Keith Hartley Memorial Lecture

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PRESSURE VESSEL FAILURES
—impact on fabrication

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It gives me great pleasure to deliver this lecture in honour of Mr. Keith Hartley, a founder member and the past President of Indian Institute of Welding. In view of his memorable services to the institute's birth and growth, we feel that it is our pleasant duty to remember him by discussing the current topics on welding, which were dear to him.

Welding was the prime suspect for the failures of welded components in the nineteen fifties. Gaining knowledge from the bitterness of these failures, the outlook on welding changed tremendously. Developments, made subsequently, has transformed welding as one of the reliable manufacturing processes.

Introduction

On an ominous Friday, the 6th May, 1966 in Cockenzie, Scotland, a 68 feet long and 5.5 feet diameter high pressure boiler drum exploded during the site hydraulic test, when the test pressure reached 3980 psi. The right hand end of the drum was split extensively by two longitudinal fractures each sixteen feet long extending to the drum sling position. The pieces of plates thrown off were mostly held by the connecting pipework, but some smaller pieces dropped a few feet away on the furnace pipe work and the insulated remote casing. In the morning chillness of 44°F, the Scotish Boiler and General Insurance surveyors, along with a number of other men, had to watch in fright and shock 'the deluge of water' that followed this historic brittle failure.

The Cockenzie boiler drum was designed in accordance with BS 1113:1958. The drum weighed 164 tons and the material was Mn-Cr-Mo-V steel of Colvilles Ducol W 30 grade. The design pressure was 2775 psi(g) at 734°F.

The impact of this explosion had made people to suspect the very idea of fabrication by welding. There were sceptic remarks about the steel, nozzle design and the NDT techniques employed. The added fact that the pressure vessels made of the same steel had failed in two other sites, including the famous one at Sizewell, made the matters worse. In addition about nineteen downcomer nozzle welds in boiler drums made of Ducol W 30 had to be repaired in-situ.

The South of Scotland Electricity Board immediately set up a panel of inquiry supported by a technical sub-committee to investigate the failure. Eminent experts like M/s. A. H. Marsh, R. W. Nichols were members in this panel.

The Committee attributed the Cockenzie failure to a crack at the toe of an economiser nozzle and adjacent angle bracket. The available evidences suggested that the crack would have developed during stress relieving. The major recommendations of the Committee were—

1. Full consideration must be given to the complex residual stress systems around design discontinuities such as nozzle openings.
2. Non-destructive testing, preferably ultrasonic testing, should be made of all positions of possible high stress concentrations such as the nozzle welds and their vicinities after all the heat treatments are completed.

In fact, the Cockenzie failure is not just one instance in the history of brittle failures. During the late 1960s a survey on pressure vessels conducted by the 'UK Associated Offices Technical Committee' revealed that of the 12,700 vessels covered, prior-to-service failures were reported in ten cases of which three were catastrophic in nature. 132 failures during service relating to 1,00,300 operational pressure vessel years were recorded in UK. Of these, 7 were classed as catastrophic.

A recent failure statistics on pipe lines from West Germany states that out of 375 failures, 161 cases have been in butt welds on pipe fittings, 82 in valve castings, 45 in weld joints of straight pipes, 51 in straight pipes, 15 in pipe bends, 8 in fine mountings and suspensions and 13 in other locations.

Besides these failures, brittle fractures have been reported in tanks, bridges, dams and ships during the forties through fifties. The systematic thought process and the detailed investigations yielded fruitful results. Developments were thought of and brought about in the four major areas which were found to be key factors from the history of failures recorded. Thus improvements were gradually made in those four areas of:

1. Design
2. Steel
3. Workmanship
4. Non-destructive testing techniques

Today, the products are designed in close reality to their actual service conditions. Base materials and filler materials are evaluated for the service conditions and suitability for fabrication by the various welding processes. The evaluation of the weld joints would, in that case, be more scientific and reliable. The welded components, requiring reliable service demand fabrication of high strength steels with high standards of workmanship meeting exacting requirements of inspection.

Developments in Design

After half a century of welding fabrication, we are now hoping to sit back and think that we have had a fair control over the actual situation of straining the steel sections—straining by way of joining structural elements and other functional attachments.

There are two basic approaches in the design of pressure vessels.

1. Design based only on global primary stresses.
2. Design based on primary and secondary stresses and stresses due to external loads.

In the case of the latter, the design should take into account the most severe combination of loadings expected to occur under coincident conditions during operation and test. Detailed stress analysis, fatigue analysis, and if required, experimental stress analysis will have to be carried out at the regions of stress concentration. This design approach would mean usage of lower factor of safety.

Sharp corners, for example, promote cracking and they are to be totally avoided in any design. Sharp corners have also led to a significant number of brittle failures, notably at service below transition temperature of the steel. An abrupt change in wall thickness can raise the local stresses. To minimise the possibility of failures, in such cases, a 1 : 4 taper or counterbore is sometimes recommended. Slip-on flanges on pipes are limited in application to no higher than Class 300, primary pressure service rating as per ANSI B31.1.

In the case of nozzles, the design is very critical. This is so because the stress concentration factors in this region, range from 1.3 to 2.8. Added to this, the welding of the nozzle require higher skill. These joints are also not amenable for meaningful evaluation by non-destructive tests. Further, more appropriate weld joint designs, considering the base materials are to be adopted. A partial penetration nozzle weld is suitable for only carbon and carbon-manganese steels upto two inch thickness as per BS 5500. Flat end covers made of plates should have a plug type weld preparation to combat lamellar tearing.

In short, the most fundamental 'strength of materials' concepts of strain and stress to the detriment of ductility and strength are being re-evolved. The modern designs in steel structures are founded on sound theoretical knowledge and experimental data, simulating the accidental level strain concentrations induced artificially by defects generated in the laboratory. The manufacturer and the user tend to mutually agree on the kind of a special fracture test, where the test temperature, the nature and dimensions of the defect and the location of the artificial defect form the frame of acceptance. Other fields of accelerated development and application are the Computer Aided Designs (CAD) and Graphics.

Developments in Steel

The behaviour of steel under the influence of different service temperatures is very vital, especially for a pressure vessel designer. The impact values obtainable at different temperatures, put together, describe the temperature transition behaviour of the steel and allows the design engineer to make a suitable choice of the material. The notch toughness approach to testing the material using 'charpy notch' and the 'absorbed energy' concepts conveniently by-pass the complexity of plastic deformation due to strain concentration.

Most of the steels which had failed in a brittle fashion were having poor notch impact strength (of the order of 10 ft.lbs). A statistical analysis of the various steels tend to conclude that a minimum notch impact value of 20 ft.lbs. for carbon and carbon-manganese steels would avoid brittle fracture. This 20 ft.lbs. criterion is even now found in some of the codes including IBR.

Resistance to brittle fracture primarily is a function of the metallurgical structure and purity of the steel. Lower content of incidental elements and dissolved gases, better cleanliness, freedom from segregation, all improve the purity of steel. The purer the steel, the lesser will be the problem of transformation embrittlement and ageing. Purity will enhance the notch toughness. Normalising, quenching and tempering and the recent thermo-mechanical and ladle refining treatments were all aimed to improve the notch toughness, consistent with the strength of the steel. These processes will minimise the chances of liquation, lameller cracks and reheat cracks in steel.

The effect of chemical composition on susceptibility to cold cracking is expressed normally as a linear weighted summation of the major alloying elements and it is known as the carbon equivalent (CE). Recent advances in the development of high strength steels have made it possible to develop strength of 50 Kg/mm^2 at a carbon equivalent level of 0.30 to 0.35. On the contrary, a conventional steel with a strength of 50 Kg/mm^2 will have a carbon equivalent of about 0.50. It is also more or less established that if the steel has the reduction in area, minimum of about 20%, in the through-thickness direction, it will not be susceptible to lamellar tearing. The recent ASTM standard, A 770 incorporates this requirement. The through-thickness tensile property is again attributed to the cleanliness of steel. Vacuum degassing and ladle refining techniques produce ultra low levels of the impurities at economical prices. A comparison of the levels of impurities obtained with conventional and recent innovative steel-making processes are given in Table 1.

Table 1 Level of Impurities

	Conventional processes	Recent processes
Sulphur	0.02%	0.003%
Phosphorus	0.015%	0.009%
Oxygen	60 ppm	20 ppm
Hydrogen	3 to 4 ppm	1.5 ppm
%RA in through-thickness direction	5 to 10	30 to 80

Welding of higher thicknesses demand resistance to cold cracking or hydrogen induced underbead cracking which is, again, chiefly a function of the carbon equivalent. Higher carbon equivalents lead to cold cracks in the heat affected zone of the weld. Cold cracking susceptibility is also influenced by the level of diffusible hydrogen in the weld metal and at the heat affected zones. From the weldability angle, preventive measures such as proper energy input, pre-heat, inter pass, delayed cooling and post weld heat treatments minimise cold cracking.

There are number of tests, mostly of technological nature, for directly evaluating the weldability of steels, taking into consideration all the cracking aspects discussed. Tests like CTS, Tekken, Transvarestraint, Thermal Cycle Simulation and Implant have been developed to assess the weldability of steels.

An increasing awareness of those tests are noted recently in our country. The manufacturers specify certain weldability tests for the type of steel selected.

Improvements in Workmanship

There are a number of groups involved in the manufacture of a product : the designer, the manufacturer, the raw material supplier and the inspection agency. Fitness-for-purpose and cost implications are always kept in mind by the above groups. Quality is an intrinsic property of any product, which has two facets : reliability and safety. We, today, live in a more reliable and creative world of technology ; dispensing away the fear that is imbibed in safety as a distant echo. Codes and specifications are only there to assist us in achieving this, by clearly placing the quality factor on an economic scale.

However, the situation in the forties through sixties had been quite different. Poor workmanship causing fabrication notches had been blamed for initiation of cracks, by an IIW Committee which went into the causes of brittle failures during this period. Some of the major areas of weakness traced by the Committee were flame cut edges, weld defects, and underbead cracks.

Gas cut edges, if left as such, without proper grinding and dressing, can be dangerous as can be seen from the fracture of a 85 mm thick plate while attempting to correct a bow by cold pressing. The gas cut edges leave a very hard zone with deep grooves, and these metallurgical notches can be a potential source of fracture.

A controllable, yet incorrigible, feature of workmanship shows itself up as weld defects. Weld defects range anything from geometric irregularities like excess penetration, misalignment and volumnar defects like porosities, slag inclusions and worm holes to the most vulnerable planar discontinuities such as cracks and lack of fusion. Talking of weld defects, I feel it is very apt to quote Mr. Helmut Thielsch—

"The effects of defects in welds and base materials on the service life of pressure vessels, tanks, and piping are largely misunderstood by engineers and in inspection codes establishing acceptability limits. Great emphasis and tight restrictions are placed on some defects, while others are ignored, even though they may be considerably more detrimental to the service life."

It will only be through efforts involving cogent review by many a qualified investigator, that widely acceptable 'fitness-for-purpose' information can be made available.

By and large, the workmanship has to be ensured by establishing written and approved welding procedures, employing skilled and certified welders and quality-minded supervisors. The welders are to be trained intensively and qualified on the different welding procedures including the material classes, the electrodes and the positions, with an accent on electrode baking, pre-heating, interpass cleaning and post-heating. It is always emphasized to impart the theoretical aspects of the welding jobs to welders and supervisors so that certain amount of quality by way of responsibility and involvement can be assured.

Trends in Non-Destructive Testing

Since perfect materials do not exist, one has to allow for a certain margin of imperfection in a component or a system. The role of inspection is to detect any imperfection exceeding the allowable margin. The field of NDT has risen to the exacting requirements of the fabrication technology. The scope of NDT does no longer confine to the shop floor inspection, but it encompasses the in-service inspection of components at site. This is in tune with the 'fail-safe' and 'replacement' concepts of the present day. NDT tends to be more and more of a quantitative estimation of flaws, with a mounting pressure from Fracture Mechanics. A probabilistic approach is evident in this area. Perhaps, one sentence would precisely summarise the state-of-the-art in NDT. "What is seen depends on how you look and how you look depends on what you are looking for."

Surface defect detection tecnniques like liquid penetrant inspection, magnetic particle inspection and other techniques like ultrasonics, radiography, eddy current testing, acoustic emission and leak testing have become very popular over the years.

The selection of a proper technique or a combination of techniques should be judiciously made taking into account the type of defects expected in the process. The type of defects vary with the welding process adopted. For example, in electroslag welding of thick boiler plates, the main types of defect expected are centre-line shrinkage, lack of sidewall fusion or interruption. Detection of these would call for a combination of ultrasonic testing, using normal and angle probes, radiographic and magnetic particle testing. Whereas, to check the integrity of a solid phase bond, like induction pressure weld, flash butt weld and friction weld, ultrasonic inspection alone would be appropriate. This should be in addition to the destructive tests conducted on samples.

It is evident that the proper use of technique and the correct interpretation, demand a great deal from the NDT personnel. The necessary skills and the job knowledge should be imparted to them through proper training and qualification. The American Society for Non-destructive Testing (ASNT) has a certification scheme, qualifying NDT personnel to three levels : operator, supervisor and technologist.

The beneficial contributions of NDT can be nullified or lost whenever the valid indications of non-destructive testing are not carefully observed, not reported or are reported falsely. The possibility is more when NDT personnel lack personal integrity or sincere motivation. There were instances of falsification of weld radiography of even nuclear components to save relatively small amount of money, substituting radiographs of good weld areas for those of poor welds to save repair costs, as reported by Bob McMaster. This topic is being wholly debated by ASNT. Each individual involved in NDT and Quality Control should do each task just as well as he would if he knew in advance that his carelessness would injure or kill himself, his loved ones, his entire family or his best friends.

Conclusion

Failure is the stepping stone to success ; of course, for the wise. May be, it is a hard way to learn. But for welding, being multidisciplinary, this was the course of growth.

The industrial growth during the second world war had one darker side, that everything had to be done, and done fast with limited resources. Even fitters were employed unscrupulously for welding tasks due to the urgencies and these led to many collapses of war time structures. The economic foundations of large firms were ramshackled as their technological strengths were put to defeat. The aftermath of these failures terrified the engineering society all over the globe.

But introspection led to steady developments over the years to follow. The major areas being in design, steel, workmanship and NDT techniques. Yes, we have learnt quite a lot. We are still learning and let the knowledge flow down. If only all those dedicated men in the chain utilise these developments gainfully, can we build the most sophisticated vessels with confidence. Let there be no more dark hours in the future of fabrication.