in addition to continuing with work to refine the design of the gusset plate at the forward end of the hangar block.

MISALIGNMENT SURVEYS

With the aim of quantifying the impact of misalignment on the fatigue life of superstructure/1 deck intersections on T23 frigates, a task was initiated in 1996 to determine the extent of any structural misalignment and investigate its influence upon structural failure. The task was carried out in three main phases:

- Development of a reliable and accurate, non-destructive, survey and reporting method;
- Survey of the Type 23 fleet;
- Statistical analysis of the results to identify any correlation between the structural misalignment and structural failure.

The survey and reporting method included techniques to measure alignment of the superstructure blocks with under deck supporting structure and superstructure bulkhead deformation. A number of techniques for both measurements were identified and reviewed.

Following the technique review, an assessment of the techniques was undertaken on HMS LANCASTER in April 1997. The results of the survey were mixed and exposed a number of problems. The trial survey concluded that alignment measurements could be taken using ultrasonic techniques, where possible, and supplemented by using weld seams as a datum when required.

The first of the T23 fleet structural misalignment surveys was carried out in August 1997 on HMS ARGYLL at Devonport Royal Dockyard. Despite the previous trial, the success of the survey was limited with few measurements successfully recorded. The survey did however identify some significant misalignment with over half the measurements exceeding tolerances defined in applicable standards at the time. Superficial examination of the bulkhead deformation measurements suggested that the deformation was as a result of trying to achieve alignment at superstructure corners.

The report of this survey, dated January 1998, concluded that due to the difficulties experienced and limited opportunities to carry out further surveys the study was not worth pursuing. The limited results collected were insufficient to determine whether misalignment had a significant influence on cracking.

FABRICATED CORNER SOLUTION

Earlier work had identified that whilst the gusset plate had reduced the incidence of fatigue cracking it had not been a completely successful solution. The fatigue life of the gusset plate itself was found to be reasonably short and thus required regular repair or replacement. Thus a more effective solution was still required. It was thought that a node corner casting might be particular effective as it should ensure precise alignment of the structure above and below deck due to its shape. In addition it would improve the fatigue classification of the joint by offsetting the weld detail away from the corner stress concentration.

In 1997 a specialist casting manufacturer was approached to develop a design and in doing so investigate the optimum “wing length” that could be achieved consistent with producing satisfactory casting and material properties. The report of the study gave details of the investigation which included production of three prototype castings with varying wing lengths, evaluation using a variety of non-destructive techniques, mechanical testing and solidification simulation.

The report concludes that the initial investigation was successful and that further development should be carried out. It recommended that further work should include:

- Obtaining fatigue properties for the cast material from the test bars;
- Simulation iterations to evaluate shrinkage present in the casting;
- Sequential production of three further castings with 200mm wing lengths to optimise the casting process with further mechanical property testing;
- Generation of S/N fatigue data for an actual cast joint for comparison with that of a welded joint.

Simultaneously interest was generated in the possibility of using a forged node rather than a casting. Although original concerns associated with the material flow to the extremities of the wings in the castings were unfounded, it was believed that a forging might eliminate casting imperfections, and the need for runner cores for a comparable cost. Due to this the forging concept was progressed instead of the additional casting work.

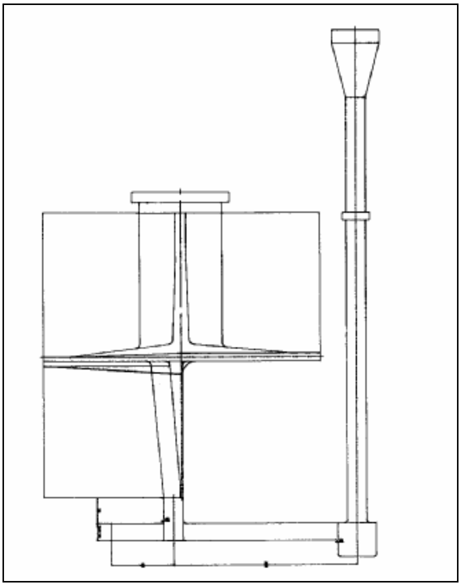

FIG.4 - CAST INSERT

Initial consultation with a forge suggested that production of a forged and machined node could be achieved for a comparable price as the cast item. It was believed that this would allow production of a node with favourable geometry and without casting imperfections which could seriously compromise the effectiveness of the node.

Work was initiated to demonstrate that a forging could be produced suitable for installation on a T23 frigate at build and in refit. This included production drawings, manufacturing procedures, ship installation drawings (including weld details) and manufacture and testing of two forgings.

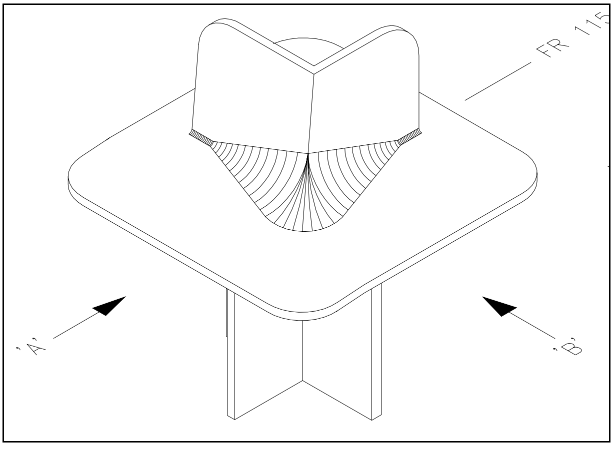

FIG.5 - FORGED INSERT

Following the success of the testing of the first forging a change was made to the requirements for the remainder of the task. It was concluded that the second forging would become a starboard ship-fit item rather than a pre-production item and a third forging would be produced as a matching port ship-fit item.

The second and third forgings were installed in HMS ST ALBANS at build (launched in May 2000). Visual survey of the upper surfaces of the forgings was undertaken in 2007 which concluded that there were no signs of cracking or fatigue. Unfortunately no access to the underside of the forgings could be achieved.

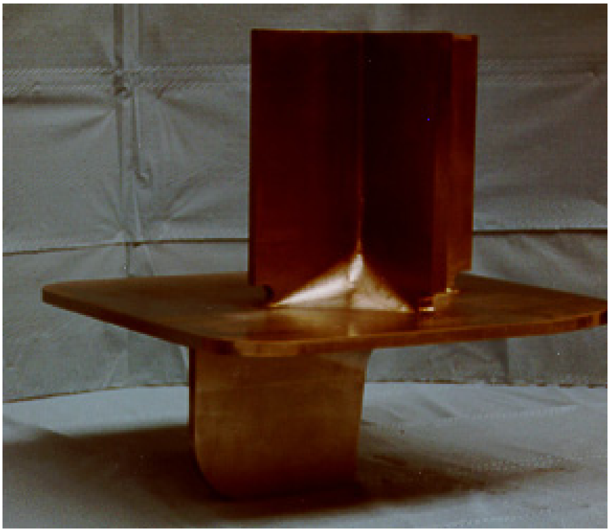

FIG.6 - FORGED INSERT (INVERTED)

The potential effectiveness of corner node forgings is now well recognised and is being incorporated into new vessels at the design stage. The Type 45 superstructure is continuous up to 01 deck, which is subjected to significant longitudinal bending loads compared to previous Frigates and Destroyers. The join between the superstructure front and 1 deck, as a discontinuity, is subjected to a stress concentration, which is particularly severe at the side shell. This area is further complicated on the Type 45 by the presence of a knuckle in the side shell and a block butt forward of the superstructure front and watertight bulkhead beneath. For the above reasons a forging was incorporated rather than the traditionally used thick gusset plate in the side shell.

CONCLUSIONS

Over the last 25 years or so extensive work has been undertaken to better understand the issues surrounding fatigue cracking associated with the intersection of superstructure blocks and 1 deck on various vessels.

There seem to be two main conclusions that can be drawn from the completed work. Firstly, every effort should be made to ensure precise alignment of superstructure blocks with under deck supporting structure at build. Secondly, careful detail design of the connection can significantly increase its fatigue life.

To date, excellent results have been achieved with the use of node forgings fitted to HMS ST ALBANS. The forgings have been very effective in two ways. The shape of the forgings means that alignment of the superstructure with underdeck supporting structure is all but guaranteed. Secondly, by careful design of the forging shape and displacing the welds away from the high stress corner, a significantly improved fatigue classification can be achieved. That is not to say that the quality of the welds ceases to be of interest, every effort should still be made to ensure high quality welds.

The forgings fitted to HMS ST ALBANS are still relatively young. Continuing to monitor the forgings throughout the life of the ship would allow a better understanding of just how effective they have been. Likewise monitoring of the forgings on T45 would add depth to the knowledge.

Production of forgings is still a relatively costly process and so any means of reducing costs would be beneficial. It has been suggested that it might be possible to achieve good results with a welded insert. Using similar geometry to that of the forging a welded insert could be produced away from the ship in an ideal environment where every effort could be made to ensuring high quality, full penetration welds that can be ground smooth.

Whilst inclusion of node forgings at build is relatively straight forward, retrofit of forgings to existing ships is unlikely to be without complication. If retrofitting forgings of the same design to the remaining T23 fleet is not feasible then work may need to continue to find an alternative. One option may be to consider an alternative design corner node insert that consists of just the deck and above deck structure. This should ease the installation of the insert; however the effectiveness of this design would need to be investigated.

RECOMENDATIONS

- Investigate the effectiveness of a welded insert relative to the forging with an aim to reduce costs;
- Investigate the feasibility of retrofitting forgings to existing ships;
- Draw together experience and lessons learnt from the development of the T23 forgings and T45 forgings to produce design guidance;
- Investigate effectiveness of topside only corner node inserts with a view to easing fit to existing ships;
- Monitoring of the ST ALBANS and Type 45 forgings to build a base of knowledge;
- Compare extent of misalignment with and without forging to quantify the effectiveness of the forging at ensuring alignment of the structure.

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References

1. Principles of Naval Architecture Vol 1 Stability and Strength, SNAME 1988.

The work that has motivated this current study has originated from unpublished work.

AUTHORS' BIOGRAPHIES

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