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Four point bend testing – Finite element analysis of the stress and strain distribution

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SUMMARY

Finite element computations of the stress and strain distribution on the tensile surface of a four point bend specimen of a 13Cr stainless steel (SS) were carried out in order to resolve the query of the method most appropriate for setting the total strain to achieve 0.2% plastic strain; in particular, whether to use tensile or bend data. Computations were carried out with very low friction at the rollers and subsequently with varying degrees of friction. The recommendation is that the four point bend specimen should be loaded to a longitudinal strain corresponding to the total strain to achieve 0.2% plastic strain as determined in separate uniaxial tensile testing. The force required to achieve that strain can be affected by friction at the rollers but provided the specimen is strain gauged this will have no impact on the strain in the central section of the specimen. However, friction at the inner rollers can induce an elevated stress on the tensile surface of the specimen opposite and this may cause cracking at that location. Such cracking should be considered an artefact.

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1. INTRODUCTION

The four point bend test method is being developed as both NACE and ISO standards. However, there has been controversy with respect to the appropriate method for setting the applied total strain and whether to use tensile or bend data for that purpose. To resolve the issue, finite element (FE) computations of the stress and strain distribution on the tensile surface of four point bend specimens of a 13Cr SS were carried out using Abaqus.

2. FE ANALYSIS

2.1 VERY LOW FRICTION AT THE ROLLERS

The specimen design adopted is shown in Figure 1, using two values of the specimen thickness, 8 mm and 4 mm. The specimen was meshed with rectangular C3D8I elements that had dimensions of 2 mm (l) × 0.5 mm (t) × 1.286 mm (d, 1.429 mm for 8 mm thick specimen). The rollers were modelled using analytical rigid surfaces. The two outer rollers were fixed, while the two inner rollers could be displaced by up to 3.5 mm. The two moveable rollers were tied together using a linear multi point constraint in the form of an equation so the displacement was applied to only one reference node and correspondingly the resulting total reaction force was obtained from this single reference node. In initial computations, a small degree of friction was modelled between the rollers and the specimen using a coefficient of static friction of 0.001 but the effect of increasing the friction coefficient was also evaluated. The von Mises material model was used in the analysis to characterise the elastic-plastic behaviour of the 13Cr steel material. The predicted stresses and strains were obtained from a node in the centre of the surface in contact with the two fixed rollers; i.e. the tensile surface.

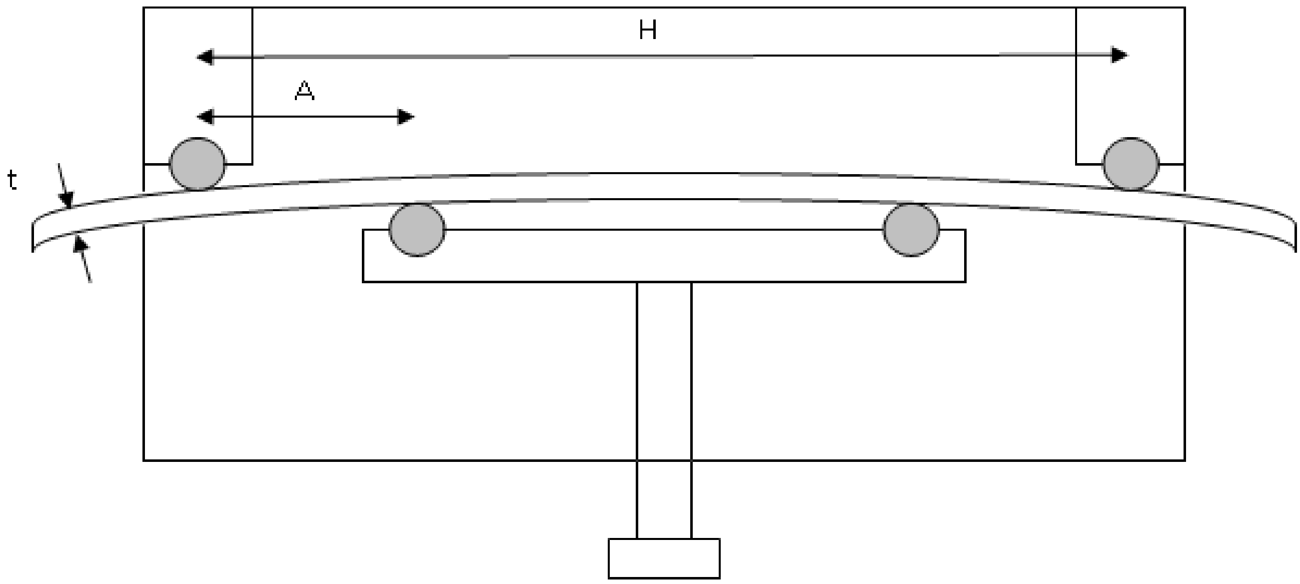

Figure 1 Typical four-point bend loading jig design.

Table 1 defines the relevant parameters adopted in the FE analysis for the two specimen thicknesses.

Table 1: Dimension (mm) for four point bend testing set-up adopted in modelling.

Thickness	Width	Length	H	H-2A	Roller diameter
8	20	140	120	60	10
4	18	120	100	50	6

Figure 2 shows a section of the experimental uniaxial stress-strain data at room temperature used in most of the computations.

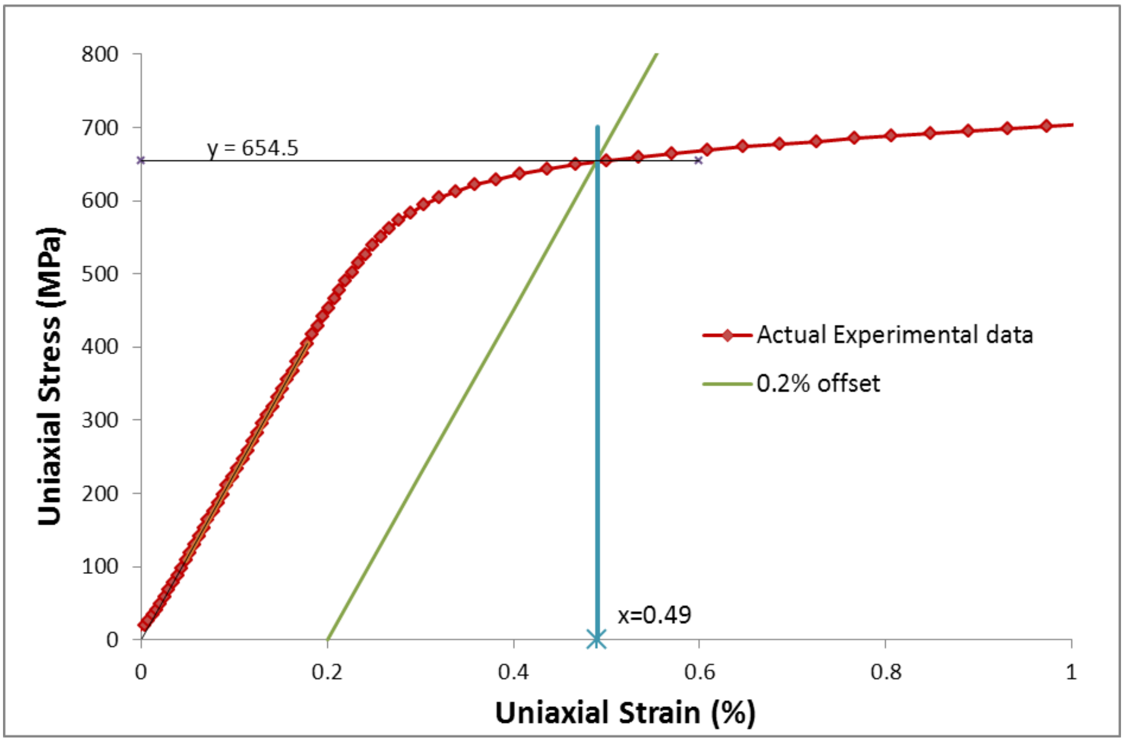

Figure 2 Section of the uniaxial stress-strain test data for a medium strength 13Cr steel at room temperature showing the total strain associated with 0.2% plastic strain.

In Figure 3, the computed longitudinal stress is plotted against the calculated principal strain as defined in the draft four point bend procedure by

$$\varepsilon_p = \frac{1}{1-\nu^2}\left(\varepsilon_l + \nu\varepsilon_t\right)$$

For this case, Poisson's ratio (ν) was taken to be 0.3.

A similar plot, but this time longitudinal stress against longitudinal strain is shown in Figure 4. In each case the total strain corresponding to the 0.2% offset (0.2% plastic strain) is shown. It will be noted that this is almost identical to the uniaxial stress-strain value, irrespective of whether principal strain or longitudinal strain is used, though more exact for the longitudinal strain.

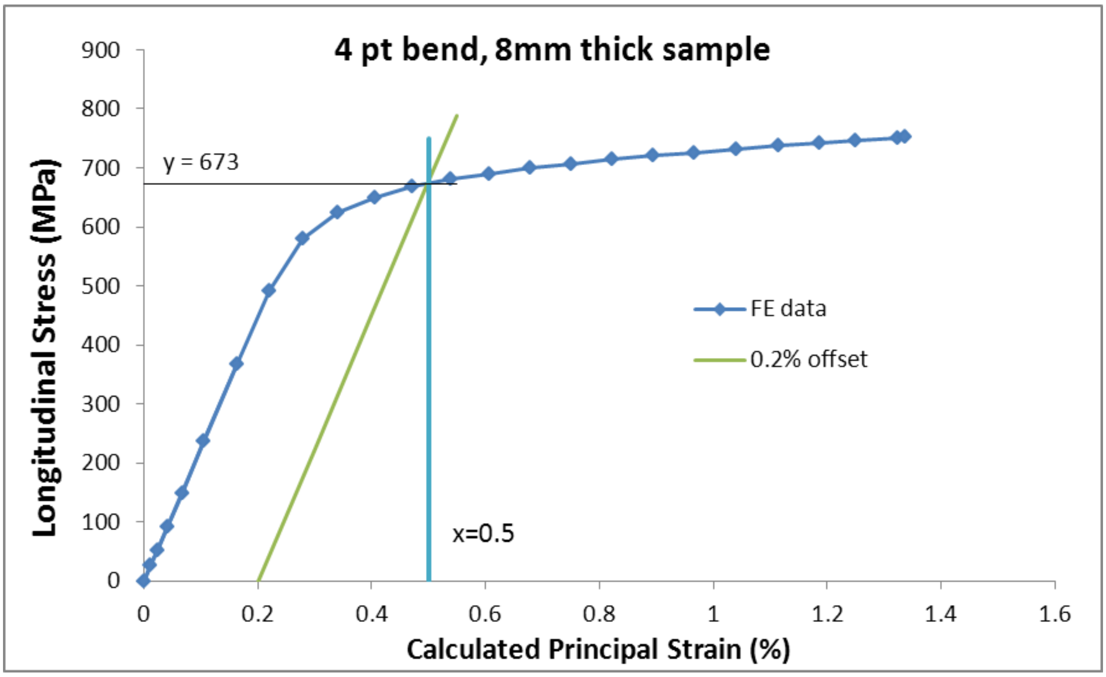

Figure 3 FE computed values for the longitudinal stress vs principal strain on the tensile surface of a four point bend specimen of 13 Cr SS.

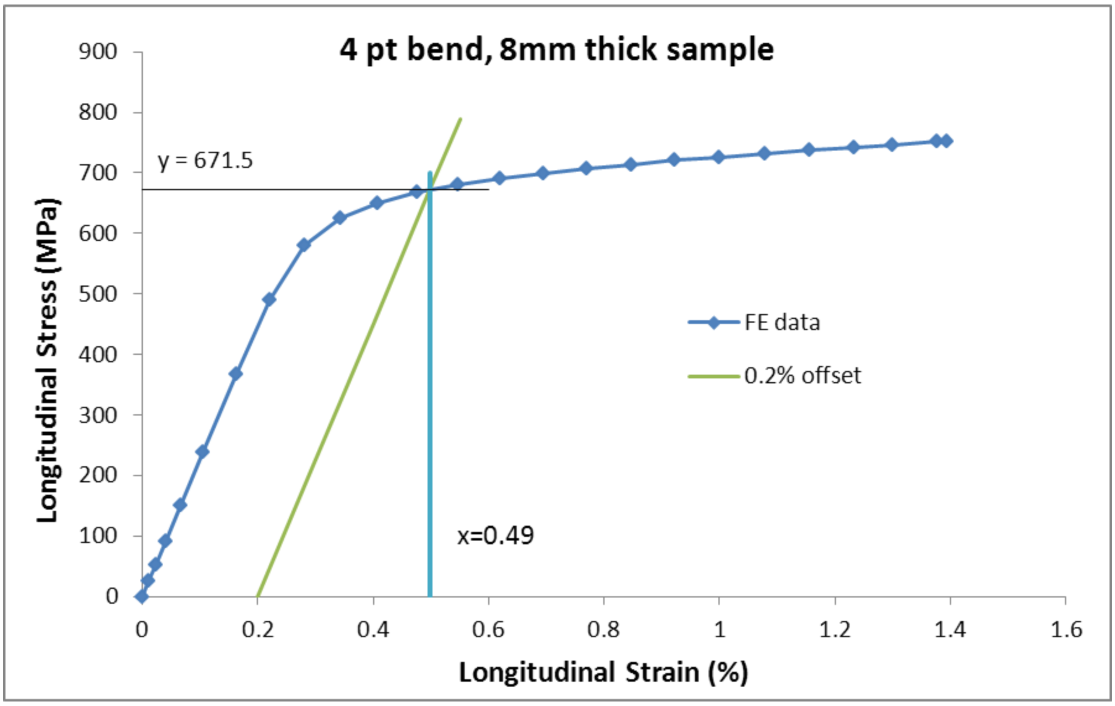

Figure 4 FE computed values for the longitudinal stress vs longitudinal strain on the tensile surface of a four point bend specimen of 13Cr SS.

In four point bend testing the stress is unknown and force (load) is plotted against strain (principal strain in the current version of the draft procedure). The total strain to achieve 0.2% offset is determined in a calibration experiment and the specimen then deflected to attain that value. It was assumed implicitly that this 0.2% offset corresponded to 0.2% plastic strain. To simulate this, the computed force corresponding to the calculated stress in the FE analysis is plotted against strain in Figures 5 and 6.

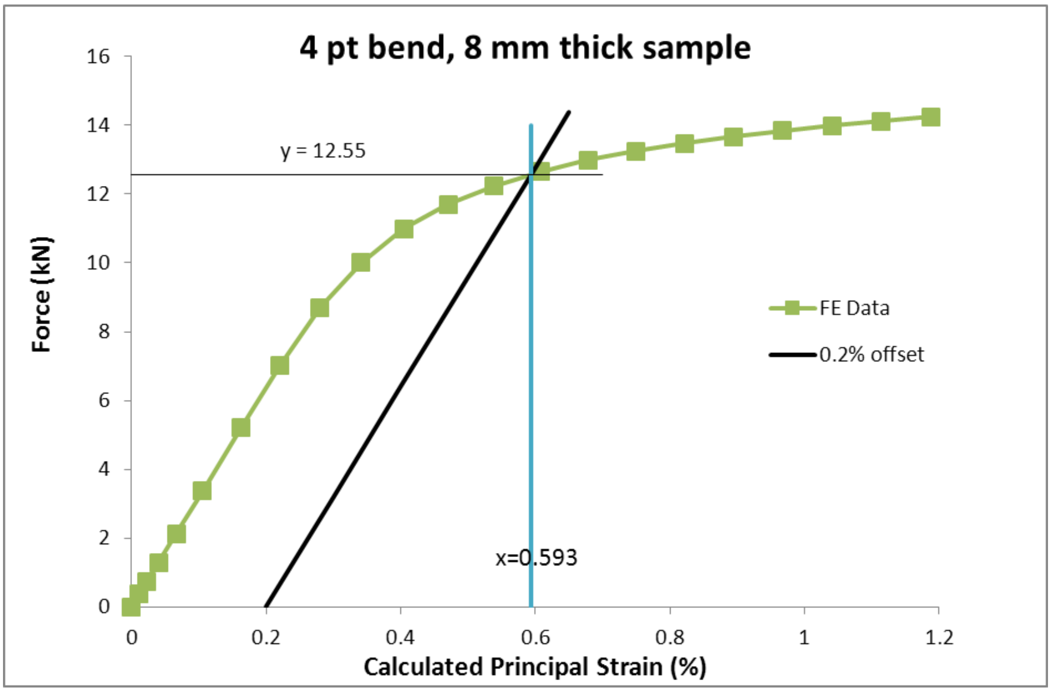

Figure 5 FE computed values for the force vs principal strain on the tensile surface of an 8 mm thick four point bend specimen.

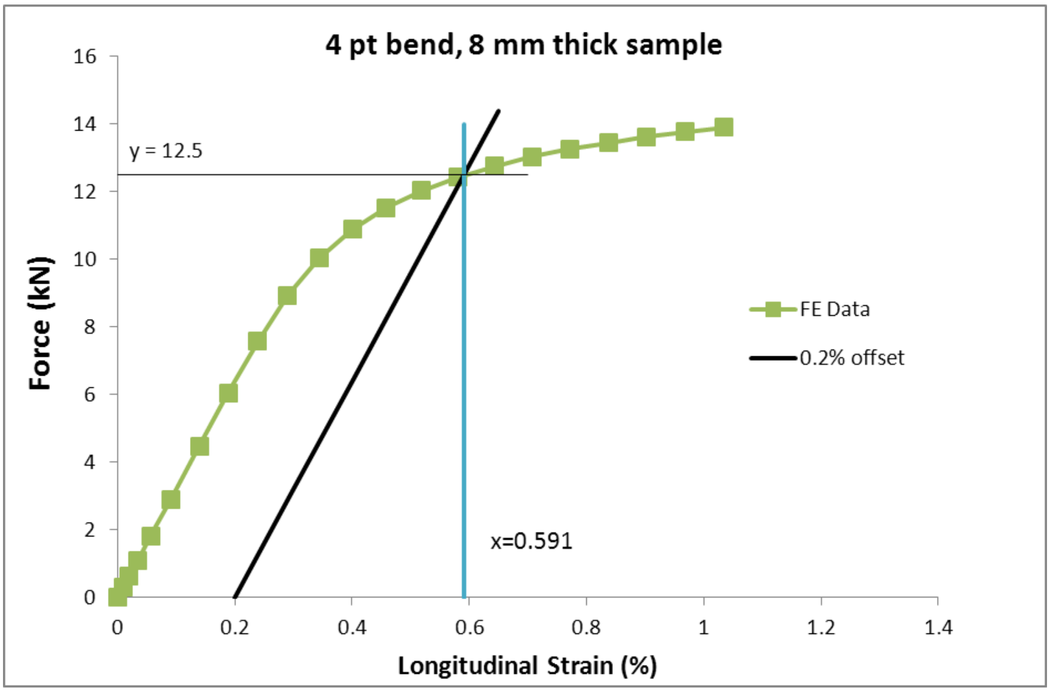

Figure 6 FE computed values for the force vs longitudinal strain on the tensile surface of an 8 mm thick four point bend specimen.

The key observation is that now the 0.2% offset indicates a total strain of about 0.6%, compared to about 0.5% that would have been deduced from the uniaxial stress-strain plot. To assess the implications for the stress on the tensile surface the stress corresponding to the total strain based on the computed flexural force-strain plot and that based on the computed uniaxial stress-strain plot are compared in Figure 7. Two observations are noteworthy. Firstly, adopting the total strain to achieve 0.2% plastic strain from the uniaxial stress-strain plot leads, in four point bend testing, to a stress of about 672 MPa that should be compared to the value of 655 MPa in the uniaxial test. Secondly, the use of the total strain corresponding to the 0.2% offset in the flexural force-strain curve leads to a stress of 687 MPa.

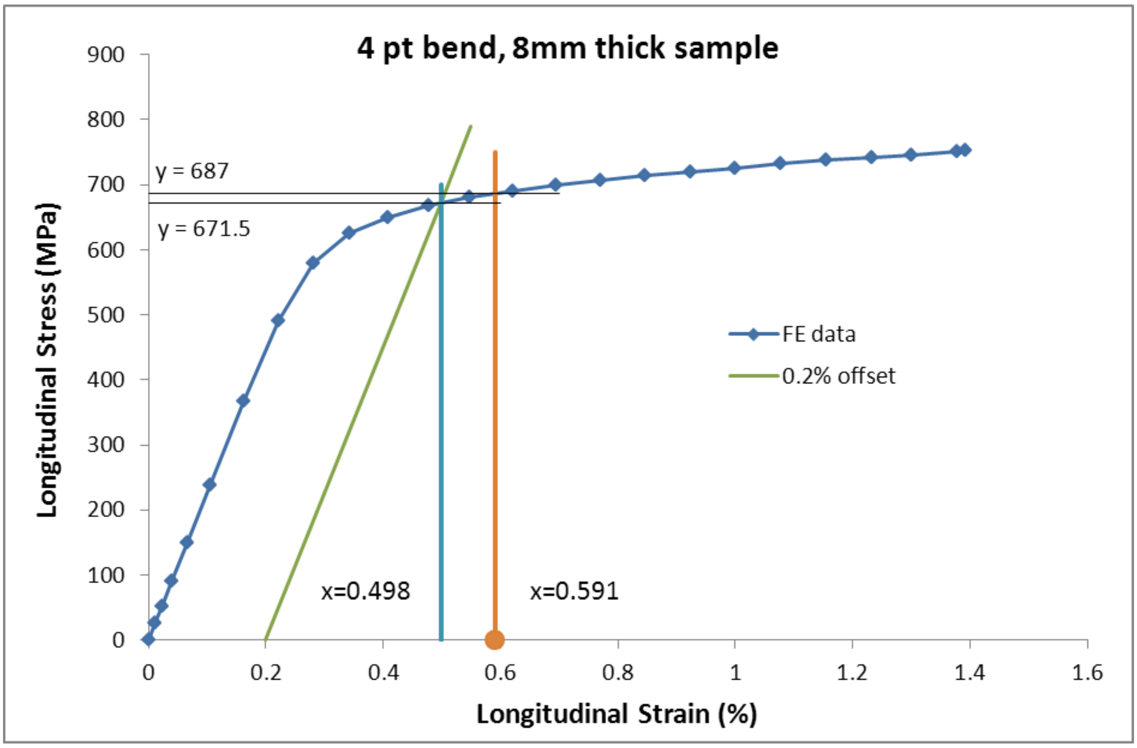

Figure 7 FE computed stress-strain plot showing computed stress derived from adopting the total strain value from the 0.2% offset in flexural force-strain plot (x=0.591) and that corresponding to 0.2% plastic strain in the uniaxial test (x=0.498).

A repeat calculation with a 4 mm thick specimen shows similar behaviour to that for the 8 mm thick specimen as shown in Figure 8.

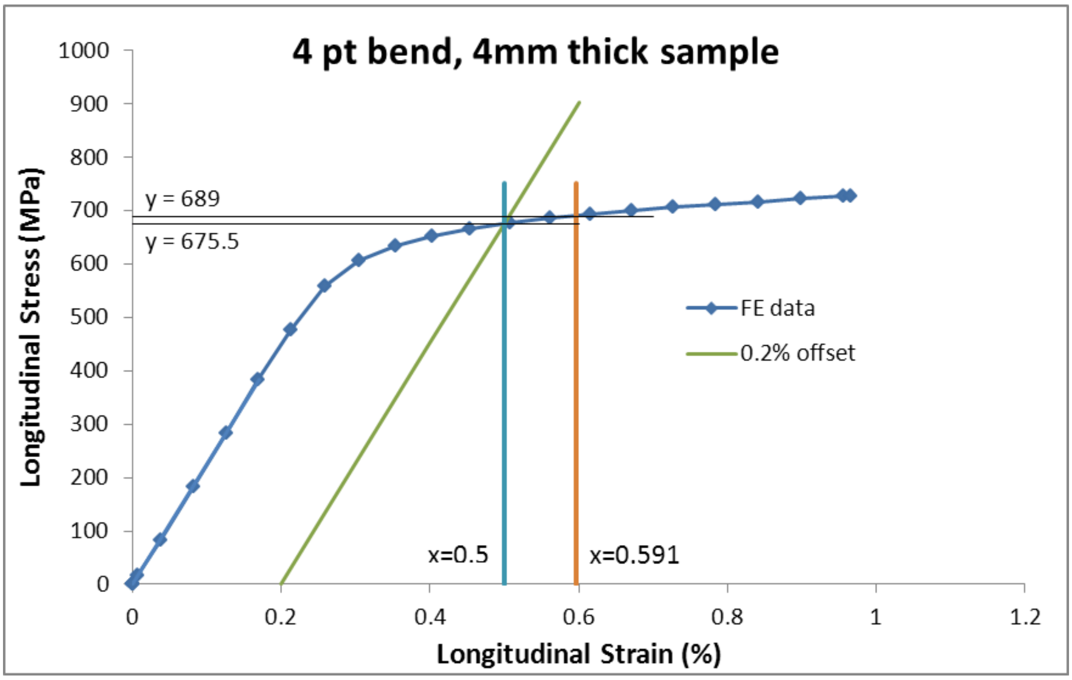

Figure 8 FE computed stress-strain plot showing implications for computed stress of adopting total strain value derived from 0.2% offset in flexural force-strain plot (4 mm thick specimen).

The main observation for both thicknesses of specimen is that the 0.2% offset in the force-strain curve in the four point bend test does not correspond to 0.2% plastic strain, despite the fact that the modulus is the same as that derived from uniaxial testing. For this example, the calculated plastic strain was closer to 0.3%. However, the magnitude of the stress and strain will be a function of the work hardening characteristics of the material. For higher strength material with limited work hardening the increase in stress would be quite small compared to the method based on total strain from the uniaxial test (Figure 9) but the plastic strain would be greater. In contrast, for a material with more pronounced work hardening than that associated with the 13Cr SS of Figure 2, the relative increase in stress as a consequence of adopting the force-strain curve to derive total strain would be greater but the increase in plastic strain smaller. Note that for the higher strength steel in Figure 9 the AYS corresponding to the uniaxial 0.2% proof strength was 950 MPa so four point bend testing based on uniaxial total strain elevates the tensile surface stress by only about 3.5% for this case.

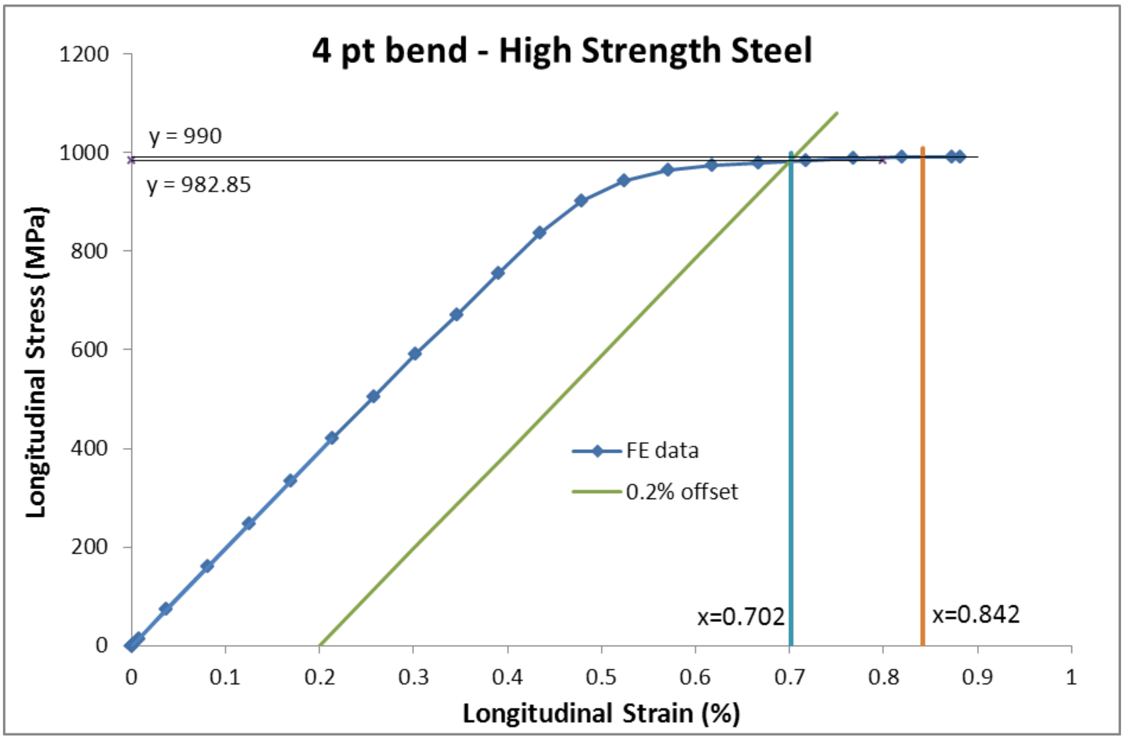

Figure 9 FE computed stress-strain plot showing implications for computed stress in high strength 13Cr SS of adopting total strain value derived from 0.2% offset in force-strain plot (4 mm thick specimen).

2.2 EFFECT OF FRICTION AT THE ROLLERS

It is important to assess whether the calculated force in the FEA shows reasonable agreement with that measured experimentally. However, the calculated force depends on the assumed value for coefficient of static friction, taken to be very small, 0.001 initially, and this may be somewhat different from that in actual experimental practice. Accordingly, the effect of varying friction at the rollers was assessed and compared to force-strain data measured experimentally. Ideally, the analysis should include rotation of the rollers and related friction between the rollers and the jig. However, rotation of the rollers is very difficult to incorporate in the FEA. Thus, only the friction between the roller and the specimen is considered.

For expediency, related to available experimental data, uniaxial stress-strain data for a slightly different 13Cr SS was used (Figure 10). Comparison of calculated load/force-strain vs measured values in Figure 11 show that the assumption of very low friction at the rollers may not be ideal. The consequence is that somewhat larger force is applied to attain the same total strain, which would concur with intuitive expectations. It might be expected that rollers that are free to rotate and move with the specimen will have a reduced impact. However, since most jigs are designed so that they are fixed with respected to the roller then there will still be frictional forces between the jig and the roller. Typical values for the coefficient of static friction between steel and ceramic are between 0.1 and 0.5 and thus cannot be assumed to be negligible. Hence, although the results for Figure 11 do not account for all aspects of the system they are indicative.

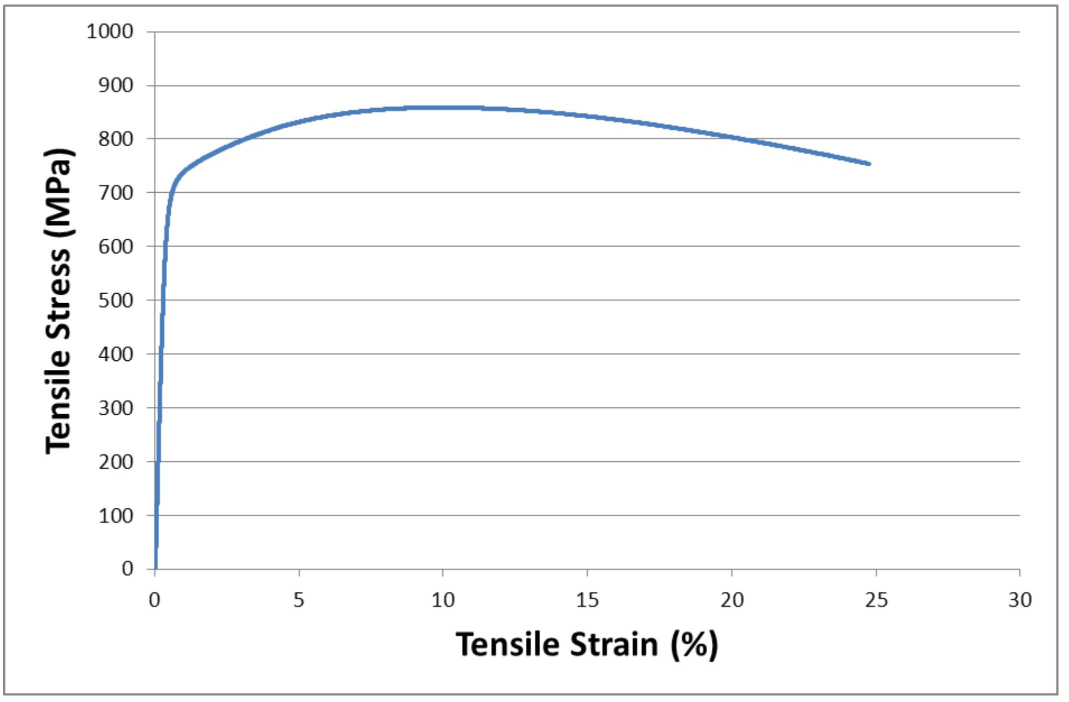

Figure 10 Uniaxial stress-strain data for a 13Cr steel used as the basis for comparing calculated force-strain with measured force-strain.

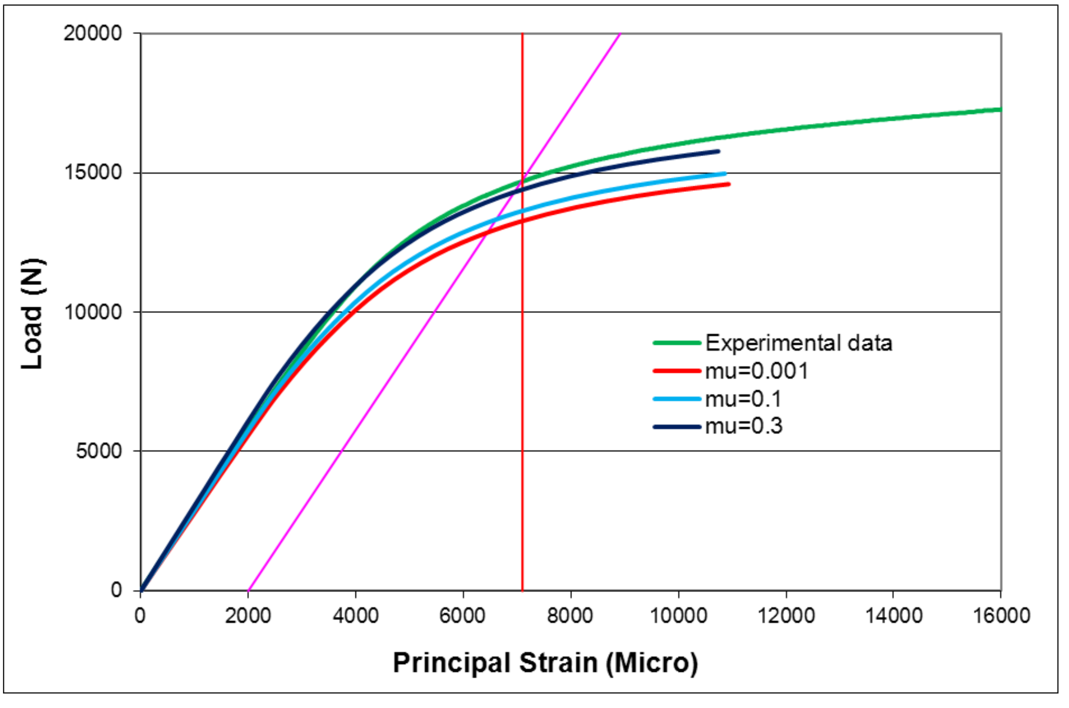

Figure 11 Comparison of predicted force (load) vs strain with measured force-strain for 13Cr steel assuming different value for friction coefficient (mu) at rollers.

The other factor to consider in relation to friction at the rollers is the impact on the stress and strain local to the rollers, as highlighted by Walters [1] and Lube et al [2]. This is demonstrated in Figure 12 where elevated strain and strain gradients can exist on the tensile surface opposite the inner rollers.

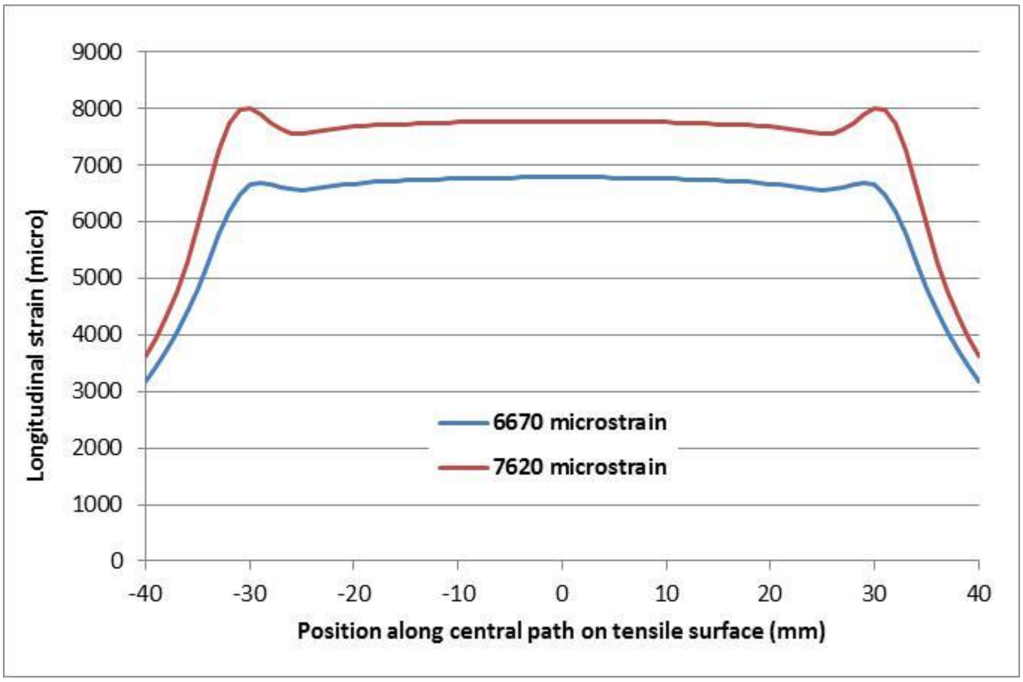

Figure 12 Impact of friction at the rollers (assuming a coefficient of friction of 0.5) on the strain distribution along the centre of a four point bend specimen.

3. IMPLICATIONS

Clearly, the adoption of the 0.2% offset procedure using force-strain data from four point bend testing is not to be recommended because it increases the stress relative to the target stress more than is desirable, with the extent being proportional to the degree of work hardening of the material. For low work hardening materials the effect on stress is modest relative to use of total strain from uniaxial data but the comparative effect on plastic strain is more significant and vice versa for high work hardening materials.

It needs to be recognised also that the use of the total strain from uniaxial data to set the total strain in the four point bend test increases the stress relative to the Actual Yield Stress for the same value of 0.2% plastic strain. In other words more elastic strain is required to achieve the same level of plastic deformation in the 4 point bend specimen than in a uniaxial specimen. However, this deviation should be accepted as there is no intrinsic way, other than FE analysis, of defining the stress on the four point bend specimen for a CRA and it is then preferable to set the level of strain corresponding to 0.2% plastic strain.

It is evident also from Figure 11 that the assumption of negligible friction at the rollers may not be reliable, which can mean that somewhat higher force/load (and by implication stress) is required to achieve the target strain derived from the uniaxial test and this may vary slightly from one test laboratory to another. However, provided the specimen is strain gauged and the frictional forces are not excessive this will not impact on the strain in the central region of the specimen. Nevertheless, there can be elevated stress on the tensile surface of the specimen opposite the inner rollers. Accordingly, any cracking specific to this region should be considered an artefact of the testing method.

The net consequence is that four point bend testing based on setting the strain to a total strain corresponding to 0.2% plastic strain determined in uniaxial testing will be conservative with respect to stress. However, two factors need to be considered: the method for testing at temperature and the variability associated with welds.

When undertaking four point bend testing at 180 °C for example, a calibration curve is derived at the test temperature to define the total strain. The test specimen is loaded at room temperature to this value but this does not allow for differential expansion between the jig and specimen. The effect of this was measured previously at NPL for a duplex stainless steel and it was observed that the degree of understrain, relative to the target total strain, was 4%. It is a small difference but would tend to reduce the stress slightly so perhaps there is a counterbalancing effect to an extent.

There is always an issue of the number of repeat tests that should be conducted for as-welded specimens since there can be differences in response for the same weld depending on where the specimens are cut around the pipe. This includes factors such as physical defects and weld root profile (steps are an additional issue). In practice, there is a compromise between cost of testing and repeatability assessment and it can be the case that four specimens pass and one fails as we have found in the past in more exhaustive testing. However, there is no wish to test five specimens every time so a degree of conservatism in stressing is not necessarily undesirable.

Finally, there is the question of which strain to load the specimen to; i.e. principal strain or longitudinal strain? The results here suggest that longitudinal strain may be more appropriate, though the difference is modest, at least for this investigation.

4. CONCLUSIONS

The 0.2% offset in the flexural force-strain curve in the four point bend test does not correspond to 0.2% plastic strain, despite the fact that the modulus is the same as that derived from uniaxial testing. For the material investigated, the calculated plastic strain was closer to 0.3%.

The total strain required to achieve 0.2% plastic strain in separate uniaxial tensile tests should be used to set the total strain in the four point bend test. In the latter respect it is the total strain in the longitudinal direction that should be adopted.

Friction at the rollers can affect the force required to achieve the appropriate total strain but provided strain gauges are used to measure the total strain this has no direct impact. However, if the coefficient of friction is large the stress on the tensile surface opposite the inner rollers can be elevated and could give rise to cracking in that region. Such cracking in isolation should be considered an artefact and be disregarded.

5. REFERENCES

[1] M. Walters, University of Birmingham, Private communication, 2013.
[2] T. Lube, M. Manner and R. Dancer, Fatigue Fract. Engng. Mater. Struct., 20 (1997) 1610-1616.