Is non-destructive testing of Welding really necessary ?

By H. C. COTTON*

Synopsis

The cost of non-destructive testing in terms of lost time is compared with other fracture safe testing techniques. It is concluded that because of code requirements NDT leads to too much repair of welding.

1. Is Weld NDT Necessary ?

The failure of two crude oil storage tanks at Fawley Refinery, England in 1951, like the Flixborough fire in 1976, marked the introduction of changes in methods of weld inspection and control which were to be profound. Things could never be quite the same again. Unlike Flixborough, the basic cause of the accidents at Fawley were not contested, although the precise mechanism was to be hotly debated for many years. It was more than evident that brittle fractures had initiated from weld imperfections in the shells of these huge tanks and that these cracks had run at high speed demolishing the whole structure in a moment. Moreover the point of fracture initiation in one of these tanks was indisputably at a cracked repair weld in a girth seam. Unbelievably, the faulty weld repair was to a groove resulting from the taking of a boat shaped probe sample. The sample had been taken to prove the quality of the seam which had turned out to be satisfactory in the first place. The faulty repair to this small groove had resulted in the total loss of the tank—it was the death knell of the destructive examination of production welds—the cure had proved more deadly than the disease.

There was a sudden swing to non-destructive testing (NDT) and especially to radiography, the use of which in industrial applications was of course known but hardly widespread. Radiography was at that time the only practicable system available for general use but little was known by inspectors about its application to steel weldments. Radiographing welds might have been more commendable if those involved had any clear notion about what to do with the exposed films. As it was, in those not so far off days, welding inspectors the world over were faced with myriads of radiographs depicting mystifying shadows the significance of which was hard to define. Soon it became evident that by means of slight changes in the composition or quality of the intensifying screens, the film grain, the density of the exposure, its contrast, the source size, source object distance, etc. etc. those tantalising shadows could be made larger or smaller or even, by means of a little judicial manipulation, to go away altogether. These effects were to lead to endless debate.

Further, those parts which proved to be most difficult to weld—around pressure vessel openings, manways, fillet welded stiffeners, etc. were found also to be the most difficult to inspect, impossible to check by practical radiographic methods in most cases and to require careful preparation even for successful surface inspection by dye penetrant or magnetic inks. Not surprisingly, such areas were frequently ignored in planning non-destructive testing schemes and in many cases they still are. For most constructions, the inevitable result was for non-destructive testing to be directed towards those areas least likely to cause trouble in welding and subject to the lowest levels of stress in testing and operation.

---

*The British Petroleum Co. Ltd., Engineering Dept., London. Reprinted with acknowledgments to Australian Welding Journal.

Yet, inexplicably, it seemed that from the time of the widespread adoption of NDT in oil storage tank, pressure vessel, pipeline, ship construction and other fields, the incidence of failure during proof testing and in operation was falling dramaticaly. This, despite the fact that the most vulnerable areas were being subjected to little more if any NDT than hitherto. There had to be a reason for this seeming paradox : it was not hard to find.

2. Notch Ductlity

At the same time as the use of NDT was rapidly expanding, the cause of the intolerance to imperfections of weld metal and certain weld heat affected zones found typically in fusion welded joints had been traced to deficiencies in notch ductility. This shortcoming it was found, could arise because of several effects, but the ratio of carbon to manganese in the steel parent metal itself was found to be very important as was dynamic strain ageing effects both in parent and in weld metal. Lack of attention to the significance of grain size in weld metals and heat affected zones was also found to be important. Weld metals in use at that time presented significant deficiencies but, more importantly, some semi killed steel plates displayed unexpected sensitivity to the temperature of weld heat affected zone isotherms which gave rise to surprisingly severe loss of notch ductility under the action of residual compressive strain effects associated with welding. The use of such steels in important welded constructions was soon discontinued or reduced to a very low level. As a result, the primary cause of low stress fracture initiation in mild steel plate had been eliminated almost at a stroke, but no reduction or change in NDT requirements was to follow. We had frightened ourselves enough : weld NDT was here to stay. In fact the trend was in the opposite direction, for the use of weld NDT was to expand greatly.

The pursuit of higher design stresses in order to reduce the tonnage use of the more costly notch ductile steels gave further impetus to the quest for the discovery of ever smaller weld imperfections and their elimination. This was because of confusion as to the precise cause of low stress fracture initiation. Higher design stresses were thought to be more dangerous than the lower levels with which there was much experience but nevertheless many areas of high stress concentration in welded fabrications were still not examined effectively merely because of the difficulties involved in applying the non-destructive testing system itself. Despite the indisputable evidence that strain intensification factors appropriate to locations containing design discontinuities become increasingly significant as the nominal stress is increased, NDT continued to be concentrated upon the inspection of simple butt welds. Yet, still, the incidence of failure was kept to a low level not least because the provision of steel with higher notch ductility means lower carbon content to preserve good carbon manganese ratio and this ensures also that weldability will be improved. As a result, weld heat affected zones will usually be sufficiently notch insensitive unless C Mn steels are used at very low temperatures or the weld thermal input is very high.

The unsatisfactory position in respect of NDT limitations was well known to many of those concerned with standardisation and inspection and before long concentrated effort was made to devise NDT techniques suitable for the examination of problem joints. This resulted in the development of sophisticated ultrasonic and other inspections systems, which were frequently difficult or slow in use, introduced problems in interpretation and required highly skilled operators. The great majority of complex areas in welded fabrications remain to this day uninspected except in the most superficial manner because the time necessary to allow for the application of more painstaking methods simply cannot be spared.

The continued good experience as measured by a low incidence of failure during testing and in service seems to be attributable to the probability that, in the main, weld joint imperfections present in those areas is smaller than the critical dimension for the notch ductility inherent in the welding procedures used.

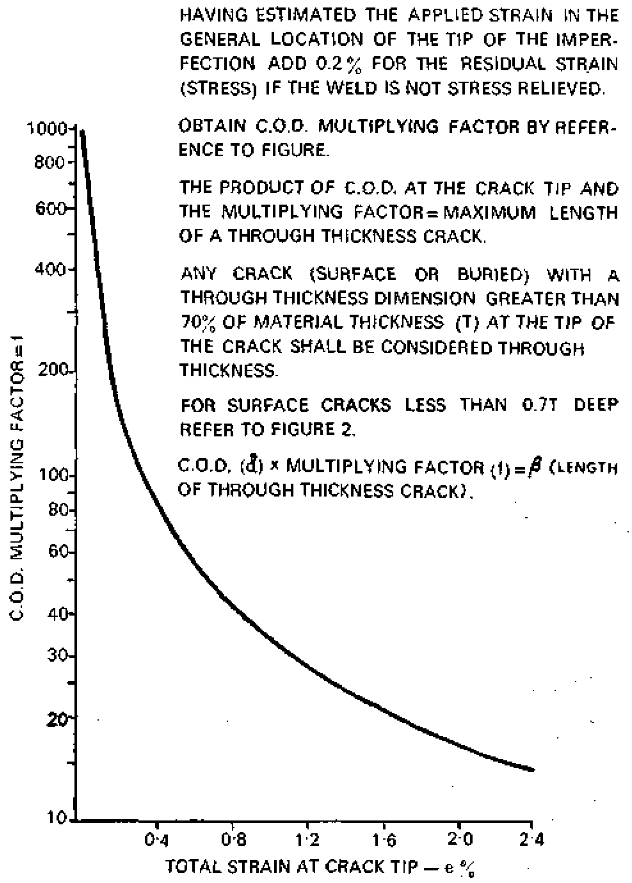
3. The Significance of Stress

It is hardly necessary to mention that critical flaw size is a function of stress and this should make the successful behaviour of welded joints around nozzles and openings in pressure vessels even more unlikely if they contain imperfections. Such areas must be safeguarded against premature failure and in lieu of non-destructive testing in such areas much reliance is placed upon overload proof testing. It is believed that a prior hydrostatic proof test of a pressure vessel at a warm temperature can be expected to blunt the tips of cracks or crack like imperfections, at the same time leaving, as an added bonus, pools of residual compressive stress to shield the now less potent crack starters ; in practice this seems to work very well. This begs the question that if the hydrostatic proof test is a satisfactory alternative to NDT in problem areas, why then should it not be permissible to discard the requirement for NDT for the simpler joints when these are exposed to the same type of proof test

Nowadays, welded constructions appear to derive their safety from a combination of effects and we are beginning to discover how to maximise these. The poor performance of longitudinal seams in transmission line pipe which, until the advent of a 100% non-destructive testing together with improved notch ductility in the welded seam, was inclined to burst frequently in the cold expander at strains in the order of 1-2% is an example of this. Pipes which manage to survive this test usually provide satisfactory life in service. The combined effects of non-destructive testing to eliminate weld flaws greater than the critical size, coupled with the provision of enhanced notch ductility to permit the increase of the size of allowable flaw sizes to practical limits and thus reduce repair requirements, has made it possible to produce a reliably safe product at an economical price. In the last few years, bursting in the expander is as much of a rarity as is the brittle fracture of pressure vessels during hydrotesting. We have solved the problem but at what a cost ! Evidently non-destructive testing, the provision of much notch ductility and proof testing are all techniques for achieving much the same result even if by different means. Is it not possible to obtain relief from one or more of these competing safety assurance systems when considerable emphasis and care is applied to the application of one of these ? In most cases, non-destructive testing is quick, clean and easy to apply. Its application to highly selected areas should surely result in some reduction in other quality assurance requirements, for example, overload proof testing. But before this can be considered, it is worth questioning whether the presently available non-destructive testing methods are capable of detecting significant imperfections and measuring their vital statistics especially in locations where there are important design discontinuities.

4. Significance of Flaw Size

A glance at Figures 1 and 2[1] is sufficient to indicate that in estimating the significance of an imperfection there is an important and fundamental relationship which cannot be ignored between the depth of a flaw and its length. Without knowing these two parameters no calculation of critical flaw size can be made. This fact is embarrassing because most, if not all, of the NDT techniques presently available only allow the accurate measurement of one of the important size parameters, that of the length. Measurement of the other important dimension, the depth of the imperfection has proved most difficult in practice in assessing the precise dimensions of weld imperfections encountered. In the field welding of pipelines for example, the non-destructive techniques used normally are capable only of measuring the length of the imperfection. This costly deficiency, i.e. that neither radiography nor ultra sonic examination can be applied in a sufficiently speedy and simple way as to measure the depth at all accurately precludes the application of realistic criteria to pipeline weld assessment. Most codes do not even mention this consideration, although they are all most meticulous in defining the exact maximum permitted length of an imperfection. Such rules are only correct for one single dimension of



HAVING ESTIMATED THE APPLIED STRAIN IN THE GENERAL LOCATION OF THE TIP OF THE IMPERFECTION ADD 0.2% FOR THE RESIDUAL STRAIN (STRESS) IF THE WELD IS NOT STRESS RELIEVED.

OBTAIN C.O.D. MULTIPLYING FACTOR BY REFERENCE TO FIGURE.

THE PRODUCT OF C.O.D. AT THE CRACK TIP AND THE MULTIPLYING FACTOR = MAXIMUM LENGTH OF A THROUGH THICKNESS CRACK.

ANY CRACK (SURFACE OR BURIED) WITH A THROUGH THICKNESS DIMENSION GREATER THAN 70% OF MATERIAL THICKNESS (T) AT THE TIP OF THE CRACK SHALL BE CONSIDERED THROUGH THICKNESS.

FOR SURFACE CRACKS LESS THAN 0.7T DEEP REFER TO FIGURE 2.

C.O.D. (δ) × MULTIPLYING FACTOR (f) = β (LENGTH OF THROUGH THICKNESS CRACK).

Fig. 1. Relationship between C O D multiplying factor and total strain at crack tip.

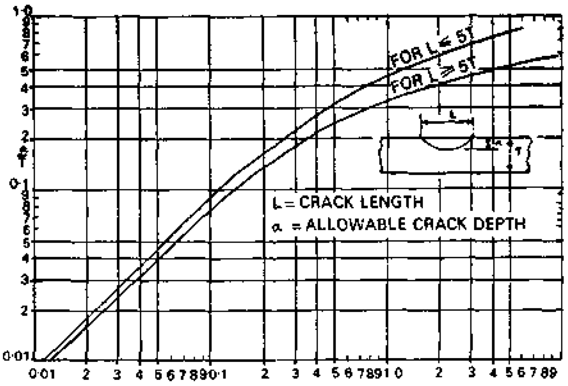


Fig. 2. Relationship between surface flaw dimensions and length of an allowable through thickness crack (β).

flaw depth and as a result much costly repair of insignificant imperfections is demanded and costs escalate without any improvement in safety. Often it is obvious to both welder and inspector that rejected imperfections are harmless but the code leaves no room for judgement.

As if these deficiencies were not enough, variations in the applied stress surrounding an imperfection arising from its particular location are commonly ignored by codes and standards, the dimensions of allowable imperfections are commonly the same for all locations, irrespective of the stress intensification factors appropriate to the areas under consideration. This is indefensible. In the case of the transmission pipeline, the practice of ignoring the significance of stress in calculating allowable flaw size becomes particularly ludicrous when it is realised that the total stress can vary between static stress in compression to cyclic stress in tension depending upon the orientation of the imperfection, its location and the type of pipeline. Axial stresses in buried pipelines for example are usually either wholly compressive or weakly tensile, except at the apexes of bends where high tensile stresses may be experienced. Longitudinal imperfections in circumferential welds in buried pipelines are thus rarely of much significance whereas transverse cracks in the same location might assume vital importance depending upon the notch ductility provided at the temperature under consideration. Little mention of the significance of transverse imperfections is made in typical pipeline codes, yet the length of imperfections axial to the girth weld forms the very basis for the allowable flaw size measurement. That such omissions should be permitted in codes affecting public safety and billion dollar constructions is incredible.

A Draft Guidance Note issued by British Standard Committee WEE/37[2] is intended for use in calculating critical flaw sizes ; this document is thought to be as reliable a guide as anything else presently available. Its application to the calculation of critical flaw dimensions for various locations in a typical pipeline or pressure vessel provides startling comparisons between the calculated sizes and those specified as rejectable in various Codes. If the calculated sizes are not totally wrong then the Codes are evidently in need of urgent revision. Figures 3 and 4 which are reproduced from another paper[1] are shown here to demonstrate how flaw size depth/length ratios are related in a typical pipeline application. It will be noted that an allowance has been made in calculating allowable flaw sizes for crack growth in service by a corrosion fatigue mechanism which was a design feature of this particular construction.

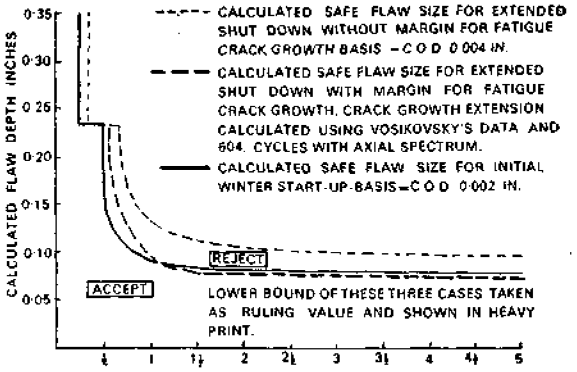


Fig. 3. Calculated safe flaw sizes for buried weld and HAZ imperfections.

(Based on Draft BS 75/77081 DC assuming imperfections are surface cracks)

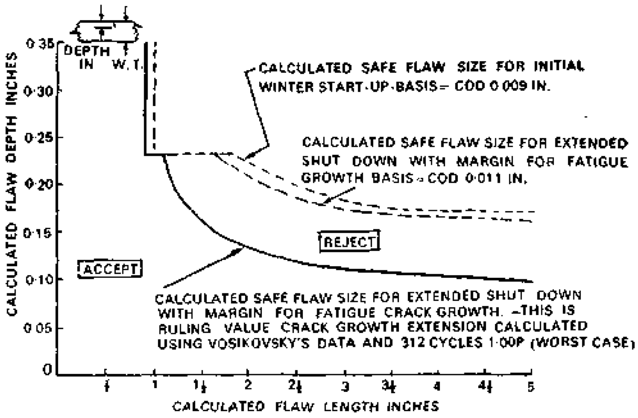


Fig. 4. Calculated safe flaw sizes for outside surface imperfections on base metal-arc burns. etc.

(Based on Draft BS 75/77081 DC assuming imperfections are surface cracks)

5. Collecting the Necessary Information

The non-destructive testing of welds is in itself neither costly nor difficult, but the cost of delay arising out of time lost in unnecessary repair work is onerous to a degree. Presently there is much resistance to non-destructive testing and any extension of its use is regarded with dismay by most owners and many fabricators. Yet a significant increase in the intensity of NDT might even be helpful in ensuring enhanced safety as well as being acceptable to those concerned if the present concomitant of extensive repair work could be avoided. However, most present Codes and Standards are simply not yet sufficiently advanced to permit this.

Non-destructive testers are not to blame for the present inadequacies of Codes and Standards, neither are inspectors or fabricators. It will probably require much joint effort before progress toward the achievement of realistic standards becomes even noticeable.

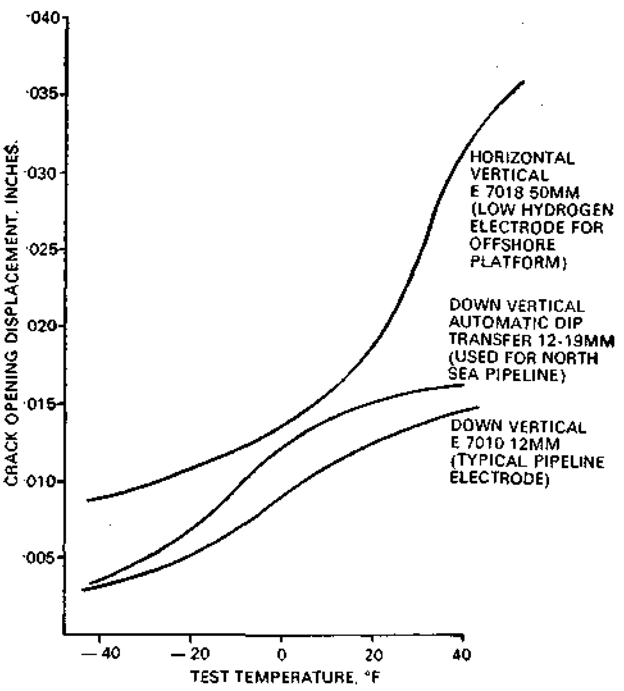


Fig. 5. Typical maximum crack opening displacement (COD) for various weld metals.

As already mentioned, no valid assessment of the significance of flaw size can be made without taking into account the intensity and nature of the stress around the imperfection, its history in terms of proof testing, mechanical and thermal stress relief, the notch ductility of the material surrounding the flaw and the effects of crack growth processes arising out of cyclic stress, creep, etc. where such conditions apply. This being true it is essential that designers be more closely involved in planning NDT requirements and they should be encouraged to associate themselves more closely with shopfloor and field fabrication processes. As far as possible it should be required that drawings give guidance as to the anticipated levels of stress in the locations for which NDT is required.

Even the provision of these data will not be sufficient in themselves to allow for critical flaw sizes to be calculated. To do this, it would be necessary to know what value of crack opening displacement (COD)[2] could be anticipated for the particular joint under consideration. This will vary according to the consumables used, the welding procedure, the use of pre or post heat treatment, the thickness of the material, and position of welding and the design temperature. This may seem to be a formidable list and if it is required that this be demonstrated by individuals for every welding procedure test, the work involved could conceivably become almost as onerous and time consuming as the alternative of making unnecessary repair welds. For this reason, it is suggested that any rigid requirement that COD testing become part of normal procedure testing should be resisted.

As an alternative, it is suggested that use be made of standard data made available through the medium of a central data bank under the control of a national or international authority such as ISO, IIW or British Welding Institute. The availability of such a bank could relieve fabricators of a laborious and costly task which can only be undertaken if the very specialised equipment required is available. Much of the required data already exists covering most thicknesses and welding procedures in common use, but the information is in the hands of individuals who regard this as proprietary knowledge. The incentive for pooling these data must be the realisation that this will lead to more realistic code requirements. There is already quite sufficient information available relating to probable COD properties to allow for a complete new look at allowable flaw sizes. COD methods of critical crack size assessment are being used regularly in such applications as offshore platforms, land and marine pipelines, pressure vessels for nuclear, petroleum and chemical industry use.

When making COD tests, much scatter is evident and it has become practice to use the lowest value obtained in calculating critical flaw size (Figure 5). This is ultra conservative but even if lower bound values of COD are adopted and if these are related to conservative estimates of stress, it is believed that the resulting computed allowable flaw sizes will permit a drastic improvement in the amount of weld repair work and thus prove to be of great benefit to the whole of industry. All this may seem a daunting task but it is a necessary one and if it is not tackled soon it is feared that much of the NDT presently applied to heavy steel fabrications will turn out to be just a sham.

6. Conclusion

There are good reasons for maintaining the present levels of non-destructive testing and even an increase in the intensity of its application might have advantages in some applications in ensuring enhanced reliability in testing and in service. However, opposition to this is evident as the ever increasing cost of repair welding, which seems presently to be inseparable from NDT and a function of the intensity of its use becomes less and less tolerable. There are reasons for this growing resistance. Constructions such as refineries, chemical works, pipelines, offshore structures and the like are now so costly and complex that delay to the completion of components can have a significant and disproportionate effect upon the total cost. One major cause of delay and probably the most important reason for failure to meet delivery promises arises out of excessive repair to welded joints. This is because certain codes demand a standard of welding quality which cannot be achieved by the processes in general use without much difficulty. For economical working, the statistical chance of achieving, first time, joints with no welding imperfections greater than the permitted size must be good. This is presently not often the case and as a result a great deal of time and money is spent trying to rectify minor weld imperfections. The significance of weld imperfections is very much dependent upon notch toughness and this means that there is a minimum required notch ductility for a given welding process and application. These relationships can be establihsed by means of COD and this should be permitted by codes and standards instead of demanding slavish compliance with unrealistic requirements.

It should not be required that COD information be established by individuals although this should be permitted. A central bank of COD data could easily be established and, this would reduce considerably the difficulties of applying fracture mechanics data to real life problems. This will require the pooling of the vast quantities of existing COD data presently in the hands of competing entities.

Acknowledgement

Permission to publish this paper has been given by The British Petroleum Company Limited.

References

1. MACAULAY, I. M. and COTTON, H. C. "Using Steel in Arctic Constructions". Conference on "Materials Engineering in the Arctic", Quebec, Canada, September, 1976.
2. "Rules for the Derivation of Acceptance Levels for Defects in Fusion Welded Joints." Draft Standard Document 75/77081 DC, British Standards Institution, 1975.
3. COTTON, H. C., DENHAM, J. B. and DOBLE, K. R. "How to Conduct COD Tests and Utilise the Results in Practice". First International Symposium of the Japan Welding Society, Tokyo, November, 1971.

TO ALL MEMBERS

Please inform immediately THE INDIAN INSTITUTE OF WELDING, 48/1, Diamond Harbour Road, Calcutta-700 027 of any change in your address to facilitate the mailing of periodicals and papers.

EDITOR