Managing Innovation using the Norman Lady and Höegh Galleon as Case Studies

By Jon Andreassen, [1] and Sverre Valsgård [2]

Abstract

During maintenance work on LNG/C Asake Maru in August 1998 widespread cracking were detected in her 9% Ni-steel spherical cargo tanks. Subsequently, the same type of cracking was detected in the cargo tanks of her sister vessel Norman Lady, but generally to a lesser depth. The metallurgical examinations carried out by DNV concluded that the cracks most probably were caused by hydrogen induced stress corrosion cracking (HISSC), and that no indication of fatigue crack growth could be seen. This opened the possibility for potential repair and refurbishment's of the vessels.

The possible repair of the cargo tanks were the crucial issue in the process. Strength analyses of the tanks were carried out by DNV. The paper also shows how these calculations were carried out with respect to the relevant design criteria, i.e. nominal stress values according to USCG, IGC and DNV criteria, fatigue life sufficient for another 20 years of operation, crack propagation rates and critical crack lengths, leak-before-failure and buckling strengths

The process to determine if the tanks could be technically and economically repaired and the philosophy behind the selection of alternative repair methods are outlined. The evaluations carried out by the owner is described as well as the scope of metallurgical, hydrodynamic and structural analyses carried out prior to repair decisions, and after repair in order to documents the result for both for the tanks and the necessary hull and systems refurbishments. The work was a joint effort between the owner, Leif Höegh & Co, the repair yards, the DNV's Marine Consultancy arm and the DNV Class Society branch with plan approval and field surveyors. All parties worked closely together to achieve the final positive result.

1. INTRODUCTION

The Norman Lady and the ex LNG Challenger are the two first large LNG carriers built to the MOSS Spherical design, and were subsequently delivered in 1973 and 1974. (See Particulars Chapter 5) At that time Leif Höegh & CO ASA (Höegh) was the owner of the Norman Lady and P&O was the owner of the LNG Challenger.

Being the prototype vessel, the Norman Lady was subjected to quite rigorous pressure testing of all the cargo tanks, while her sister, the LNG Challenger was not subjected to the same testing regime.

Both vessels had a somewhat nomadic trading pattern the first years, engaged with partly spot-cargoes of mainly LPG combined with lay-up periods. From 1977, the Norman Lady entered into the ADGAS' LNG trade between Das Island in UAE and Japan, and remained under that charter party up to mid 90ties, when she was engaged by Enagas SA for another 13 years contract of LNG-trading.

The LNG Challenger, which changed her name to LNG Pollenger, continued her "short-contract" trading, but mainly in LNG-trades up to 1987, when she was sold to a Japanese Consortium, renamed the Asake Maru, and put into service mainly between Japan and Indonesia. Later, in 1998, she changed name again, this time to the Mystic Lady, (after the Mystic River, where Cabot's LNG terminal is located in Boston) as she was supposed to be employed in a long-term charter contract with CABOT LNG of Boston, MA after an extensive refurbishment program.

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[1] Captain, Project Manger Newbuilding, Höegh Fleet Services AS, Oslo

[2] Senior Principal Engineer, Technical Solutions, Maritime, Det Norske Veritas, Hoevik

At the end of the Norman Lady's engagement in the ADGAS' LNG Project, Höegh engaged Det norske Veritas (DNV) to undertake a Lifetime Extension Study for the vessel, in order to prepare her for another long-term employment contract. The study, which emphasized and focused on the strength of the hull and cargo containment system, concluded that, by relatively simple means, the vessel's life-expectancy could be extended significantly.

In late August 1998, as Höegh was about to take technical management of the Mystic Lady, (ex LNG Challenger), a non destructive test (NDT) of the cargo tanks revealed many smaller hair-line cracks along the welds of the tanks. Several investigations were conducted, and it was soon concluded that the cracks were related to the environment inside the cargo tanks during operation of the ship, or even as far back as during the building of the vessels. The cracks were classified to be Hydrogen Induced Stress Corrosion Cracks (HISCC), which may have been created under circumstances where water had been present inside the tanks for some time (at least 14 days). It was further concluded or anticipated that the cracks were found in all internal welds of all the five tanks on board.

This was of course very alarming news to Höegh, being the operating owner of the sister vessel, the Norman Lady. Needless to say, it was difficult to believe that there should be cracks in the cargo tanks of the Norman Lady. At every dry-docking in the past, the cargo tanks had been checked in accordance with DNV's requirements, with procedures for ultrasonic and liquid Dye Penetrant testing (DP), and without any indications of such cracking.

As feared, the same kind of cracks was discovered on the Norman Lady, although not to the same extent as on the Mystic Lady. It was decided that by the first opportunity the tanks should be gas-freed and checked. So in October 1998 this work started with NDT personnel from DNV.

The tanks were gas freed, and DP was applied along welding seams on a spot-check basis. Steel surface was cleaned with steel brushes to remove oxidation. On completion of the spot-wise control of the first tank, it was concluded that the tank showed no signs of the reported defect, except for two very minor indications that were difficult to interpret. It was decided to grind off the mill scale in these areas for further check.

This changed the picture completely! Surface cracks could now be seen clearly, running parallel to the weld, in the heat affected zone, abt. 2 mm from the weld fusion line. The tested areas were done all over again, this time by grinding. It appeared that all the tanks showed this defect, evenly distributed all over. From spot checks of abt. 8% of the total amount of welding, it was estimated that 50-60% of the area was affected.

The reason for the difficulty in detection, we know now, is that the 9% Ni steel has a very tough mill scale, due to the double normalisation it has been through at the steel mill. Over all the years with routine checking, also with DP, this has apparently been under-estimated with regard to its capacity to camouflage the HISC Cracks. These events, both on the Norman Lady and the ex LNG Challenger, led to a process where the best available resources and know-how were utilised, in order to address the problem and develop procedures to resolve the cracks in the cargo tanks, and also to ensure the a reoccurrence would not take place.

This paper emphasizes on the process of realistically analysing the opportunities and limitations of the two vessels. Sound innovative thinking, and a scientific approach, combined with extensive experience and know-how in LNG-shipping, enabled Höegh to take the necessary actions to bring the cargo tanks back to their full design potential, and also to carry out the reinforcements and refurbishment necessary to operate the vessels for another 20 years.

2. HÖEGH GALLEON

In 1998 the vessel was taken to Kawasaki Heavy Industries Shipyard in Kobe for a major refurbishment before she should enter into a T/C with Cabot, a Boston-based LNG trader. During this refurbishment, in the summer of 1998, Höegh and Mitsui OSK Lines agreed that Höegh should take technical management of the vessel. The ship was again renamed, this time to Mystic Lady (after the Mystic River, where Cabot's LNG terminal is located in Boston).

Höegh acquired the vessel on December 4, 1998 from Mystic Gas Transport SA (Managed by Mitsui OSK Lines) after their decision to demolish her. Höegh was of the opinion that the decision to demolish the vessel was made without elaborating all possible opportunities for future utilisation. As she is the sister vessel of the Norman Lady, Höegh had plans to utilize much of the components on board as spare parts for her sister, but it became more and more challenging to rebuild the cargo tanks, and refurbish the rest of the vessel in order to prepare her for another long-term charter party.

Subsequently, the Mystic Lady was taken from Japan to Johore River in Malaysia, where she was laid-up. Various inspections and studies with regards to a future re-activation were conducted. Apart from the cargo tanks the vessel was relatively sound, and the reports from DNV after their Hull Evaluation Study and Condition Assessment Program (CAP) confirmed this. Most important - besides restoring of the cargo tanks - was the necessity of renewing the coating system in the ballast tanks and various dry-tanks and pipe ducts.

As mentioned above, the vessel was undergoing a refurbishment in Kawasaki Heavy Industries' Kobe Yard from May 1998. In addition to detecting the tank cracks, several systems on board were totally upgraded with new, modern components, and others were repaired/refurbished as found appropriate, planning for a future shipment contract for the vessel lasting up to 10 years.

The fact that this was done was partly the reason for Höegh to decide to keep the vessel going, and this was hence also the beginning of the total rebuild of Höegh Galleon. Comprehensive feasibility studies were made, and it was demonstrated that the economics in the project were promising, provided that a reasonable solution could be fond to restore the cargo tanks.

2.1 Technical Evaluations

The most demanding operation of the whole project was of course the rebuilding of the cargo tanks. In order to achieve that, three different technical solutions were discussed, all having their advantages and disadvantages.

Alternative 1

- Replacing the Cargo Tanks with new aluminium tanks. With new aluminium tanks, the vessel would have had a cargo containment system with a life-expectancy in excess of the 20 -25 years as anticipated for the rest of the vessel, where the ballast tanks and hull then would be the crucial areas.
- Several shipyards were able to undertake building of the new tanks, but this solution was rejected due to the extensive cost of new tanks.

Alternative 2

- Replacing the Cargo Containment System with new GTT Membrane System also including renewal of whole fore-section of the vessel. This alternative came late in the process, and may have been somewhat controversial. Daewoo Heavy Industries, Okpo (DHI) proposed to fit a completely new forepart of the vessel. This conversion would include a new containment system of the GTT Membrane System fitted into a new hull, from the engine room bulkhead to the bow.

- The new hull would be built according the latest design for DHI LNG tankers, but with the same dimensions as for the present hull of the Höegh Galleon. For a while this alternative looked very tempting, but the price for the "new" ship became too high, and the idea was abandoned.

Alternative 3

- Rebuilding of existing the cargo tanks by a complete excavation of all internal welds and then rewelding the cargo tanks.
- During the period after the cracks had been discovered in August 1998, several investigations and analyses were made on the phenomena, and during this process Höegh came in contact with Chicago Bridge & Iron (CBI). CBI proved to have experienced staff of metallurgists and welding engineers with extensive knowledge pertaining to the welding, inspection and control of 9% Nickel Steel constructions, which is widely used in LNG onshore-tank farms, as well as in the tanks of the Höegh Galleon and the Norman Lady.
- Further studies, tests and analysis were made, both in the welding laboratory of CBI and in the metallurgic laboratory of DNV, and it became more evident that this alternative would bring the vessel back to its "full design potential" if the re-building procedures were followed. In this process DNV and CBI were working closely together with Höegh in developing the welding-testing-and control procedures for the cargo tanks.
- DNV also performed numerous of calculations of the strength of the cargo tanks, in order to ensure that rebuilding the tanks according the procedures laid down, would restore the tanks integrity, and comply with all relevant requirements given by USCG, IGC and DNV.

As the damage assessment and calculation methods for the Höegh Galleon and the Norman Lady are similar, these are combined in a separate chapter at the end of this paper.

2.2 Pilot Project

In order to test out all the procedures apart from the laboratory testing, it was decided to conduct a Pilot Project, where ¼ of one tank would undergo a complete restoration of all welds. In late October 1999, the vessel was shifted from Johore River to Karimun Sembawang Shipyard, and CBI was engaged to carry out the pilot project. Very early in the process it was clear that the procedures made for this project was working well, although some adjustments were made along the road. On December 31st. 1999 the pilot project was successfully completed.

The Pilot Project clearly demonstrated that the cracks in the LNG tanks could be restored to its full design potential, and below we are giving a brief description of the procedures used in this process.

2.2.1 Crack Detection

The Alternating Current Field Measurement (ACFM) method was used to examine all welds in the quadrant. The HAZ along both edges of the welds were examined. Approximately 1100 meters of HAZ was examined using ACFM. The ACFM examination confirmed the presence of HAZ cracking for all welds. It should be noted that none of the cracks could be seen with the naked eye. The DP method could also have been used to detect the cracks but it would have required substantial work to prepare the rough surface for examination. A useful characteristic of ACFM is that it does not require the surface of the weld or HAZ to be conditioned by grinding.

The ACFM method was also used to measure the depth of cracking. The depth of cracking varied but was typically in the 4-6 mm range. Typically, circumferential welds were found to have slightly deeper cracks than vertical welds. The deepest cracks found (about 9 mm) were located in the circumferential equator course welds. It should be noted that a substantial portion of the two equator course welds had been previously gouged. This was apparently done during the time the ship was examined in Japan. ACFM was found to be a reliable and efficient inspection method for detecting the cracks and for determining their depth.

2.2.2 Crack Excavation

Cracks were removed using a combination of carbon arc gouging and grinding. The initial excavation was done primarily using the carbon arc gouging process. The excavated area was also roughly shaped by carbon arc gouging to facilitate good welding groove conditions. It was sometimes possible to visually see the crack in the rough gouged surface if it was not fully removed. After carbon arc gouging, the excavated groove was ground to remove rough edges and surface oxidation to prepare the cavity for DP examination. The prepared cavity was examined by DP to confirm the removal of all cracks. Since the cracks were typically very fine, the DP inspection was done with an extended dye penetrant dwell time of 1 hour minimum. The extra time improved sensitivity by allowing the dye to penetrant into very fine tight cracks. Often after initial DP examination, remnants of cracks not fully removed were still visible in the cavity. These were sometimes lengthy areas along the edge of the excavation or could also be very small intermittent areas. All such areas were removed by grinding and or gouging and the DP examination was repeated until the cavity was found to be free from of cracks.

2.2.3 Welding

The excavated areas were welded when the cavities were confirmed by DP to be free of cracking. Two welding procedures were available for use. The primary welding procedure was intended for use with direct current electrode positive (reverse polarity). An additional using alternating current was also available for use if magnetised plates were found. Magnetism can make welding with direct current very difficult. No magnetised areas were encountered so this procedure was not used. Both of the procedures were limited to a maximum depth of 15mm. As no cracks were found that exceeded this depth, all welding was done using existing procedures.

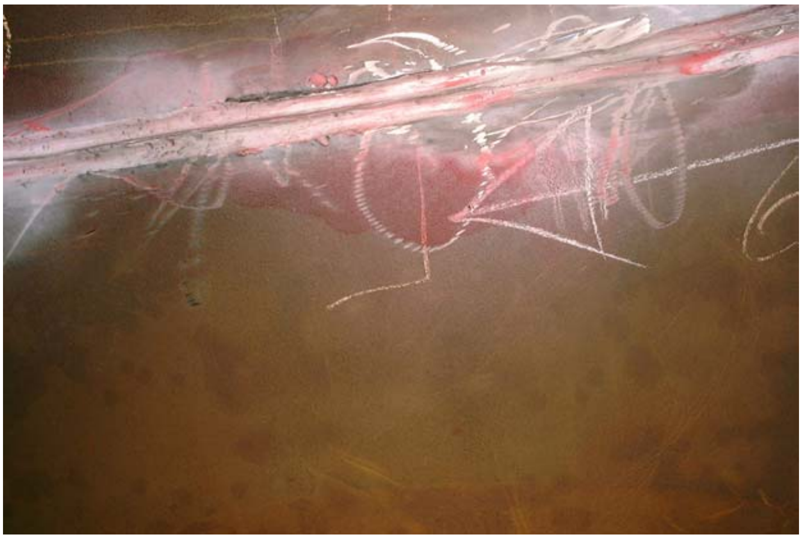
The welding procedures required restricted heat input so as to reduce heat build up during welding. Similarly, welding interpass temperatures were restricted to a maximum of 65º C. These measures were taken to reduce heat build up on the outside of the weld so as to minimize melting of the external insulation. Random checks of the insulation showed melt back of approximately 25 – 30 mm maximum.

The reduced heat input requirements for welding typically resulted in a minimum of two passes and often three or more passes to restore the excavated area to full thickness. Vertical welding was typically done using 2.4 mm and 3.2 mm diameter electrodes. Circumferential seam welding was typically done using 3.2 mm and 4.0 mm diameter electrodes. ESAB OK92.55 electrodes were used for all welding.

Most excavated areas were prepared and welded as two separate grooves along each side of the original weld joint. There would typically be a remnant of the original weld remaining between the two grooves. Fig 1 depicts a typical weld of this type.

When the excavated areas were deep and wide resulting in only a thin sliver of original weld remaining between the two HAZ excavations, the two areas were combined into a single excavation. The equator areas typically had such deeper cracks and these areas were combined into a single excavation that included both original weld HAZ areas. Fig. 2 shows the combined excavation for the equator areas during welding.

2.2.4 Pictures



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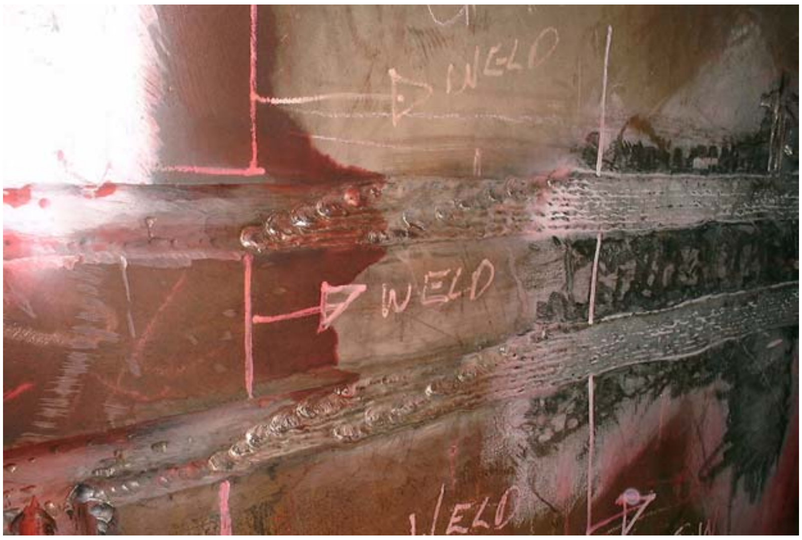

Fig. 2 shows the combined excavation for the equator areas during welding

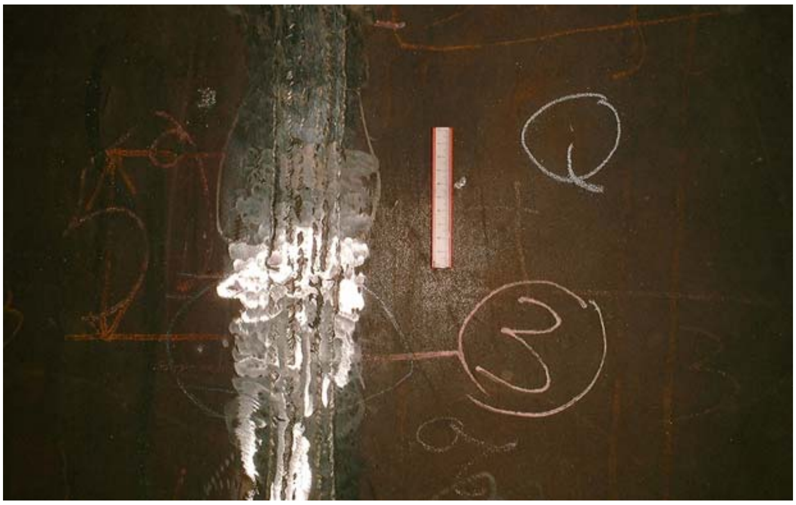

Fig. 3 show typical areas after welding and grinding

Fig. 4 shows a welded area completed & DP examined

No unexpected difficulties were encountered during welding. The resulting welding appeared to be of high quality. Completed welds were ground so as to prepare them for DP examination. Figure 3 show typical areas after welding and grinding.

2.2.5 Weld Examination

Following welding, the completed welds were first DP examined and then Ultrasonic Testing (UT) examined. The DP examination occasionally showed small welding defects that needed to addressed by grinding or to be rewelded. No cracking was found in any of the welds examined. Figure 4 shows a welded area that has been DP examined.

UT was performed on 100% of all the rewelded areas, using a procedure developed for the Pilot Project. This procedure permitted the UT examination to be done from the inside surfaces of the sphere. No access to the outside surface of the sphere was available as these areas were covered with insulation. Creep wave transducers were used for the examination. Calibration blocks were made from welded 9% Nickel steel to simulate the type of defects anticipated in the welds.

These examinations revealed a total of 6 rejectable indications ranging from 50 to 100 mm in length. The defects were slag and lack of fusion along the edge of the repair cavity. No evidence of cracking was found in the welds.

2.2.6 Hardness Testing

Hardness testing was conducted in many of the welded areas. The results are well within the maximum allowable hardness during construction, which was 450 HV.

2.3 Conclusions

The procedures developed to perform the rewelding showed to be effective in detecting the cracks, in removing the cracks and in rewelding of the affected areas. The procedures employed are relatively standard techniques and can be readily accomplished by skilled craftsmen properly supervised. The manpower required to accomplish this work was reasonable in size and was able to complete the work in a relatively short time frame of approximately 7 weeks which was a very reasonable time frame. All tests carried out to the restored welds proved to have been successful, and then the vessel was ready to undergo a full-scale restoration.

2.4 Hull

A hull structural re-analysis was performed. The objective of the work was to document the effect of the hull upgrading carried out following the CAP survey and additional local strengthening for increased fatigue life. The target additional fatigue life was another 20-30 years of operation in worldwide environment.

The analyses were based on measured scantlings; steel renewal and upgrading following the CAP survey carried out in January 1999. The valid Rules for the ship are the 1971 Rules and no upgrading is brought further than the original (as built) thickness.

Hull capacity has been checked for the midship section based on net scantlings giving a capacity margin of 1.48 both for sagging and hogging.

Fatigue life is a function of Sea State; the selected design solutions, local designs, weld quality and workmanship as well as the corrosion protection offered by the corrosion protection system. Further, a ship operating in a worldwide environment will have a fatigue life of double that of a ship operating in a North Atlantic environment.

2.5 EXECUTING THE REFURBISHMENT

During the Pilot Project, where it became more and more apparent that the procedures of restoring the integrity of the cargo tanks were working according to expectations, the plans of refurbishing the rest of the vessel were already well in progress. A very comprehensive work specification was put together, trying to accommodate the requirements from the owners that the vessel should trade for another 20 years.

Several shipyards were invited to give offers for the whole project. This trigged a stiff competition between the yards, and some heated internal discussions, before it was decided a split-solution, where CBI was awarded the restoring of the cargo tanks, and Sembawang Shipyard (Karimun and Singapore) were awarded the "ship-repair" part of the contract. Highly qualified sub-contractors were assigned to carry out much of the renewal of cabling and automation as well as re-insulation of the cargo tanks.

In parallel with planning the refurbishment, Höegh was trying to offer the ship to future charterers. The main challenge in that process was to convince the charteres that they hired a ship, which would perform perfectly for the whole chartered period of up to 20 years, and Höegh's BOD to admit funds for the refurbishment, before a charter-party was committed. - A tricky "chicken-or-egg" situation. After long and tough discussions, a charter party was signed, and the contracts with the shipyard and contractors were immediately executed.

Soon the whole ship was transformed into an inferno of rubbish and wasted steel-plates, with dust and dirt everywhere. For many it was difficult to imagine that a ship repair, rather than a ship breaking was going on. Although it was planned for extensive renewals, more were exposed during the process.

2.5.1 Restoring of all Cargo Tanks

After a smooth transition from the Pilot Project into the Main Project, the cargo tanks were completed almost according to schedule on July 8th. 2000. Totally about 21000 metres (21km) of welds were excavated and rewelded, using the same procedures which were used for the pilot project.
The rebuilding of the tanks involved removing the dome section at top of each tank, where all the process piping penetrates into each of the tanks. It was necessary to remove the domes in order to remove the cracks in the 9%Nickel-steel material adjacent to the piping.

Upon completion of all welding and NDE examinations which included a 100% UT of all the welds, all the tanks were shot-blasted to grade SA2 and vacuum-cleaned. As a final test, each tank was gradually pressurised to a pressure substantially above the normal working pressure for such LNG-tanks.

It shall also be mentioned that various critical assessments done on the cracking of the cargo tanks have been evaluated by independent bodies as Battelle Institute (US), The Welding Institute of UK and SINTEF (NO), without having any objections to DNV's findings. During the process of restoring the cargo tanks, Höegh kept close contact with representatives from USCG, who witnessed the process on board by several occasions.

2.5.2 Hull

The Hull Capacity, Fatigue Analysis and Condition Assessment Program (CAP) carried out during the winter of 1999 indicated that some 180 tons of steel needed to be renewed, and which later was adjusted to 300 tons. Additional reinforcement of the hull by fitting some 8700 soft-nose steel-brackets inside the ballast tanks was necessary. A complete overview of the condition in the ballast tanks was not possible to have before all the tanks were thoroughly cleaned. After cleaning and sandblasting, the initially estimated 300 tons of steel-renewals, turned out to be in excess of 600 tons.

All the ballast tanks, more than 80,000m^2, have been blasted and given a complete new paint-system. In the order of 8700 new brackets have been fitted to longitudinal through web and bulkhead connections. Longitudinals in the double bottom, bilge area, inner side of bottom wing tank, inner side and outer shell of side tanks were strengthened with new brackets. The total amount of steel needed for this upgrading was about 64 tonnes for the brackets alone. All external surfaces have been sandblasted to grade SA2.5 before given a new paint system.

The Hull Capacity and Fatigue Analysis “as carried out” are elaborated in a separate chapter at the end of this paper.

The calculations show that after modifications LNG/C Höegh Galleon is good for another 20-30 years of world-wide trading.

2.5.3 Other Refurbishments

Much of the insulation of the cargo tanks’ external areas was damaged due to the extensive NDT of the external welds. New polystyrene foam panels were applied by Unitor on an area covering about 3.500 m^2. The insulated pipes on deck were also re-insulated as found necessary.

- Renewal of all the cabling on deck and much in the rest of the vessel along with a new “State-of-the-Art” automation system was delivered by Kongsberg-Simrad, and covers the following sub-systems:
    - Turbine control system
    - Boiler control system
    - Diesel engine control system
    - Turbine generator control system
    - Power management system
    - Auxiliary machinery control system
    - Cargo control system
    - Ballast control system
    - Watch call system
- A new Custody Transfer Measurement System was designed by Simrad-Autronica, using radar-technology for measuring the levels in the cargo tanks. This system is integrated into the vessel’s cargo automation system.
- 2 new enclosed lifeboats and davits were fitted
- Full up-grading of the entire accommodation with new flooring, walls and ceilings. Some of the living quarters were totally rearranged. New furniture in all living quarters was provided.
- New windows were fitted in the entire superstructure
- Cargo Control Room (CCR) was moved from fore-deck up to the bridge, where the previous Radio-Room has been converted to CCR
- Entire external surfaces cleaned for old paint and re-painted.
- Removed all LPG-related facilities on board, as LPG never will be carried on board this vessel.
- Installed two new N_2 Generators. The vessel is now self-sustained with N_2, and utilising the two existing LN_2 tanks as N_2 buffer tanks.
- Installed two new de-humidifiers with capacity of 5000m^3/h at dew point -43ºC

- Renewed air-compressors for several utility systems

- A new incinerator was fitted, and a separate compartment was built to that purpose.

- The vessel had been subject to a CAP inspection of the machinery systems before commencement of the refurbishment. Several recommendations for improvements were given to the Höegh. After the refurbishment the condition was verified during the sea-trials 13th – 15th February 2001, and 23rd February – 3rd March 2001, as well as a sea-trial 15th – 20th March 2001. The machinery has been rated CAP 2

3. ANALYSES, CALCULATIONS AND DISCUSSIONS

The distributions of defects observed during inspection of the 9% Ni steel tanks of the two ships indicated that the discovered defects were spread more or less evenly in all segments and welds throughout the inner surface of the tanks. No defects were then, or later, detected on the outer surface. The cracks in the tanks of Höegh Galleon were generally deeper than in Norman Lady. This may be attributed to the rigorous prototype pressure testing carried out on Norman Lady thereby removing some of the high residual welding stresses that will be the driving crack opening force for Hydrogen Induced Stress Corrosion Cracks.

Due to the actual crack depths it was decided that Norman Lady could be repaired by grinding whereas the deeper cracks in Höegh Galleon needed full rewelding. Here, the cracks were removed with a combination of carbon arc gouging and grinding.

3.1 Upgrading of the Cargo Tanks

The sister ships LNG/C Norman Lady and LNG/C Höegh Galleon (ex. Asake Maru) are unique in the sense that they were the first and only large size (87 500 m^3) LNG Carriers of the MOSS Spherical tank design that were built with tanks in 9% Ni steel. All later vessels have been built with Aluminium tanks. The ships were delivered from the Rosenberg Yard in Stavanger, Norway in 1973 and 1974 respectively. Being the prototype vessel, Norman Lady was subjected to quite rigorous pressure testing of all the cargo tanks, while her sister (named LNG Challenger at the time) were not subjected to the same rigorous testing regime.

3.1.1 Cargo Tank Cracking

During upgrading work of the *Asake Maru* in August 1998, cracks were discovered in the cargo tanks. Cracks with depths of 5-7 mm were found by Dye Penetrant testing (DP) after surface grinding of the weld HAZ areas (weld heat affected zones). At the time crack lengths were not recorded. DNV was commissioned to carry out non-destructive testing of the inside of the cargo tanks. “Boat samples” were cut from the cracked areas (the horizontal welds at the equator) and examined at the metallurgical laboratory at DNV Høvik, Norway.

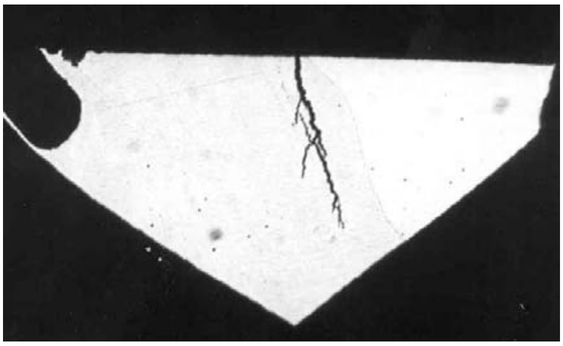

Fig. 5 Boat Sample from NORMAN LADY

Cracks with a depth of up to 5.5 mm were observed on the examined samples. The cracks were located at the HAZ close to the equator weld seams, and were oriented parallel to the weld seams. Small cracks were also observed in areas without DP crack indications, i.e. on the upper side of the upper equator weld seam in tank no. 3. The examinations indicated that the cracks were most probably caused by hydrogen induced stress corrosion (HISSC). The hydrogen necessary for the cracking (embrittlement) is produced due to a corrosion process between water and metal. Hence, the cracking must had happened during periods when the temperature had been above 0 °C.

H_2S is a strong promotor of hydrogen induced stress corrosion cracking. However, analyses of the corrosion products in the cargo tanks revealed no sulphur, and it could not be shown that a possible H_2S contamination of the cargo had affected the cracking process.

Following these findings, DNV was in beginning of November 1998 commissioned to carry out non-destructive testing of the inside of cargo tank no. 3 of the sister ship *Norman Lady.*

Two specimens from the weldments (boat samples) were brought back to DNV's metallurgical laboratory for closer examination. This showed that cracks were present in tank no. 3, and that the cracks were caused by stress corrosion cracking. No evidence of fatigue cracking could be seen. Due to the result of this investigation DNV was requested to carry out non-destructive testing of the remaining tank nos.1, 2, 4 and 5. This testing, which also included testing of the outside of the cargo tanks, was carried out in December 1998. The main results can be summarised as follows:

- *Wide spread cracking were found on the inside of all inspected / tested tanks.*
- *The crack depths in Norman Lady were not as deep as in Asake Maru, generally in the order of 0.5 to 3.5 mm, in four locations down to 4 mm, while a crack of 4.5 mm was found in one location.*
- *No cracks were found in the very limited areas (4 m in each of the tanks 1, 2, 4 &5) inspected from the outside.*
- *A high hardness of the welds, up to 418 Vickers was measured across the HAZ.*
- *From the investigation of the two boat samples it was concluded that Hydrogen Induced Stress Corrosion Cracking (HISCC) caused the cracks.*
- *The testing included thickness measurements of shell plates in the inspected areas. The results indicated that the excess thickness was in the order of 0.5 -1.5 mm.*

The high hardness of the weld indicate that high weld residual stresses still existed in the tanks and had not been subject to shake-down effects as in a normal ship weld. The residual stress will act as a driving force for HISCC as there will an equilibrium condition between tension at the outer surfaces and compression in the middle of the plate. For Norman Lady it is known from the pressure testing at the Yard that some of the residual stresses may have been shaken out due to the rather high loads imposed on the tanks during testing. This could be heard as audible "booms" during the filling process. This may explain the fact that the cracks found in Norman Lady were not as deep as in Asake Maru due to the presence of a smaller driving force (residual welding stress).

3.1.2 Repair Strategies

The cracks sizes reported from the inspections above were found to be such that the tanks of NORMAN LADY were considered to be repairable with grinding. In a letter to Höegh Fleet Services AS (Höegh) DNV Class stated the conditions for repair of the cargo tanks of LNG/C Norman Lady, [1].

(Quote) "When originally designed the cargo tanks were specified with plate-thickness in excess of that required by the design criteria. Further, the plates were delivered with only plus tolerances. Thus cracks with a limited depth may be removed by grinding. This is provided the thickness after grinding satisfies the minimum required plate thickness as found in the calculations. Our preliminary calculations indicate that the acceptable depth of grinding to remove the crack tips without rewelding will be:

- *4.0mm where the plate thickness is 30.0mm.*
- *3.0mm where the plate thickness is 23.0mm.*
- *In locations where the plate thickness is more than the specified 30.0 or 23.0mm, 50 % of the excess thickness may be added to the acceptable depth of grinding.*

Final calculations must be provided to confirm the above. These calculations shall show that:

The stress across the remaining plate thickness does not exceed allowable values (USCG, IGC & DNV).

- *Fatigue life acceptable.*
- *Crack propagation rates acceptable.*
- *Buckling strength acceptable.*

Further it might be possible to consider acceptance of slightly deeper grinding without rewelding for short lengths based on special consideration of the stresses in the actual location." (Unquote).

Calculations according to the above requirements & criteria were carried out by the consultancy arm of DNV. These showed that the tanks would fulfil the set requirements and that grind repair was feasible. However, during the grinding process deeper defects than the generally maximum allowable were found in areas of limited length. It was also verified that all tanks had a 2 mm surplus thickness. Hence, the equator belt is 32 mm and the tank shell outside the equator belt is all 25 mm thick.

In order not to require an excessive amount of rewelding, DNV Class worked out new, more detailed acceptance criteria for maximum depths and lengths of defects in the various tank zones. These covered also defects (of limited length) being deeper than the generally accepted depths of 5 mm for equator and 4 mm for the tank shell. The repair was carried out in strict adherence to the set requirements, and whenever the criteria could not be fulfilled rewelding was carried out.

However, due to the larger crack depth (5 to 7 mm) found in Asake Maru (now Höegh Galleon) grinding was not considered a viable alternative for this vessel. During the grind repair of the tanks of Norman Lady it became clear that it was possible to remove the cracks in the inside welds of the tanks of Höegh Galleon by arc air gouging followed by 100 % grinding and Dye Penetrant (DP) testing before rewelding. After rewelding and weld surface grinding 100% DP and ultrasonic testing was to be carried out to verify the quality of the welds. This procedure was on Höegh's request worked out by Chicago Bridge & Iron (CBI) and was then the selected rewelding strategy for Höegh Galleon.

In order to test the procedure a pilot project was carried out on a 90^{o} section from bottom head to top head of tank no 4. This test confirmed that the procedure worked, that all cracks could be reliably removed and be rewelded up to the original plate thickness.

3.1.3 Design Basis for the Spherical Cargo Tanks

Fig. 2 shows the layout of the tanks and the equator profile. All 5 tanks have the same thickness and the same equator profile. Plate strakes A-B-C and F-G-H are all 23+2 mm and D-E are 30+2 mm. The tank diameter is 33.1 m for tank nos. 2, 3, and 4 and 31.0 m for tank 1 and 5.

The thickness of the upper hemisphere is governed by a minimum thickness requirement, which at the time of construction of the vessel was R/950 where R is the radius of the tank. This has later been modified to R/1300, which corresponds to the required buckling strength to withstand an external overpressure of 0.2 bar, ref. [2]. For the old requirement this corresponds to a minimum thickness of 17.4 mm for tank 2, 3 and 4 and 16.3 mm for tank 1 and 5. The thickness of the lower hemisphere is determined by a partial filling seagoing condition, which requires a shell thickness of 23 mm due to buckling considerations. Additional basic design conditions are buckling of the tank shell in empty seagoing condition and allowable membrane stresses while fully loaded at sea.

3.1.4 Stresses in Cargo Tanks

Due to the pitch motions and accelerations of the vessel the two most heavily loaded tanks are no 1 and 2. Hence, the structural analyses were concentrated on these two tanks. The most defect sensitive areas are where the stress levels are the highest. This is in the bottom area (the South Pole) and around the equator zone.

Fig. 6 shows a change in thickness from 32 to 25 mm at 80° and 81° in the upper and lower hemisphere respectively. Since the inner surface is straight (smooth) the change in thickness is made on the outer surface. Shift in the mid-surface of the plates of (32-25)/2 =3.5 mm leads to an extra bending moment with associated meridional bending stresses. The associated stress concentration factor on meridional (vertical) membrane stress is in the order of 1.27. This factor has been included in the fatigue & fracture mechanics analyses.

3.2 Fracture Mechanics Analyses

A basic condition for the design of the spherical cargo tank system is the “leak-before-failure” principle. This means that potential cracks shall propagate through the thickness before reaching any critical length. A gas detection system shall therefore be arranged to detect potential gas leaks. After a through-thickness leak the tanks shall have a 15 day time window for the vessel to go to port and unload her cargo. The minimum acceptable time for the crack to penetrate the thickness is the maximum value of the planned operational lifetime of the vessel and 20 years.

Further, current DNV practice is that if leak-before-failure cannot be proven a safety factor of 10 shall be applied to the calculated fatigue life. Under such conditions this means that for a planned operational life of 20 years, a 200 years fatigue life has to be demonstrated.

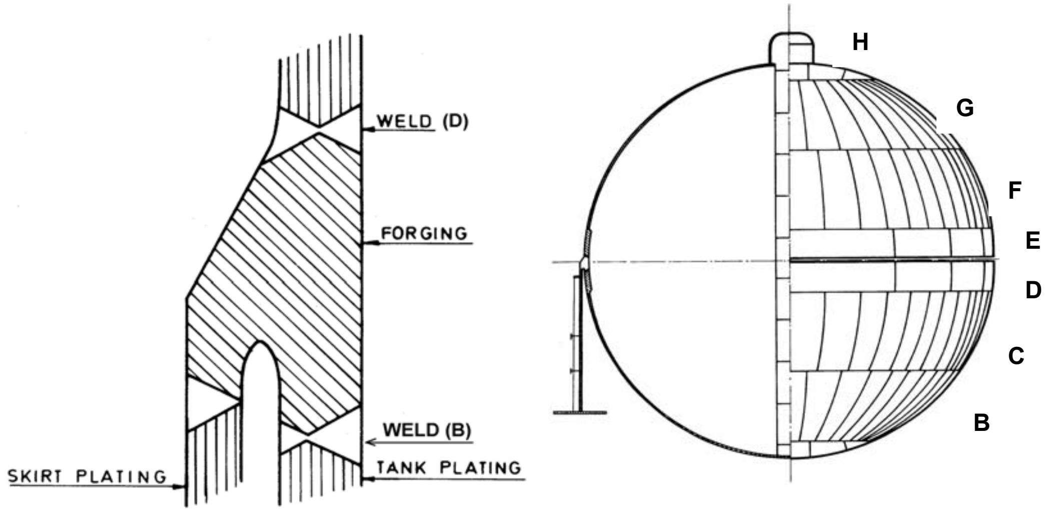

Fig. 6 Tank Configuration

The distributions of cracks in the tanks of both vessels indicated that the cracks had to be considered as more or less evenly distributed in all segments and welds in the tanks. This means that in fracture mechanics analysis of crack growth/fatigue the initial defects (observed cracks) have to be assumed infinitely long. Regardless of stress distribution in the weld cross-section, the cracks will as a worst case scenario propagate more or less uniformly through the thickness over considerable parts of the circumference, and failure will occur as rupture of the tank shell over the same length. As final fracture will occur immediately when the crack penetrates the thickness *leak-before-failure will not* *apply* and gas detection cannot be relied on. Repairs therefore had to be carried out in order to restore fatigue life and to ensure that "leak-before-failure" and gas detection again could be relied on.

Table 1 Material data for 9% Ni steel (constants in Paris' equation and CTOD data)

Test Condition	**σ_{mean} [MPa]**	**Test temp. [^oC]**	**m**	**C [N, mm]**	**CTOD**	**Comments**
Parent material						
Plate L	157	RT	2.3	$3.05\ 10^{-11}$	0.26	Critical crack length calc.
" L	157	-162	2.7	$1.18\ 10^{-12}$		
" LT	157	RT	2.6	$3.96\ 10^{-12}$	0.26	Thickness direction calc.
" LT	245	RT	2.9	$7.85\ 10^{-13}$		
Weld Metal	157	RT	3.0	$2.44\ 10^{-13}$	>0.87	
HAZ	157	RT	3.4	$2.30\ 10^{-14}$	0.64	
Equator zone						
Plate		-162			>1.05	
HAZ		-162			>0.86	

Legend: RT = Room Temperature, HAZ = Heat Affected Zone

3.2.1 Material data for Fracture Mechanics Analysis

When the spherical gas tank concept was developed in the early 1970'ies extensive fracture mechanics testing and analyses were carried out in order to prove the feasibility of the leak-before-failure concept and the overall safety and soundness of the design. Material data from these investigations are summarized in ref. [3] and also listed in Table 1 below.

The Heat Affected Zone (HAZ) is only 2-3 mm wide. Even if the defects were discovered in the HAZ the crack growth through the thickness will for an X- type butt weld grow perpendicular to the surface and hence travel most of the time in the parent plate material.

Hence, for this reason the most conservative fracture mechanics material data for parent material has been used in the calculations as shown in Table 1.

3.2.2 Critical Crack Lengths

The critical crack length is defined as the maximum through-thickness crack that will instantaneously fail when subjected to the 20 year extreme load (still water + wave). Analyses for a range of Crack Tip Opening Displacement (CTOD) values and stress values have been performed by the fracture analysis software "CrackWise" developed by *The Welding Institute* (UK). Crack lengths for alternative CTOD values and stress levels are shown in Fig.7.

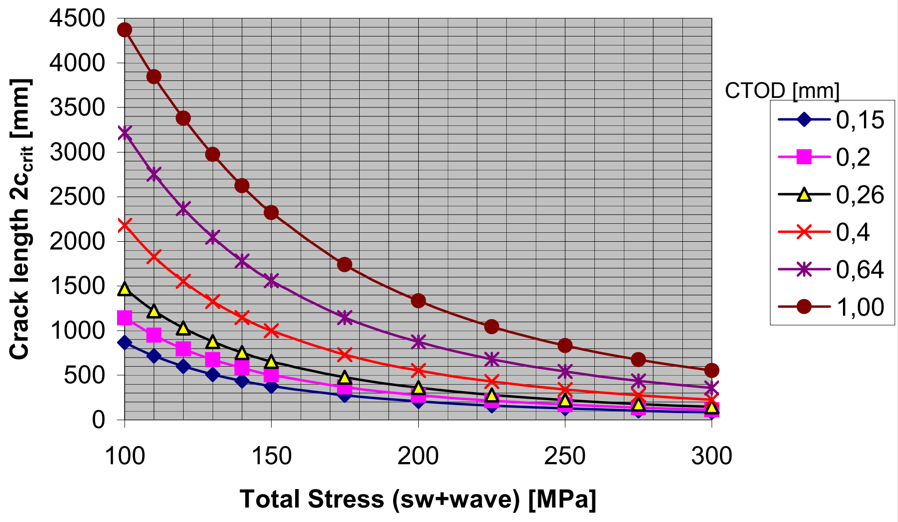

Fig. 7 Critical crack length $2c_{crit}$ [mm]

3.3.3 Fracture Mechanics Analysis Procedure

The sequence of the fracture mechanics analyses carried out on the tank shells consists of three main steps.

1. Analyse crack growth in the thickness direction as well as the circumferential/meridional direction to see if the crack will penetrate the thickness or grow in length.
2. If the crack grows in length an additional 200 years of fatigue life has to be proven. However, if the crack penetrates the thickness a 20 year additional fatigue life is required.
3. Check if crack length at penetration of thickness plus 15 days of full through-thickness crack propagation is less than the critical crack length $2c_{crit}$.

The “FatigueWise” fracture mechanics analysis software developed by *The Welding Institute* (UK) is used in the present crack propagation/fatigue analysis.

Both vessels have been trading for about 25 years, Norman Lady mostly on the Arabian Gulf –Japan trade or similar waters. Höegh Galleon has been trading from south-east Asia to Japan/Korea including a 4 year period as storage tanker in the Arabian Gulf and a 4 year period trading on North Atlantic to Boston and in the North Pacific from Alaska to Japan. In average this represent a wave environment similar to “world-wide” trading as defined in ref. [4]. According to current DNV fatigue analysis practice, [4], this is less severe than the North Atlantic environment with a factor of $(0.8)^m$ $=0.56$. (For the governing parent material data, $m = 2.6$ as given in Table 1.) This means that the 25 year actual trading corresponds to an equivalent North Atlantic trading time of $T_e = 0.56*25 = 14$ years. Hence a total fatigue life of 14 + 20 years had to be proven when leak-before failure applies.

3.3 Critical Crack Depths before Repair

Fatigue/crack propagation analyses have been carried out for both 34 years of fatigue life and 214 years of fatigue life assuming infinitely long initial defects ($2c_0 = 1000$ mm) and 25 mm long initial defects ($2c_0 = 25$). Note that in a fracture mechanics sense the 1000 mm long defect represents an infinitely long crack.

Table 2 Maximum calculated allowable initial crack depth (before repair)

Position	Stress Range [MPa]	Max. allowable initial crack depth a_0 [mm]				Initially observed crack depths [mm]	
		$2c_0 = 1000$	$2c_0 = 25$	$2c_0 = 1000$	$2c_0 = 25$	Norman Lady	Höegh Galleon
		214 years	214 years	34 years	34 years		
1 D	140.5	Na	na	0.15	0.9	(0.5-4.0)	(5-7)
3 B	130.7	Na	na	0.11	0.4	(0.5-4.0)	(5-7)
Tanks 2-4							
UH 80°	73.0	0.7	1.4	3.0	>5	(2.5-3.5 + 4 &4.5)	(5-7)
LH 81°	68.0	1.1	1.8	3.5	>5		
Tanks 1&5							
UH 80°	74.4	0.6	1.3	2.8	>5	(2.5-3.5 + 4 &4.5)	(5-7)
LH 81°	80.1	0.2	0.6	2.4	>5		

Legend: UH = Upper hemisphere, LH = Lower hemisphere, na = not attainable
1D = above equator at centre line, 3B = below equator at 45 degr. off the centre line, Fig. 2

Table 2 lists the maximum calculated initial crack depths for the most sensitive positions in the tanks. The results for 214 years represents *from a fracture mechanics point of view* the maximum allowable crack depths for the ship to operate for another 20 years if leak-before-failure cannot be proven. The 34 year results refer to a situation where leak-before-failure can be proven. Here, a very good safety margin is maintained before the cracks reach their critical lengths $2c_{crit}$.

The results show that 214 years of fatigue life is not attainable for the equator for long defects. At the equator 34 years is attainable with long but very shallow defects. In the tank shells the 214 years condition leaves rather small defect margins, whereas the 34 years condition for both long and short cracks looks like a better proposition. In conclusion, the results show that *repairs need to be carried out* since the calculated maximum crack depths in most cases are significantly smaller than the observed cracks.

3.4 Strength after Repairs

3.4.1 Analysis Procedure for Grind Repair – Norman Lady

Grinding of the welds to remove cracks will leave a circular groove with an agreed radius in the weld zone and with a depth and length as allowed by DNV Class. For long grooves this leads to a shift in the position of the shell force resultant due to the change in thickness at the position where the grinding is carried out. This results in an eccentricity that set up extra bending stresses over the ground cross-section. The increase in stress level at the surface of the remaining cross-section can be described by a stress concentration factor relative to the membrane stress in the reduced cross-section given by:

$$K_g = 1 + 3d/t$$

where

d = depth of grove or indent
t = thickness of shell after grinding

Further, the radius of the groove is important for the stress concentration factor originating from the presence of the groove itself. A larger radius will be beneficial in reducing the stress concentration factor. On the other hand, this is very demanding in terms of equipment for carrying out a well-controlled grinding process. Hence, the following solution was selected: The horizontal welds at the equator profile have been ground with a 30 mm radius, whereas all other welds have been ground with a 10 mm radius.

Stress concentration factors calculated by FEM analyses. K_t is the groove concentration factor due to the groove radius, and $K_{tot} = K_g K_t$. The analysis verified the analytical formula for K_g given above. These two stress concentration factors have been included in all the analyses carried out for the grind repair of Norman Lady.

For a groove of limited length, which goes deeper than the accepted infinitely long grooves, DNV Class required that the distance to the next such area should be *3 times the accepted length* [1]. As compared to the circumference of the tanks (about 100 m) the accepted groove lengths are rather short and it may be unduly conservative not to consider stress redistribution from the area of the short deep groove to the area in between. Hence, in order to arrive at a reasonably conservative envelope criterion for use in the analyses an *equivalent groove depth was defined as the depth of the infinitely long groove plus a quarter of the additional depth of the short groove*.

3.4.2 Procedure for Rewelding – Höegh Galleon

The cracks in the inside welds of the tanks were removed by arc air gouging followed by 100% grinding and DP testing before rewelding. After rewelding and weld surface grinding 100% DP and ultrasonic testing was carried out to verify the quality of the welds, see sect. 3.2.2 above.

3.4.3 Nominal Allowable Stress Control

The IMO/USCG criteria allow a nominal equivalent membrane stress of 162.5 MPa and a surface stress (membrane plus bending) of 325 MPa. Both values refer to total stresses (static plus dynamic) for the long-term extreme load condition. North Atlantic dynamic loads with a return period of 20 years are used as a reference.

The governing welds are the welds above (D) and below (B) equator, Fig.6. After grinding Norman Lady had a utilisation of the allowable code stresses of 0.88 whereas Höegh Galleon had a utilisation of 0.56. The results show that the allowable code stress criterion is fulfilled with ample margin for both vessels.

3.5 Buckling Strength

The buckling strength has been checked in the “as-built” condition according the procedure in ref. [2].

In a buckling sense, the grooves from the grind repairs represent minor, very localised, geometrical imperfection effects on the shell surface. In order to assess the effect of grinding on buckling strength the production tolerances (shell imperfections) was increased corresponding to the eccentricity effect of the grinding depth. Two levels of eccentricity were analysed, i.e. 0.5 and 1.0 times the equivalent grinding depth. The analyses showed that the buckling strength with LNG cargo of the grind repaired tanks of Norman Lady is acceptable without filling restrictions as the necessary buckling thickness is nowhere exceeding 25 mm which is the actual “as-built” thickness of the tank shell. For LPG cargoes the GM values had to be restricted to 2.5 m for filling ratios above 50 %.

For the Höegh Galleon with no grove effect due to grinding, the buckling strength margins are equal or better than for Norman Lady.

3.6 Fatigue Life and Crack Propagation

The condition of grind repair is that all detectable cracks should be ground / gouged away and subsequent inspection carried out to verify that the grinding and gouging had been properly carried out. In theory this means that no initial defect that could serve as a starting point for subsequent fatigue crack growth should be left behind.

A vitally important condition for the repairs was *that no defects were discovered on the outside* of the tanks. It was therefore most important to ascertain that the probability of outside cracks was small. For this purpose, procedures applied in Risk Based Inspection (RBI) of process plants were applied, ref. [5-6].

The length of welding in each tank is approximately 2000 m, leaving 4000 m of HAZ to be inspected. For each tank somewhere between $\sqrt{4000} = 63$ m and $\sqrt[3]{4000} = 16$ m of weld length should be inspected.

In the case of Norman Lady 50 m of weld length on tank no. 1 and 4 m of welds on each of the tanks 2, 3, 4 and 5 had been inspected without finding cracks.

In addition to the inspections carried out by Mitsui O.S.K. Lines in Asake Maru in tank no. 3 during the summer of 1998, 176 m of weld length, or 352 m of HAZ length, had been inspected in tanks 1, 4 and 5 as basis for the rewelding work of Höegh Galleon. This represents an average of 117 m of HAZ length for these 3 tanks and an average of 70 m for all 5 tanks.

For both vessels, no cracks, or crack indications were found. Based on the above criteria, this was felt to represent a sufficient statistical basis to support the assumption of no cracks in the outside welds.

Table 3 shows a summary of the results for the most sensitive area of the tanks after grind repair of Norman Lady and the rewelding of Höegh Galleon. The results for Höegh Galleon are listed in parenthesis in the Table.

Table 3 Fatigue lives after repairs, Norman Lady & (Höegh Galleon)

Position	**Crack depth a_0 [mm]**	**Stress Range [MPa]**	**Parent material ($2c_0 = 25$ mm)**			**Equivalent depth of grinding Norman Lady**
			Cr. inside	**Crack from outside, weld**		
			T [years]	**T [years]**	**T [years] IU**	
1 D	0.1	167.5 (125.2)	>>1000	27.7	-	(5 mm)
	0.5	“	45 (55)	22 (34)	58	
3 B	0.1	210.3 (112.4)	158	10.5	-	(5 mm)
	0.5	“	20 (71)	8.5 (34)	60	
Tanks 1&5						
UH 80°	0.1	208.4 (75.5)	175	13.5	-	(4.9 mm)
	0.5	“	24 (>>1000)	10.8 (48)	56	
LH 81°	0.1	220.3 (80.9)	121	11.3	-	(4.5 mm)
	0.5	“	20 (>1000)	9.1 (307)	58	
Tanks 2- 4						
UH 80°	0.1	204.6 (74.2)	198	14.2	-	(4.9 mm)
	0.5	“	26 (>>1000)	11.4 (500)	57	
LH 81°	0.1	186.8 (68.5)	410	19.1	-	(4.5 mm)
	0.5	“	55 (>>1000)	15.1 (832)	53	

Legend: UH = Upper hemisphere, LH = Lower hemisphere, IU = Inspection Updating

As potential crack propagation from the outside is a limiting parameter an extra column is added to the result tables labelled “Inspection Updated (IU)”. This is based on an *inspection updating philosophy* which is widely used for inspection and inspection planning in the offshore and process equipment area. The procedure used is as follows:

1. The normal weld tip defect usually embedded in standard fatigue SN curves is 0.1 mm.
2. The minimum crack that can be detected with dye penetrant testing is about 0.5 mm deep.
3. The tanks have been inspected from the outside without finding any trace of defects after 14 years of equivalent North Atlantic fatigue life.
4. If the calculated time for crack propagation from 0,1 mm to 0,5 mm crack depth is less than 14 years, the fatigue lives for 0,5 mm defect depth and up can be multiplied with the ratio (14/calculated life from 0,1-0,5 mm).

After grinding/welding the material is considered brought back to “as new” condition and a calculated lifetime of 20 years is sufficient. From the outside, however, 34 years of fatigue life is required.

The results show that for small cracks ($2c_0$= 25 mm) leak-before failure is obtained in the whole tank system. The acceptance criteria are fulfilled in general for a defect depth of 0.5 mm. Further, the residual lifetime is far better than the code requirement of 15 days. *The results show that the fatigue lives after grind repair and rewelding of the tanks fulfil the set requirements.*

3.7 Discussions

3.7.1 LNG Cargoes

In the calculations conservative assumptions have been applied throughout. The most important ones are:

- Conservative material data has systematically been used; ref. Table 1 with associated discussions.
- When evaluating the vertical welds in the 30 mm equator belt a reduction factor of about 0.62 on the circumferential stresses have not been included at the equator profile. This is caused by the thicker equator profile acting much the same as a ring stiffener in a pressurised cylindrical tank.
- The acceleration values used in the design of the vessel were based on the simplified IGC formulas. Direct analyses have later been carried out using our state-of-the art WaSim code with a GM value of 0.8 m for a homogeneous full load condition. The low GM gives a rolling period of 33 seconds and much reduced (50%) transverse accelerations. Further, the vertical accelerations are reduced with about 20%. This reduces the dynamic stress levels in the tanks and hence increases the fatigue life.
- All fatigue/crack propagation analyses have been carried out as if the vessel was trading 100% in a homogeneous full load condition. Allowing 10% for port calls and off-hire should leave 45% to full load and 45% for ballast trading. Keeping in mind that inertia forces are the dominating dynamic effect, all fatigue life predictions can be increased at least with a factor of 1,8.
- An *Emergency Discharge* operation procedure has been checked. The conditions were discharge pressure of 2.15 bars for fillings up to 50 % and 1 bar for fillings up to 100%. The results of the analyses confirmed that Emergency Discharge is feasible.

3.7.2 LPG Cargoes

The potential for carrying LPG cargoes, which have a maximum specific weight of 0.6 t/m^3, was also checked for Norman Lady.

Due to the 20 % higher cargo density of LPG some of the conservative assumptions made for the LNG cargoes had to be relaxed. By using the state-of-the-art computer code WaSim the design accelerations initially used for the vessel was shown to be rather conservative. For this reason new hydrodynamic analyses with WaSim was carried out for LPG loads covering a range of GM values from 0,77 m in a fully loaded condition (tanks 1, 2, 3 & 4 full and 5 almost empty) to 6,8 m in ballast (all tanks empty). The results of the hydrodynamic analyses were then used as input to new analyses of the spherical tanks with the DNV tank design programme NVKULE, [8] for both LPG cargo and the LNG design case.

3.7.3 Discussions and Conclusions

In order to operate with LPG cargoes after the grind repairs the pressure relief valve setting (MARVS) had to be reduced from 0.7 kp/cm^2 to 0.25 kp/cm^2. Further, from the analyses the following conclusions can be made:

1. As for the LNG case the *minimum thickness* requirement is the same for LPG and hence found in order.
2. The *total membrane shell forces* are not larger than for the design LNG case provided GM is kept below 6.8 m. This means that allowable membrane and bending stresses are within the code requirements.
3. *Buckling strength* allowing for the effect of grinding has been evaluated as for the LNG case by increasing the production tolerance requirement by the eccentricity effect from the equivalent depth of grinding. The results show that by requiring the GM value to be less than 2.5 m for filling ratios above 50% the necessary buckling thickness is nowhere higher than 25 mm which is the actual “as-built” thickness of the tank wall.
4. Further, it was found that if GM is equal or less than 2.5 m the dynamic shell forces are equal or less than used for the LNG design case. Hence, the *fatigue life and crack propagation rates* of the tanks are acceptable and not less than for the LNG case.
5. An *Emergency Discharge* operation procedure was also checked. The conditions are discharge pressure of 2.15 kp/cm^2 for fillings up to 50 % and 1 kp/cm^2 for fillings up to 100%. The results of the analyses show that Emergency Discharge is possible.

The above shows that by reducing the MARVS pressure from 0,7 kp/cm^2 to 0,25 kp/cm^2 and limiting the GM value to 2,5 m for filling ratios above 50 %, trading with LPG is fully feasible and acceptable. Going back to the fourth bullet point in sect. 4 above the factor of 1.8 on fatigue life still stand. This means that a reserve factor $(1.8)^{1/m} = 1.25$ on the dynamic stress values (m=2.6) has still not been taken into consideration.

3.8 Upgrading of Hull Structure of Höegh Galleon

Höegh requested DNV to propose necessary steel renewal and upgrading of the hull following the Condition Assessment Programme (CAP) inspection onboard the vessel in the Johore River in January 1999, ref. [9]. The CAP-report included results of a comprehensive UTM to document the effect of the modifications in terms of local strength, hull girder capacity and fatigue life.

As basis for the strength analyses sea keeping and wave load analysis were carried out with WaSim for the previous trades of the vessel as well as for North Atlantic trade, Ref. [10]. The DNV strength analyses showed that

- Nominal stress values were according to USCG, IGC and DNV criteria
- Fatigue life was sufficient for at least another 20 years of operation based on recommended steel renewal and strengthening.
- Crack propagation rates and critical crack lengths were in accordance with USCG, IGC and DNV criteria

- Buckling strength was equal to newbuilding standard

Steel renewals due to corrosion loss of thickness of the hull structure members were carried out and some 8700 soft-nose brackets were fitted to longitudinal stiffeners in web frames and bulkhead transitions in order to improve fatigue life, all according to the recommendations given by DNV, Ref. [11].

All ballast tanks were sandblasted and re-coated.

After these renewals and modifications the “as carried out”-analyses prove that the vessel is capable of trading for at least another 20 years subject to normal classification practice. The final structural work was completed in Singapore in February 2001 and the vessel is satisfying a CAP 1 rating (highest rating corresponding to class newbuilding) of the hull structure.

4. VESSELS’ PARTICULARS

Length Overall	249.5 m
Beam	16.0 m
Depth	23.0 m
Draft	10.6 m
Gross Tonnage	71,496 gross tonnes
Class	Det Norske Veritas
USCG	Built to USCG requirements
Cargo Tanks	
5 tanks	~87,500 m^3 capacity
#’s 1 & 5	31.0 m diameter
#’s 2, 3 & 4	33.1 m diameter
Material	9% Nickel Steel UHB 2N 90[1] ([1]Similar to DNV 20-2 & ASTM A-353)

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