# FUNDAMENTALS IN DESIGN OF WELD JOINTS

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## INTRODUCTION

The Technology of Joining metals by welding has undergone considerable developments since its inception The developments an on going process, has been fuelled by demanding application requirements The design methodology of welded joints and fabrication techniques have also evolved with time So is the case with inspection techniques It is generally agreed that the presence of discontinuities/defects in welded joints is unavoidable The earlier conventional acceptance standards for welds were closely related to

a Achievable standards of good workmanship

b The detection capability of available inspection methods and

c Supporting evidence of satisfactory performance in service

In the absence of any knowledge of engineering significance of weld disincontinuities/defects these acceptance criteria were formulated without any direct relation to their effects on structural integrity However the intensive research in recent years on exploring the significance of weld defects and their impact on service performance of welded structures has provided for changes in approach to design & fabrication of weld joints

This paper attempts to present some of the design aspects of weld joints which affect the service performance of the welded structure/component

### Salient Aspects of weld joint design

While it is anticipated that designer would have correctly accounted for all the loading details, made proper choice of materials and assured acceptable level of quality during fabrication of welded structure, early failures can still occur as indicated in fig-1 due to lack of adequate knowledge on the behaviour of weld joints (1) This clearly highlights the importance of understanding the behaviour of weld joints as a means to ensure & enhance the service performance of a structure/compo-

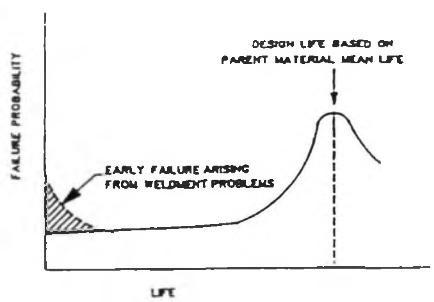



Fig 1 Schematic representation of the probability of failure during the life of a Welded Component

TABLE 1
**CHARECTERIZATION OF WELD DISCONTINUTIES / DEFECTS**

Weld Process & Procedures Related
A Geometric
- Misalignment
- Undercut
- Concavity or convexity
- Excessive reinforcement
- Poor reinforcement
- Poor reinforcement angle
- Overlap
- Burn through
- Backing ring-lack of penetration
- Insert ring-lack of fusion
- Backing-left on
- Incomplete penetration
- Lack of fusion
- Shrinkage
- Surface irregularity-ripples

B Other
- Arc strikes
- Slag inclusions
- Tungsten inclusions
- Oxide films
- Weld dressing
- Spatter
- Arc crater

Metallurgical
A Cracks or Fissures
- Hot
- Cold or delayed
- Reheat, stress-relief or strainage
- Lamellar tearing

B Porosity
- Spherical
- Worm-hole

C. Heat-affected zone microstructure alteration
D. Weld metal and heat-affected zone segregation
E Base plate delamination

Design
A Changes in section stress concentration
B Weld Joint Type.

nent Towards this end, it is essential to characterise the weld defects/discontinuities apart from the fact that weld by itself may present a structural discontinuity Table 1 lists the majority of weld discontinuities under three broad classifications (2). It must be noted that not all the defects have the same magnitude of influences on the weld performance the type, nature (crack, planar or 3D) and orientation are some of the finer aspects that must also be clearly defined An appreciation of the influence of the defects on the performance of welds would be the most appropriate step before attempting to analyse a weld joint.

By far fatigue failure of weldments has received wide attention among researchers as it is one of the main factors that limit the life of structures Welding introduces flaws which act like pre-existing cracks and hence the importance of fatigue in welded structures. The profile deviations such as under cut or excess reinforcement greatly influence the fatigue strength of butt welds Fig. 2 shows the variation of fatigue strength vs reinforcement angle (3). The main cause for reduction in fatigue strength of misaligned transverse butt or cruciform welds is inroduction of additional tensile stress due to secondary bending which can be estimated by analytical methods by incorporating suitable SCFs (4). Fig-3 shows the comparison of experimental values for SCF and those predicted by the emperical relation (5) It can be seen that emperical relation provides an upper bound for the experimental values and can safely be used for misaligned butt joints Transition butt welds (Fig-4) also gives rise to similar effects as offset butt welds and in order to minimise the secondary bending effects a transition slope of more than 1 in 3 is preferred. In addition to offset misalignment dealt

TABLE 2

STRESS RUPTURE FACTORS FOR $10^5$ Hrs

| Temp° F | SS 304* | SS 316** | ALLOY 800H*** |
|---|---|---|---|
| 850 | 0 97 | 0 92 | 1 00 |
| 900 | 0 95 | 0 82 | 1 00 |
| 950 | 0 93 | 0 72 | 0 86 |
| 1000 | 0 91 | 0.62 | 0 82 |
| 1050 | 0.91 | 0 66 | 0 83 |
| 1100 | 0.89 | 0 64 | 0 83 |
| 1150 | 0.81 | 0 66 | 0 83 |
| 1200 | 0 71 | 0.64 | 0 83 |
| 1250 | 0 57 | 0.60 | 0 82 |

* Welded with E 308 or ER 308
** Welded with E 316 or ER 316
*** Welded with Er Ni Cr (INCO 82)

above, angular distortion or out-of-roundness (ovality) could also be present in fabricated components (6) One such example is peaking in shells indicated in fig-5 whose origin could be traced to either incorrect rolling or incorrect welding (7) As a worse combination, if all three are additive at a location, additional bending stress equal to the direct stress could be present, which has to be taken into account during design It must however be noted that joints subjected to bending are not sensitive to misalignment (8)

Fracture mechanics analysis has become an efficient tool to quantify the critical values for various weld defects eg 2-D planar cracks. The result could also be conservatively extrapolated to 3-D defects knowing that these def ts any case are less severe than the cracks of the same size A typical analysis (9) on butt weld joint (fig-6 ) indicates that misalignment/eccentricity of 15% of the plate thickness, which in practice is quite realistic, increases the critical value by about 100% irrespective of the plate thickness Fig-7 indicate the emergence of fatigue cracks leading to root failure or crack development from toe as a function of critical defect size vs thickness for various values of weld angle as indicated in fig-6 This phenomenon highlights how the surface cracks or LOF/LOP in the root influences the fatigue strength of the structure A fatigue crack from surface will be accelerated due to corrosive environment However results of a study (10) indicate that eccentricity (offset, transition etc) is

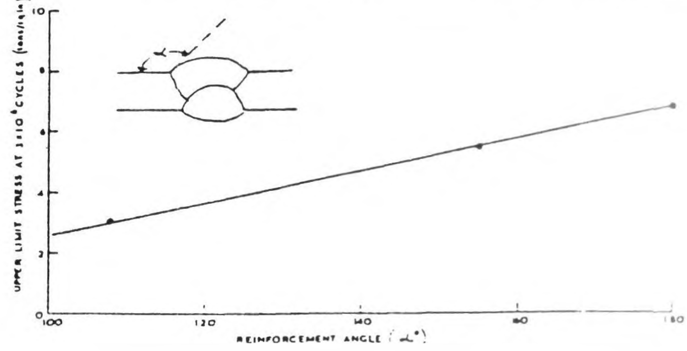


Fig 2 Effect of reinforcement bead angle on fatigue strength of transverse butt welds

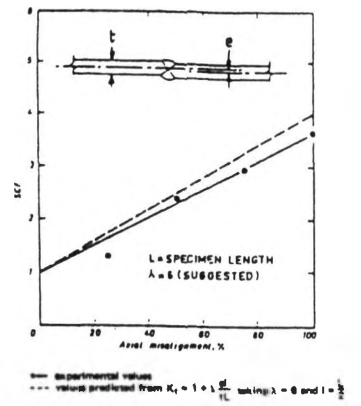


Fig 3 Comparison between experimental values of SCF and those predicted by Eqn. for $K_t$

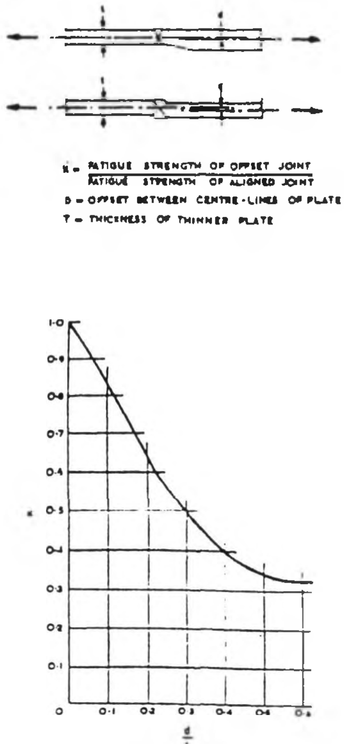


Fig 4 . Fatigue strength of offset or misaligned Butt-Welded Joints

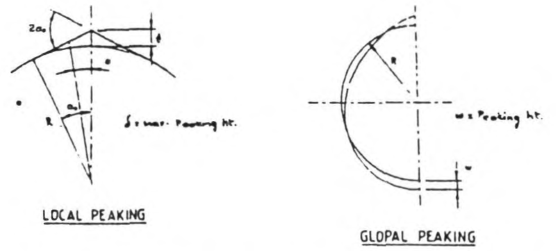



Fig 5 : Peaking phenomenon in Rolled - Welded cylindrical shells

more significant to probability of fatigue failure than the effects of corrosion Hence, efforts to increase the fatigue strength of high stressed welded joints should be concentrated on improval of the weld geometry and other structural details/restraint that affect the weld performance Many a times surface cracks appear near recess in stiffeners of a cross stiffened structure due to stress concentration effects This can be overcome by redesigning the recess opening as shown in fig-8 (11) In practice the effects of misalignment on stress not only depend on magnitude of misalignment but also on factors which influence the ability of the weld joint to rotate under induced bending moments Unless it is demonstrated that restraint on the joint reduces the influence of misalignment, the secondary bending stress should be calculated assuming no restraint.

Assuming that misalignment have been accounted for, there are two general principles for improving the fatigue life of welds namely to reduce SCF or to clamp the weld toe with compressive residual stresses The former can be achieved by removing the crack like imperfections and shaping the weld to give a more favourable profile Fig-9 shows methods of improved weld sequence profile (toe radius) to enhance the performance of weld and corresponding reduction in SCF is also indicated (12) There are many methods such as over loading, shot peening, grinding etc to introduce surface compressive stresses Analysis results show that weld toe treatment by grinding can improve the fatigue crack propagation life by upto 53% (13) Ref-14 discusses various such methods and their effect on fatigue strength All the methods have a marked influence on fatigue strength at comparitively larger number of cycles Literature survey also indicates that the fatigue strength of the weld is more influenced by the weld shape rather than on the slight undercut of usual depth (0,1 mm to 1 5 mm) (15) It is also indicated that the effect of PWHT in improving the fatigue performance of the weld is only slight or even negligible and is only helpful for negative values of R <-0.25 (16).

The quantification of the effect of fabrication quality on component performance has been possible with the advent of 'fitness-for-purpose' analysis procedures forming a basis for assesment of imperfections in welds This provides obvious link between the fatigue design rules and fabrication quality Methods for calculating the secondary bending stress to asses the influence of misalignment on service performance of the component are included in some 'fitness-for-purpose' procedures The acceptance of tolerable defects, with the adoption of 'fitness-for-purpose' criteria, should not construed as an excuse for reduction in

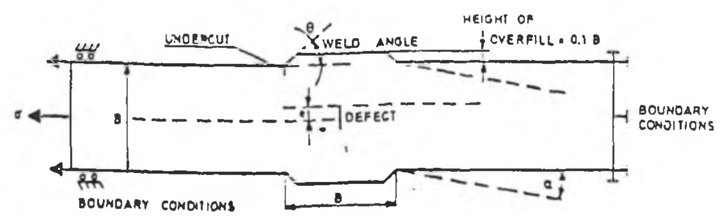


Fig 6 Model for analysis on the Butt Weld Geometry

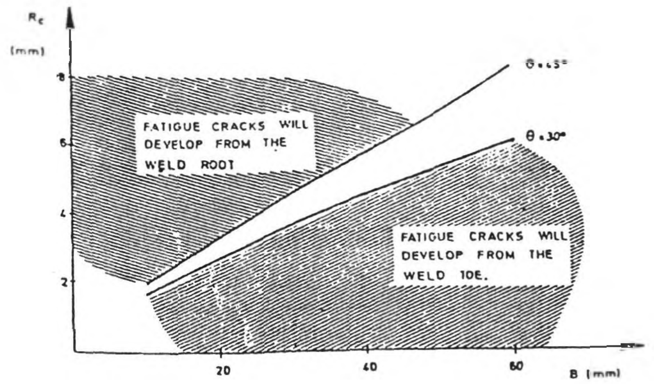
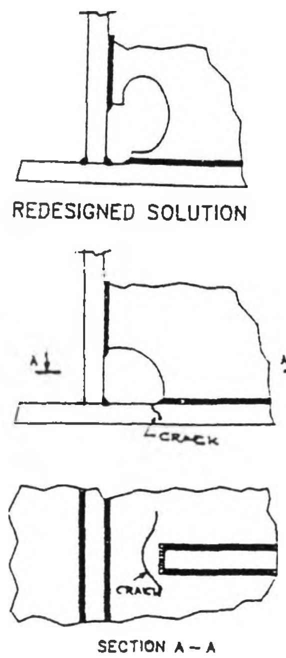


Fig 7 Critical defect size as a function of thickness for two different Weld Angles



REDESIGNED SOLUTION
Fig8 Typical 'RATHOLE' recess positions where cracks develop

quality When the incidence of weld discontinuities increases, steps should be taken to rectify the situation without necessarily requiring that defects be rectified. This is schematicaly indicated in fig-10, the first limit indicating a threshold beyond which measures are taken to reduce the incidence of further weld defects, the second representing the repair level (17,18)

At elevated temperatures, the long term reliability of welded construction is affected by failure of weldments by creep & creep fatigue interaction damage (19) Considerable amount of work has been done on the weldability and joining procedures of the material, while the elevated temperature design procedures have received little attention Minimal guidance for the weldment design is available in current design codes, except for ASME N-47 class-1 Nuclear components code case which is by far the most accomplished code on high temperature design aspects as of now One difficulty faced in establishing reasonable design margins is the lack of weldment creep data A study carried out to specify the lower bound for the allowable strain design limits indicates that a strain reduction factor of 0 33 is required for the weldment design It must be noted that the strain reduction factor is smaller than 0 5, which implies that the rule for weldment design in the ASME CC N-47 might not be sufficiently conservative (20,21,22 23,24) ASME CC N-47 also provides values for weld metal creep rupture strength reduction factors for various materials (Table-III) to be applied during weld design for elevated temperature applications A study to assess the adequacy of the strength reduction factor indicates that for lower stress level (i e longer life time) the code specified values are conservative (25)

Instances of longitutidinal weld failures in piping due to different creep properties of the base metal & weld metal have been reported in literature (26). The carbon content of the weld is often below that of the base metal to simplify welding This factor by itself would be expected to lead to higher creep rates in the weld metal Increasing the creep strength of the weld metal above that of the base metal is not necessarily a solution to this problem The results of parametric study performed to analyse the above problem has several implications for the designer indicating that apart from proper selection of materials to improve the creep performance of weldments at elevated temperatures attempts must be made to optimise the weld geometry as well to achieve the desired results

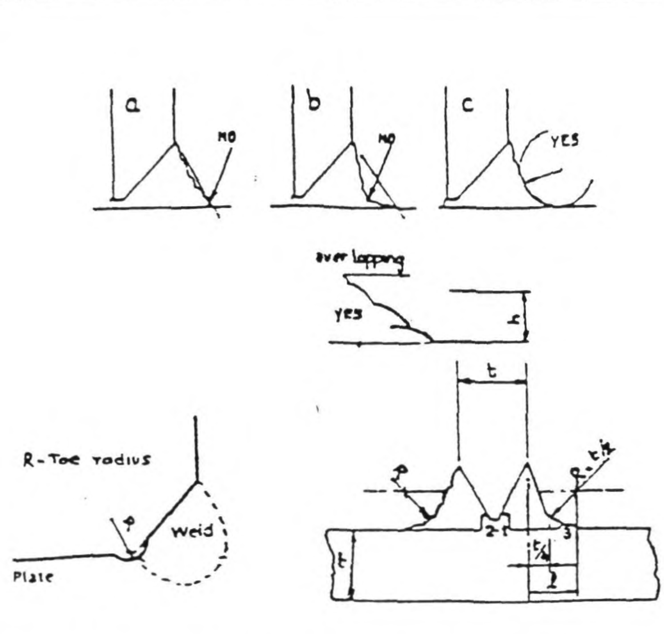



Fig 9a : Improved weld sequence and Weld Toe Profiles

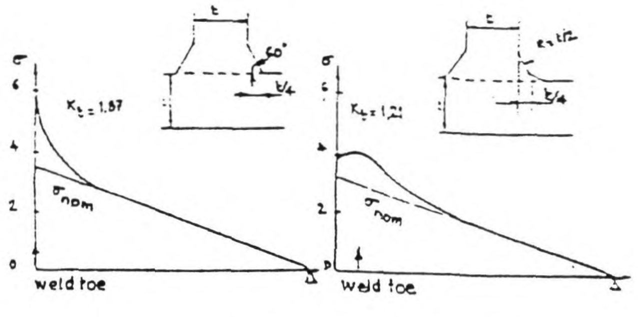



Fig 9b : Reduction in stress concentration factor due to improvement in weld profile

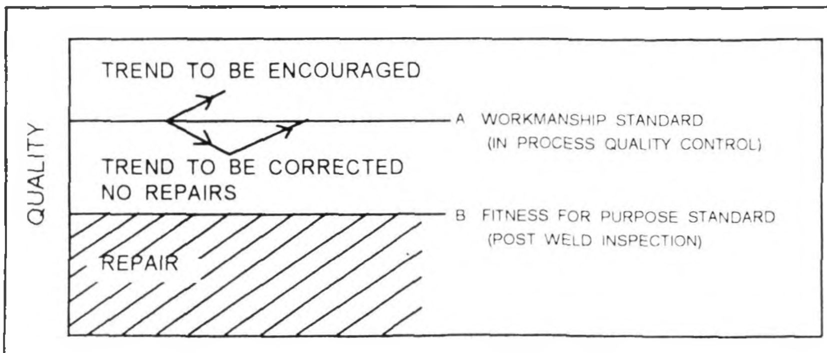



Fig 10 : Fitness - for - purpose approach to quality control and acceptance levels

The other area of interest is the study & elimination of residual stress in welded structures (27). It is possible to control/minimise residual stresses to a large extent by employing proper fixtures & choosing correct sequence of welding. One interesting observation is the effect of geometrical imperfections and residual stress introduced during weld of a circular cylindrical shell ($r/t = 500$). The calculations to estimate the axial buckling load including grometrical imperfections but ignoring residual welding stresses produced actual buckling loads which were well below the ideal loads. However, the additional residual welding stress produced only slight additional reductions amounting to less than 5% (28). Hence, it is important to understand the effect of residual stress on component performance depending upon the type of application. It may not always be advantageous to spend efforts in trying to minimise/eliminate residual stress in all welded constructions.

Nozzle-shell weld is of concern in pressure vessel and piping industry. Design codes (29,30) provide guidelines for area compensation by way of weld reinforcement from strength considerations. This region presents a structural discontinuity and also exhibits a different behaviour as compared to adjacent material in case of thermal transients owing to differential thermal inertia (31). All these aspects need careful attention during design. Features such as rounding off sharp edges or provision of re-entrant nozzles are some of the typical solutions to the above problems. For critical applications, from thermal fatigue considerations, it is suggested to avoid weld directly at the junction. The choice of forged nozle or shell pullout must also be exlored, if econimics permit.

Very often, in practice, there is necessity to join dissimilar metals together as in piping systems of power plants. Literature survey (32,33) indicates that failures of such joints primarily stems from the mismatch between the co-efficient of thermal expansion (CTE) apart from metallurgical considerations. A typical example is a joint between ferritic (2.25 Cr - 1 Mo or 9 Cr - 1 Mo) - austenitic (316 LN) stainless steels in nuclear power plants. In addition to the CTE mismatch, carbon migration also contributed to the failures in these joints. Though this situation has been tackled in the past with Nickel based welds, a better solution is to introduce a tri-metallic junction having a short length of Alloy 800 spool in between with 16-8-2 weld on austenitic side and Inconel 182 weld on ferritic side (34,35)

## Summary

Process of designing and fabricating a welded joint in a component begins as early as weld edge preparation spanning upto final inspection and subsequent acceptance. While it must be appreciated that it is difficult to cover the entire gamut of activities involved in each of the stages, an attempt has been made to present sailent aspects pertaining to design of weld joints. The areas covered in the presentation have been so chosen to highlight, that it is not only the weld quality or welding process that is receiving attention in the R & D activities but the weld geometry as well. The emphasis of R & D activities now appear to focus on the weld geometry recognising it as one of the parameters influencing the component/structural life. While the phenomenon of residual stress in structural failures has been given importance its impact on the structural load bearing capability has to be well understood before making attempts to reduce it as otherwise, it may result in unnecessary increase in overall costs. Various international design codes such as ASME, BS, DIN, etc provide guidance, which has to be necessarily consulted during designig of welds in addition to the aspects discussed above.

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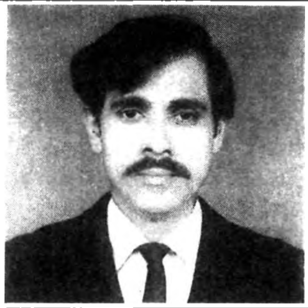
**We are glad to announce that Shri Shantanu Moulik from ACC-BABCOCK Ltd. Durgapur of Calcutta Centre has successfully completed the AM-IIW Examination 1994 conducted by The Indian Insitute of Welding**





## OBITUARY

*We are deeply shocked by the sudden demise of Shri George Abraham who passed away on 2nd September, 1994.*

*After graduation from BHU in 1962 he joined SAIL as a GE in 1963 and served SAIL (BSP) till the last. He received Shram Vir Award twice. He was a member of our Institute under Bhilai Branch and served commendably as the Chairman of Technical Committee during NWS '93 held at Bhilai.*

*He leaves behind his wife and two children. May his soul be rest in peace.*