Measurement of Residual Stress in a Welded Branch Connection and Effects on Fracture Behaviour

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Abstract. The branch analysed in this paper was not post weld heat treated, resulting in significant residual stresses. Assessment codes assume these to be at, or close to, yield. An integrity assessment of a welded branch connection was carried out using these high assumed residual stresses.

The weld then had residual stresses determined by neutron diffraction, performed using ANSTO’s residual stress diffractometer, Kowari. The maximum measured residual stress (290 MPa or 60% of yield) was much lower than the yield value assumed by assessment codes. Reanalysing with the actual residual stresses almost doubled the critical crack size, increasing the safety of the connection.

1 Introduction
Gas pipelines have connections to feed new facilities, especially gas-fired power stations. The connections are made on in-service pipelines by hot-tapping, welding directly onto a pressurised pipeline. The branch is welded directly to the ‘live’ pipeline and then reinforced with 2 half sleeves cut from the pipe.

Figure 1 Pipe, branch welded on, components of reinforcing sleeve, and completed branch connection, welds are shown with bold lines.

The welding process generates significant residual stresses which may contribute to premature failure. Residual stress will generally reduce the critical flaw size for crack growth. Methods of measuring residual stress include destructive and non-destructive techniques such as Sachs boring and ring slitting, ultrasonic and magnetic methods, and diffraction methods using x-rays or neutrons. Neutron methods have great penetrating power, giving information to a depth of approximately 30 mm in steels. Reliable fracture mechanics assessments require accurately
determined residual stresses. However, the conservative assessment of brittle fracture in codes such as BS 7910 [1], coupled with a high level of assumed residual stress (At yield strength, BS 7910-7.2.4.1) leads to very small critical crack sizes.

2 Component material and geometry
The connection is made from X70 ferritic steel with a minimum yield strength of 483 MPa. The reinforcement sleeve is in contact with the outer surface of the run pipe, and is welded to the run pipe at the ends of the sleeve, and also to the branch. By symmetry, a quarter model was used for all models (figure 2a). The residual stresses were measured where they are expected to be highest, where the connection is stiffest at the saddle. The integrity analysis was performed where the operational stresses are highest, conservatively using the residual stress from the saddle.

![Figure 2a Quarter model of branch showing arrangement of components.](image)

![Figure 2b Measurement points over welded region.](image)

3 Neutron residual stress measurements
The residual stress measurements were performed on the Kowari strain scanning instrument at ANSTO. Because the basic principles of this technique are well known [2,3,4] only details specific to this measurement will be reported. Through-thickness scans were performed across the weld and parent. A monochromatic beam with $\lambda = 1.666$ Å and diffraction from Si{400} planes were used to analyse the Fe{211} plane. A nominal gauge volume of $3 \times 3 \times 3$ mm$^3$ was used to perform scans at 15 positions (figure 2b), the measurements were all at least 6 mm from the surface. A section through the weld and parent was cut into a 6 mm thick plate to derive $d_0$ values across the weld, heat affected zone (HAZ) and parent. The $d_0$ values were measured at the same 15 positions as the strains were measured, the values for the parent, HAZ and weld metal varied by less than 0.3%.

4 Analysis results
Residual stresses were measured in the saddle, the connection had not been hydrotested. The maximum stresses (290 MPa) were along the weld direction (figure 5a, b, c) with lower stresses both in the direction of the branch and in a direction normal to both the run and branch pipes.
Figure 3a Stresses in direction of weld (out of page), maximum stress is 290 MPa.
Figure 3b Stresses in direction of branch (vertical), maximum stress is 187 MPa.
Figure 3c Stresses normal to branch (horizontal), maximum stress is 138 MPa.

5 Integrity modelling

The branch can fail by plastic collapse or by brittle fracture, these failure mechanisms are modelled separately. The plastic collapse is not affected by residual stress, and occurs at a higher pressure than brittle fracture, and thus is not considered further. The brittle fracture analysis considered a flaw through the entire weld at the position of highest stress under operation, aligned axially to the run pipe situated at the weld crotch.

The toughness value of the weld was conservatively assumed to be a minimum of 40J Charpy V value at the minimum expected service temperature, this was converted to a $K_{IC}$ value of 74 MPa√ using Appendix J.2.1 in BS7910-2005. Stresses were taken through the weld at the operating pressure of 16.6 MPa to input into the British Nuclear R6 integrity code [5] which is based on BS 7910-2005.

If this vessel were to be hydrotested the residual stresses would be reduced. The reduction is more significant at the crotch, where the weld is parallel to the major hoop stress. Thus the residual stresses were measured at the saddle. The stresses are taken at the crotch, where pressure induced stresses are highest. Combining these two stresses is a conservative method of assessment,

The stress values are based on the 5 greatest measurements within the weld, with a mean of 259 MPa and a standard deviation 29.9 MPa. Four estimates of the residual stress were used in the analysis:

- The mean value of 259 MPa.
- The maximum measured value of 290 MPa.
- A very conservative estimate of residual stress is the mean plus 3 standard deviations, giving a value of 349 MPa. If the values in the weld are normally distributed, and the area sampled is representative of the weld stresses, this ensures a probability of 0.135% that a residual stress will be above this value.
- The yield strength value assumed by BS 7910 of 483 MPa.

A single fracture mechanics case is presented, that of a through wall cracking equivalent to the full section weld defect in crotch. This is a very conservative model as weld cracking will only penetrate the outer sleeve (a
possible 14 mm deep crack, not a full thickness 28 mm crack). The inner sleeve has higher toughness (80 J vs. 40 J) and once cracking moves from the weld into the parent metal, residual stresses are much lower. Additionally, the stresses reduce away from the branch weld, while the analysis assumes they are constant. These conservative results are shown in figure 9.

**Figure 4** Critical crack size with different residual stress values.

### 6 Conclusions

The design of a branch connection has been analysed and has been found to be fit for service. The residual stresses were measured by neutron diffraction using ANSTO’s residual stress diffractometer, Kowari. The branch was shown to be safe with the large residual stresses assumed in BS7910. The maximum stresses occurred in the direction where the connection was stiffest, along the weld. Transverse stresses were lower due to lower constraint.

Reanalysing with the actual residual stresses significantly increased the critical crack size using very conservative estimates of residual stress based on these measured values.

### 7 References

[1] BS 7910:2005 Guide to methods for assessing the acceptability of flaws in metallic structures

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