Lloyd's approach to Quality assurance of Welded structures

J. A. FREW*

ABSTRACT, Lloyd's Register has been in existence for over two hundred years, primarily with the object of ensuring that the construction of ships and subsequent condition throughout service is to a satisfactory standard. During the last fifty years, this service has been extended to include the inspection of equipment intended for major projects such as gas, oil and petrochemical complexes, as well as nuclear, hydro-electric and fossil fuel power generation units.

The paper outlines the Society's general approach to quality assurance and the controls necessary to ensure product adequacy for the intended use at the specific design conditions and for the required period of service.

Reference is made to design, material choice, method of manufacture, fabrication and welding procedures, inspection and testing during manufacture and in-service inspection and maintenance. Recent problems encountered during heavy fabrication, detection of imperfections by non-destructive examination and the evaluation of their significance towards failure are discussed.

1 Introduction

Lloyd's Register of Shipping was founded in 1760 to provide a service of ship classification to the shipping community—insurers, ship owners, ship builders, and merchants ; the management of the Register being controlled by the insurance interests. In course of time, ship owners became dissatisfied with the conduct of Lloyd's Register and set up their own Register. Both operated for a number of years in competition, each with a bias towards the interests of their principals and not necessarily to the benefit of the shipping community as a whole. Fortunately in 1834 a reconciliation of interests was effected and Lloyd's Register of Shipping was reconstituted in the form we know it today, as a voluntary association of underwriters, owners and builders equally represented on the Committee of Management. In essence, it is a body corporate having no shareholders and has no interests to serve beyond those of supplying a technical service to clients who wish to avail themselves of the facilities. The revenue of the Society is used to service the organisation and to maintain and up-date the technical competence of the staff.

The Society publishes Rules for the Construction and Classification of Steel Ships which are maintained under constant review and are modified and extended in the light of experience and developing technologies.

*Mr. Frew is the Managing Engineer, Industrial services, Lloyd's Register of Shipping, U.K. The paper is reprinted from Australian Welding Journal Sept./Oct. 1973.

It was in 1934 that the Rules included, for the first time, tentative requirements for fusion welded pressure vessels, which were the first published in the United Kingdom covering this new form of construction. The development of Lloyd's Register's interests in the non-marine field stems from around that date. These have extended to include the inspection of equipment in the oil and chemical processing, and the power generation industries. More recently the Society has included the inspection of bridges, buildings, and off-shore drilling and production platforms for the oil industry.

Over the period, considerable changes have taken place in the oil, chemical and power generation industries with an ever constant demand for higher efficiency and greater economic viability. Higher design pressures and temperatures have necessitated closer control of plant manufacturing procedures, with increasing reliance on quality control to attain and maintain adequate engineering standards to assure satisfactory operation under the working conditions for the envisaged service period.

As pressure vessels, boilers and structures for the process and power generation industries are usually manufactured for a specific purpose on a "one-off" basis, statistical methods of quality control are not usual although this is applied where justified.

Lloyd's Register normally stipulates an involvement starting with approval of design, including materials followed by inspection and testing.

It is appropriate to outline the Society's approach to inspection under these headings.

2 Design

Appraisal at the design stage extends beyond the calculation of thicknesses and includes an assessment of materials to be used, together with manufacturing and welding processes to be employed. Service conditions must be carefully reviewed to ensure that design parameters chosen are appropriate. At this stage, the efficacy of the fabricator's controls are established and the suitability of non-destructive testing methods considered in relation to the joint geometries involved.

Failures are usually associated with the influence of some element not envisaged or catered for in the design stage. If the true causes of failures were accurately established and assessed, repetition might well be avoided. Brief comment on a few types of failures may not be out of place here.

Overload and general yielding is most unusual and, in most cases, accidental. Overload due to excessive pressures can be catered for by fitting adequate relief devices.

The most common form of failure is by fatigue and this mode is perhaps the least appreciated. It is important to assess the anticipated range and frequency of load cycling and to pay close attention to detailed design to minimise stress concentration effects.

Failure by fast or brittle fracture is now widely understood as are the precautions to be adopted, such as the selection of a notch tough material and avoidance of notches and discontinuities in the structure. It must not be overlooked that a normally ductile material can fail in a brittle manner at locations where complex and triaxial stress fields exist.

Creep failures are often associated with overheating due to temperature excursions in the firing of boilers or process heaters. Creep failure often involves intergranular breakdown of the steel with poor ductility resulting from sustained loading at excessively high temperatures.

The effects of corrosion often lead to premature failures in service, Some of the main forms are general wastage of exposed metal surfaces, isolated pitting, galvanic action between dissimilar metals, intergranular corrosion in the case of austenitic steels, and stress corrosion cracking.

Failures by erosion are not common, generally occuring where abrasive products are being handled, particularly in pipelines with bends and elbows. Erosion can also accelerate corrosion rates by removing a protective corrosion product film.

It is important to emphasise that in the design appraisal due note is taken of the effect of fabrication, welding and heat treatment processes on the materials used and that consideration of failure modes is based on the material properties in their final condition.

3 Materials

The selection of materials for use in a welded structure, pressure vessel or other item of pressurised equipment is dependent upon the service conditions. In his selection of materials, the designer will assess the service requirements, i.e., in the case of a pressure vessel the design temperature, design pressure, corrosion environment, economic factors and required life.

Considerable background knowledge exists regarding the strength and suitability for the use of carbon and low alloy steels but as temperature ranges are extended upwards and downwards, less information is available particularly for the low alloy steels. Furthermore, the information that is available may have been obtained from a relatively small number of tests and consequently the confidence level may be of a low order, necessitating the adoption of precautions possibly including provision for in-service monitoring.

Problems such as lamellar tearing are being overcome by the production of cleaner steels having good through thickness properties as well as by improved weld detail design. This is of paramount importance in bridge construction and the construction of offshore structures for oil and gas industries where a large amount of fillet and Tee-butt welding occurs. The need for materials having good weldability has led to improvements in steel making practice, giving better control of the chemical and physical properties of the steel produced.

4 Fabrication

As part of his contractual obligation, a fabricator is required to conform to a particular code or standard. These are often not very specific about forming, machining, welding and, where necessary, heat treatment, but are normally quite specific about shape and dimensional tolerances.

Deviations from designed form present a considerable problem in unmachined large diameter thick walled pressure vessels. The fabricator requires as great a tolerance as possible to facilitate manufacture, whereas the designer wishes to restrict deviations from shape to ensure that design stresses are not exceeded in service.

Welder procedure qualification and production tests for standard type pressure vessels of 50mm thickness and under, present little difficulty to the modern fabricator. However, as thicknesses increase because of differences in heating/cooling rates between the test plates and the actual fabrication, procedure and production test results may no longer be truly representative of the properties of the actual vessel material.

A pressure vessel may consist of plates forgings, tubes and weld metal, all of which may have slight differences in chemical composition, mechanical strength and grain size. In addition, geometrical differences may exist, e.g., large changes in sections. As a result, the response to heat treatment may vary throughout a vessel. In the case of large heavy walled pressure vessels, slow cooling rates may give rise to unfavourable metallurgical structures which may affect the choice of minimum temperature for final hydrostatic testing of the vessel on completion of fabrication, or at some future date during the operational life of the vessel. The problems of postweld heat treatment of a large site built vessel to a specific temperature which ensures all parts have been effectively heat treated are considerable.

5 Testing

It is essential that adequate testing procedures are instituted in the quality assurance programme and that these should be representative of all facets of fabrication.

These tests could include :

1. In the case of a very complex structure tests on a scale model to verify design assumptions.

2. Material tests to verify the chemical and physical properties.

3. Welding procedure and welder qualification tests.

4. Non-destructive tests. The application of these and the techniques employed should be related to the actual design geometry.

Throughout fabrication the items of plant will have been subjected to quality control checks, using radiographic, ultrasonic, magnetic particle, dye penetrant, and other non-destructive testing techniques as appropriate, to verify soundness. Each form of non-destructive testing has limitations and all are complementary. With radiography, the detection of certain flaws, e.g., fine cracking and lack of side wall fusion may be difficult, if unfavourably oriented to the source of radiation, or the geometry of a weldment may make radiographic interpretation impracticable. With ultrasonic examination, the technique employed must be appropriate to the geometry of the weldment and the surface condition. Coarse grain structures make ultrasonic methods of examination extremely difficult.

It is customary on completion of fabrication to conduct a final acceptance test in the form of an overload. In the case of lifting appliances, a test load in excess of the working load would be applied. For a pressure vessel, a test pressure is applied related to the design and working pressure. Where the design temperature exceeds a specified value, usually 100°C, most codes require a proportionate increase in the test pressure to compensate for any decrease in material strength at the working temperature.

The use of electric resistance strain gauges during pressurisation or overloading to monitor performance provides means to confirm the validity of design assumptions and methods. Acoustic emission techniques are being used increasingly to monitor heavy walled pressure vessels. Acoustic sensors fitted to the vessel pick up any vibrational energy emitted from the vessel during the hydrostatic test. The application of this technique to in-service monitoring is being pursued in relation to nuclear vessels which are inaccessible for normal inspection during service.

6 Recent Developments

The growing world shortage of oil has prompted the exploitation of fuel reserves previously considered unprofitable and impracticable. The search for new sources of oil is now being conducted on off-shore sites throughout the world.

Probably the most hostile marine environment is that of the North Sea and structures being developed for this area represent an extrapolation of existing knowledge. To establish margins of safety it has been necessary for proposed structures to be formulated into a mathematical model consisting of an array of elastic finite elements and then for various loading conditions to be considered. For this purpose, Lloyd's Register has developed a complete structural and fatigue analysis programme applicable to fixed structures, considered by many to be one of the most advanced computer analysis systems available.

Sophisticated inspection methods now available reveal defects previously undetected and have reshaped ideas on what is and what is not acceptable in a welded fabrication. It is now accepted that many welded structures containing defects have performed satisfactorily throughout their service life. The need to assess the significance to failure of imperfections has led to the science of fracture mechanics. The science permits an analytical assessment to be made of the significance of a defect and to define a defect acceptance level for a specific application.

Some codes have defined general acceptance levels for weld defects and whilst Lloyd's Register undertakes inspection to these codes the attitude has always been that the Surveyor carrying out inspection has the discretion to require the repair of defects on the basis of his engineering judgement.

In this connection it will be appreciated that the presence of a small defect critically positioned in a structure, be it a ship, pressure vessel, bridge, etc., can give rise to serious problems in service. At a critical size, energy may be available in the structure for the crack to propagate of its own accord, leading possibly to a catastrophic failure. With this in mind the Society has written two computer programmes related specifically to hull structures to assist clients.

The first programme has been designed on the basis of one of several analytical approaches which have been developed to predict this behaviour. The technique is dependent on a reliable knowledge of material properties to determine crack growth rate under reversals of stress, and also the critical crack size.

The second programme provides an estimate of the fatigue life of structures subject to fluctuating loads. The programme requires a knowledge of the stresses occuring in the structure and the fatigue characteristics of the material.

The calculations can be used either to provide comparative information between structures or in more specific cases where data are reliable, as a direct method of failure prediction.

7 Manufacturers' Approval

Lloyd's Register have, for many years, operated schemes for the approval of manufacturers producing equipment in conformance with the Rules for Construction and Classification.

The Society have encouraged systematic quality control and the current trends by many manufacturers in this direction is most welcome.

All manufacturers seeking approval must, in the first instance, satisfy the Society that they have a clearly defined management structure ensuring that the executives responsible for quality and inspection functions, and their subordinates, are free from production pressures. They must have a responsible policy for the recruitment and training of personnel for production as well as inspection duties.

Where steel is to be supplied with the LR Brand the steel making processes, inspection techniques, and testing facilities, are approved by the Surveyors who attend regularly at these works, ensuring that the arrangements for steel making and inspection are satisfactorily maintained.

For pressure equipment, the Society's Rules include for three main classes of vessel. Fabricators seeking approval are required to carry out preliminary tests to demonstrate their ability to construct vessels to the appropriate classes. These tests include weld procedures for various types of steel in specified thickness ranges.

More recently, the Society has introduced a Quality Control Scheme for Batch and Line produced equipment. The scheme applies to the certification of items produced in quantity, such as valves, where it is impracticable to examine each item during all stages of manufacture. In these cases, the manufacturer is required to define a quality control programme ensuring that adequate standards are maintained with arrangements providing for detection of discrepancies, together with effective corrective action throughout production. The scheme requires the maintenance of detailed records of the results of inspection and tests.

8 Conclusion

In conducting the business of independent inspection, the approach of Lloyd's Register is that all aspects and matters having an influence, direct or indirect, on the fitness for purpose and the safety in service of any fabrication, must be considered and their significance assessed. To operate effectively the Society must be aware of the functional needs of the purchaser in respect of safety and service requirements. A co-operative relationship between inspector, designer and manufacturer is of paramount importance.

APPENDIX

Ship Structural Steels

As outlined in the foregoing paper, the choice of material for a specific application depends upon the functional needs of the purchaser in respect of safety and service requirements.

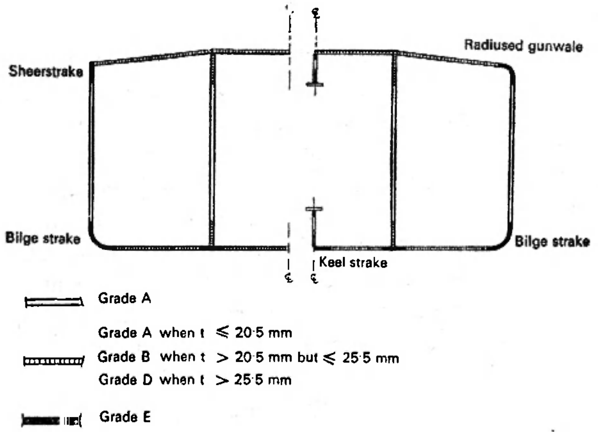
To illustrate this, Lloyd's Register Rules for the Construction and Classification of Steel Ships make provision for a series of steels to cater for different prime applications as follows :—

Mild Steels

There are four grades which have the same physical properties apart from notch toughness i.e.
Yield Stress : 24 kg/mm^2 min.
Tensile Strength : 41/50kg kg/mm^2
Elongation (on 5.65 $\sqrt{So}$) : 22% Min.

Grade A — This is a carbon steel of composition
Carbon : 0.23% max.
Manganese : Not specified but for material over 12.5 mm thick ratio of Mn/C is to be not less than 2.5.
Deoxidation : Usually semi-killed but rimmed steel is acceptable up to 12.5 mm thick. Material over 50 mm thick is usually silicon killed.
Heat Treatment : Usually "as-rolled".
Charpy V-notch requirement.
None specified but 2.8 kgm at + 20°c is expected.

Grade B — This is a carbon manganese type of steel of composition :
Carbon 0.21% max. Manganese 0.80% min.
Deoxidation : Usually semi-killed but sometimes silicon killed. Rimmed steel is not acceptable.
Heat Treatment : Usually "as-rolled".
Charpy V-notch requirement :
2.8 kg.m. min. at 0°C. Batch test — one set of three impact test pieces per 40 tonnes.



Typical Distribution of Steel Grades—Mild Steel. Simplified midship section for an oil tanker over 260 metres in length.

Grade D — This is a carbon manganese type of steel composition :
Carbon 0.21% max. Manganese 0.60 to 1.40%.
Deoxidation : Varies according to national practice. In many countries supplied as semi-killed and in others as silicon killed or aluminium treated fine grained steel. Rimmed steels are not acceptable.
Heat Treatment : Rules require normalising or controlled rolling for thicknesses over 25.5 mm but frequently steelmakers elect to heat treat material of less thickness.
Charpy V-notch requirement :
Either 4.8 kg.m min. at 0°C or 2.8 kg.m min. at—20°C. The test temperature is presumably at the option of the steelmaker but this is a transient requirement and it is intended in a future revision of the Rules to adopt only one test temperature. Batch test like grade B steel.

Grade E — This is a fine grained carbon manganese steel of composition :
Carbon 0.18% max.
Manganese 0.70 to 1.50%.
Aluminium (acid soluble) 0.015 to 0.06%, or
Aluminium (total) 0.020% min.
Deoxidation : Fully killed fine grained practice (Aluminium treated).
Heat Treatment : Normalised
Charpy V-notch requirement :
2.8 kg.m min. at—40°C. One set of three impact test pieces are required from each piece rolled.

In addition to above limits for carbon and manganese contents it is also a requirement for all grades, to ensure adequate weldability, that C + Mn/6 does not exceed 0.40%.

High Tensile Steels

There are four different strength levels each subdivided into three grades with differing notch toughness. The strength levels are designated by the value of the specified minimum yield stress.

Strength Level 27 : Grades AH27S, DR27S and EH27S. These are carbon manganese steels of composition :
Carbon 0.18% max. Manganese 0.70 to 1.60%.
Deoxidation : AH27S. Usually semi-killed but sometimes silicon killed.
DH27S. Either semi-killed or aluminium treated fine grained steel. EH27S. Required to be fine grained steel.

Heat Treatment : AH27S. Usually "as rolled".
DH27S. Required to be normalised or controlled rolled over 25.5 mm thick.
EH27S. All thicknesses are required to be normalised.
Mechanical Properties :
Yield Stress : 27 kg/mm^2 min.
Tensile Strength : 41/52 kg/mm^2 min.
Elong (on $5.65\sqrt{So}$) 22% min.
Charpy V-notch :
AH 2.8 kg.m min. at 0°C.
DH 2.8 kg.m at — 20°C.
EH 2.8 kg.m at — 40°C.
Material is batch tested — one tensile and three impact test pieces per 40 tonnes except for grade EH27S where impact tests aie required from each piece rolled.

Strength Level 32 : Grades AH32, DH32 and EH32. These are fine grained carbon manganese steels of composition :
Carbon 0.18% max. Manganese 0.80 to 1.60%.
Deoxidation : Usually all grades are supplied as aluminium treated fine grained steels.
Heat Treatment : Rules currently require for AH32 and DH32 grades that material over 12.5 mm thick either be normalised or controlled rolled. It is intended however to revise this requirement and permit thicker materials to be supplied in the "as rolled" condition. Normalising is required for EH32S.
Mechanical Properties :
Yield Stress : 32 kg/mm^2 min.
Tensile Strength : 45 to 60 kg/mm^2.
Elong (on $5.65\sqrt{So}$) : 22% min.
Charpy V-notch :
AH 3.2 kg.m. min. at 0°C.
DH 3.2 kg.m. min. at —20°C.
EH 3.2 kg.m. min. at —40°C.
Test frequency same as strength level 27.

Strength Levels 34 and 36 : Grades AH34S, DH34S, EH34S. Grades AH36, DH36 and EH36.
These are fine grained carbon manganese steels of composition :
Carbon 0.18% max. Manganese 0.80 to 1.60%.
Deoxidation : Usually all grades are supplied as niobium treated, silicon killed, fine grained steels. Occasionally supplied as niobium treated semi-killed steel and more recently vanadium treated steels are being used.
Heat Treatment : Normalising or controlled rolling is required for AH and DH grades over 12.5 mm thick. Normalising is required for grade EH in all thicknesses.

Mechanical Properties : See Table 1.

TABLE 1 Mechanical Properties

	Strength Level 34	*Strength Level 36*
Yield Stress :	34.5 kg/mm^2 min.	36 kg/mm^2 min.
Tensile Strength :	62 kg/mm^2 max.	50 to 63 kg/mm^2
Ratio. Yield/ Tensile	0.85 max.	—
Elong (on $5.65\sqrt{So}$) :	22% min.	21% min.
Charpy V-notch:	AH 3.5 kg.m. min. at 0°C.	—
	DH 3.5 kg.m min. at —20°C	—
	EH 3.5 kg.m. min. at — 40°C.	—

For all strength levels, in order to ensure adequate weldability, the contents of residual elements are restricted and also a maximum carbon equivalent is specified. This is calculated from the following formula :

$$C.E. = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15}$$

and is not to exceed 0.41% where it is not intended to have any restriction on the types of electrodes used for welding. Where the welding consumables and processes used are all of the low hydrogen type the carbon equivalent content may be increased to 0.45% maximum.

Welding Consumables

It is required in the Rules of Lloyd's Register that all welding consumables used in hull construction are to be "type" approved. The initial approval tests consist of tensile and charpy V-notch impact tests taken from pads of deposited weld metal and similar tests plus bends from butt welds which where appropriate are prepared in different welding positions. Additionally, check tests are carried out annually on approved welding consumables and generally these consist of only mechanical tests from pads of deposited weld metal.

Welding consumables are graded according to the charpy V-notch impact values obtained and also may additionally be designated by the letter "H" indicating that they are of the low hydrogen type.

The requirements for approval tests of welding consumables are summarised in Table 2.

Grade 1 welding consumables are suitable for welding grade A (AH) to any grade of ship steel. Grade

2 consumables are used for welds between grades B and/or D (DH) steels or to grade E (EH) steel. Grade 3 consumables are required only for welds between plates of grade E (EH) steel.

Application of Steel Grades

Grade A steel is the basic material used for ship construction and the use of grades with superior notch toughness is confined mainly to the midships portion (0.2L forward and aft of centre line) of the hull where applied stress levels are higher. It is also recognised that a possible brittle fracture is dependent on thickness and the use of the different grades is as follows :

Mild Steel

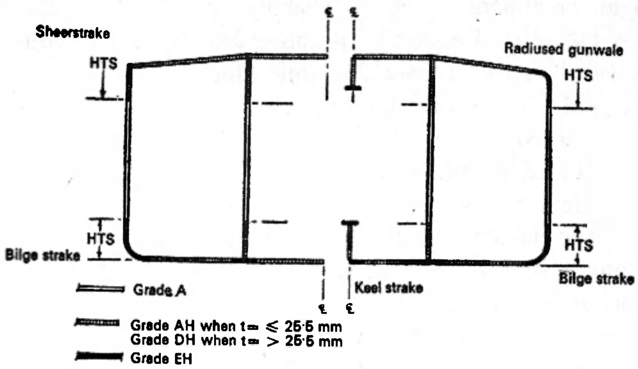
Grade A up to 20.5 mm thick.
Grade B over 20.5 up to 25.5 mm thick.
Grade D over 25.5 mm thick.

Higher Tensile Steel

Grade AH up to 25.5 mm thick.
Grade DH over 25.5 mm thick.

The use of grade E (EH) steel is confined to certain positions such as the bilge strakes and sheerstrakes and is intended to function as a crack arrester in the unlikely event of a crack initiating in either the deck, side shell or bottom.

Typical simplified midship sections are attached to illustrate the above.



Typical Distribution of Steel Grades—Higher Tensile Steel. Simplified midship section for an oil tanker over 260 metres in length.

When higher tensile steel is used, the thickness of material required is reduced generally in proportion to a scantling factor evaluated as undernoted :

$$\text{Scantling factor } R = \frac{25}{Y} \text{ or}$$

$$0.059 \frac{L}{D} \text{ or } 0.725$$

whichever is greater
when Y = specified minimum yield stress kg mm²
L = length of ship metres
D = moulded depth metres

It is generally recognised that in the as welded condition, the fatigue strength of higher tensile steel is little, if any, better than that of as welded mild steel, and it is for this reason that an overall minimum value of 0.725 for the scantling factor has been introduced.

TABLE 2

	Mild Steel		*Higher Tensile Steel*	
All Weld Tensile				
Yield Stress	31 kg/mm² min		36 kg/mm² min	
Tensile Strength	41 to 57 kg/mm²		50 kg/mm² min	
Elong : (on 5.65 √So)	22% min		22% min	
Cross Weld Tensile				
Tensile Strength	41 kg/mm² min		50 kg/mm² Min	
Cross Weld Bend				
Angle and Diameter of former	120° over 3t		120° over 3t	
Charpy V-notch	*Manual or semi-automatic*	*Automatic*	*Manual or semi-automatic*	*Automatic*
Grade 1 at +20°C	4.8 kg.m. min	3.5 kg.m min	4.8 kg.m min	4.0 kg.m min
Grade 2 at 0°C	4.8 kg.m. min	3.5 kg.m min	4.8 kg.m min	4.0 kg.m min
Grade 3 at —10°C	6.2 kg.m min	4.5 kg. min	6.2 kg.m min	5.2 kg.m min
or at —20°C	4.8 kg.m min	3.5 kg.m min	4.8 kg.m min	4.0 kg.m min