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Four point bend testing – Finite element analysis of the stress and strain distribution accounting for lateral specimen curvature

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Four point bend testing – Finite element analysis of the stress and strain distribution accounting for lateral specimen curvature

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SUMMARY

Finite element (FE) computations of the stress and strain distribution on the tensile surface of a four point bend specimen of a 13Cr stainless steel (SS) has been carried out previously for flat specimens. However, four point bend specimens prepared from pipeline material with the weld root intact are inherently curved laterally, with the extent of that curvature dependent on the inner diameter of the pipe. To assess the potential impact of that curvature on test methodology and test results, supplementary FE computations were carried out on specimens from a pipe with a relatively small inner diameter of 12.1 cm with specimen widths of 20 mm and 12 mm. The results indicated that for elastic loading the stress and strain tended to increase towards the specimen edges (i.e. thicker section of the specimen). Above yield, the total strain and the plastic strain were higher towards the edges but stress relaxation and redistribution following yielding resulted in a very small variation in stress across the specimen, with a maximum away from the edges. To limit the potential effect of curvature, it is recommended that the width of the specimen be minimised for small diameter pipe, with a width to specimen thickness ratio not greater than 1.5.

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CONTENTS

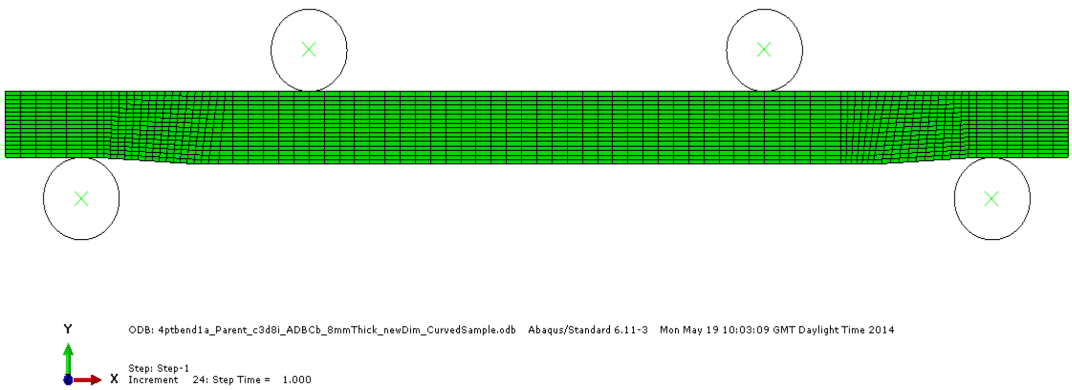
1. INTRODUCTION

The four point bend test method is being developed as both NACE (TG 494) and ISO standards (ISO/DIS 16540) for testing resistance to sulphide stress corrosion and cracking and stress corrosion cracking. To support the testing methodology FE computations of the stress and strain distribution on the tensile surface of four point bend specimens of a 13Cr SS had been carried out using Abaqus (1). The initial work focused primarily on the appropriateness of using tensile data vs bend data (the latter using the 0.2% offset) for defining the total strain to give 0.2% plastic strain in the centre of the bend specimen, with the conclusion that the tensile data were the most apt. An additional feature considered was the extent of local strain enhancement due to friction at the inner rollers. In all computations, the specimens were considered to be perfectly flat. However in testing pipeline steels with a root weld that is to remain intact, it is inherent that there will be some degree of curvature across the width of the specimen. Common practice is to machine flat one side of the specimen and also the curved section that would otherwise be in contact with the outer rollers (to avoid roller failure), with some tapering in that case to minimise stress gradients. As for flat specimens, strain gauges are then fixed to the centre of the specimen on the parent plate either side of the weld and a force applied until the total strain at one strain gauge attains the prescribed value. The question arises as to the extent to which the curvature of the specimen affects the stress and strain profile across the specimen and perhaps the location of greatest susceptibility to cracking. To resolve this issue the FE analysis has been extended to examine the effect of specimen curvature. Since the goal is primarily to assess the effect of curvature, parent material only was assumed; otherwise, the mechanical properties of the weld filler and the heat affected zone (HAZ) would have to be accounted for and that is an unnecessary complication.

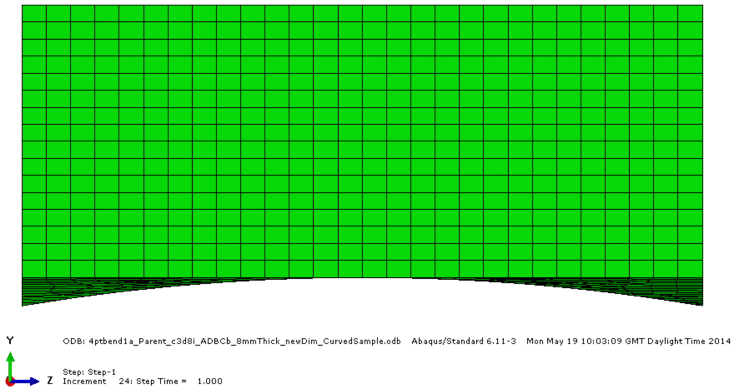
2. FE ANALYSIS

2.1 Specimen details

The specimen design adopted is shown in Figure 1.



(a)



(b)

Figure 1. Profile of the test specimen (a) longitudinal view; (b) transverse view showing flat ends and curved central region

The dimensions of the specimen were as adopted previously: width of 20 mm or 12 mm, length 140 mm and thickness at centre of specimen 8 mm, outer roller spacing 120 mm, inner roller spacing 60 mm, roller diameter 10 mm. The specimen was prepared from a relatively small diameter pipe of 6″ OD (15.24 cm) and wall thickness 0.625″ (1.59 cm). The friction coefficient was 0.001, which is idealised but does not impact on the conclusions from the study. The material properties for the 13Cr martensitic stainless steel were as adopted in the previous study, with Poisson's ratio 0.3 (1). Details of the FE analysis can be found also in that report.

2.2 Results

The projected longitudinal stress vs strain behaviour at the centre of the specimen is shown in Figure 2 and the comparative value for a flat specimen in Figure 3. It is evident that differences in stress and strain at the target plastic strain of 0.2% are too small to have an impact. In other words the total strain to achieve 0.2% plastic strain at this location is nearly identical.

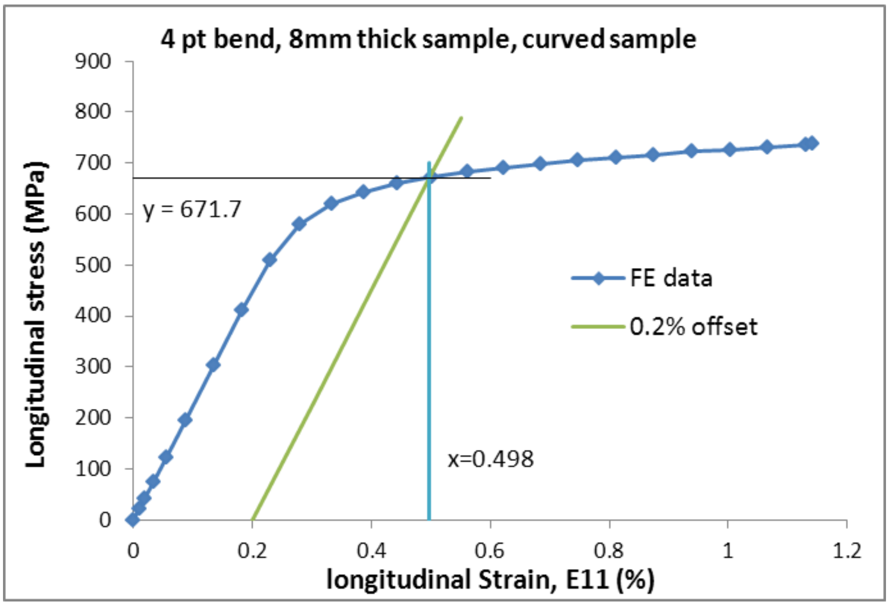


Figure 2. FE computed values for the longitudinal stress vs longitudinal strain on the tensile surface at the central point of a curved four point bend specimen of 13Cr SS with width 20 mm.

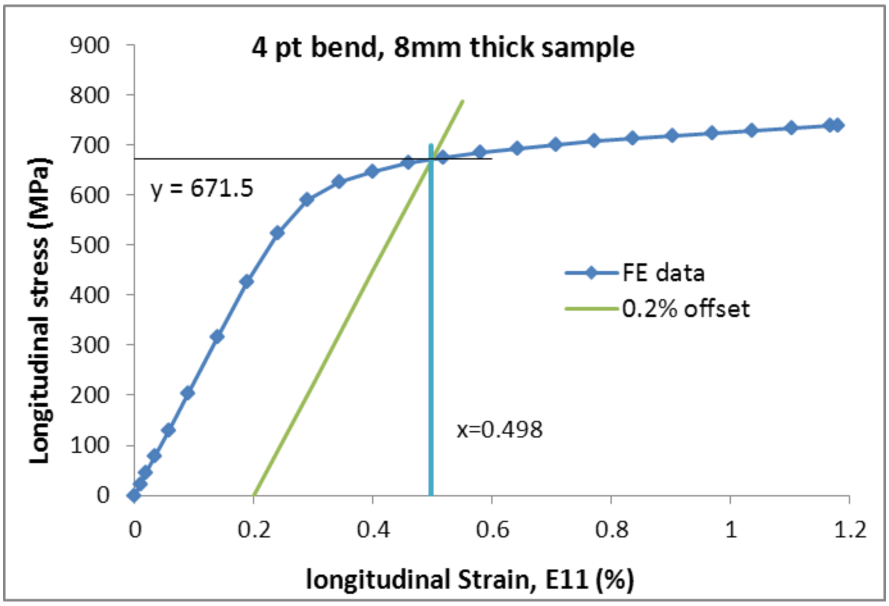


Figure 3. FE computed values for the longitudinal stress vs longitudinal strain on the tensile surface of a flat four point bend specimen of 13Cr SS with width 20 mm.

However, the varying thickness across the specimen should lead to variations in stress and strain across the specimen. This is highlighted first in the elastic region, as reference, in Figure 4. Under elastic loading the strain profile mirrors the stress profile with both becoming higher towards the edges. For comparison, the stress for the flat specimen was just less than 204 MPa and the strain about 0.09.

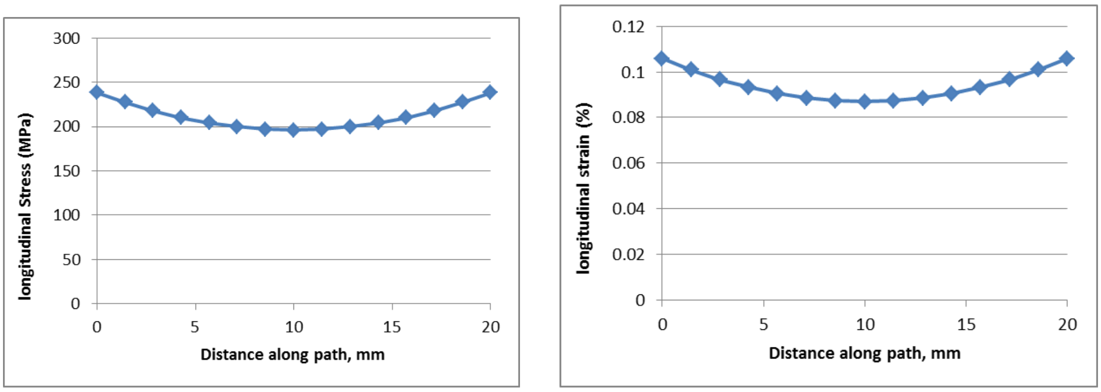


Figure 4. Stress and strain profile at the surface across the 20 mm width of the curved specimen, at mid-section, under an arbitrary purely elastic loading condition.

When the stress is above yield the variation of the stress and strain across the specimen is more complex, as illustrated in Figure 5. These data are derived from computations at a total strain slightly greater than that corresponding to 0.2% plastic strain (see Figure 2). For the flat specimen, the longitudinal stress was about 675 MPa at the centre of the specimen, the total strain 0.519% and the plastic strain 0.22%. For the curved specimen, the total strain when the stress was above yield still shows the same trend as for elastic loading. The plastic strain mirrors the trend with a maximum plastic strain at the edges of about 0.3% and about 0.21% at the centre. However, the stress variation is more complex, though the mean stress is only slight higher than that for a flat specimen.

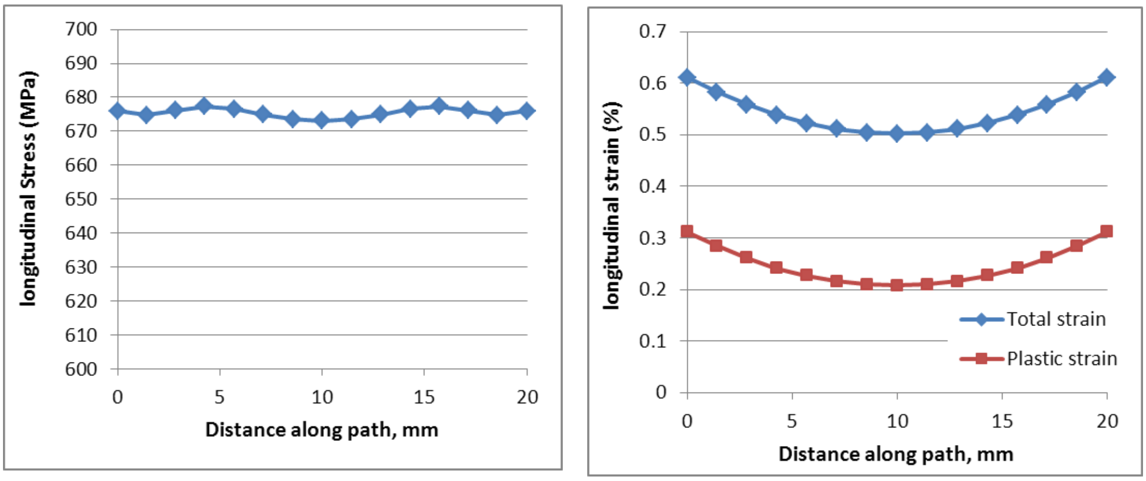


Figure 5. Stress and strain profile at the surface across the 20 mm width of the curved specimen, at mid-section at a plastic strain at centre close to 0.2%.

The effect of curvature of the pipe will be to shift the neutral axis (plane of zero stress) from the mid-thickness of the specimen in a flat specimen towards the curved region (FE analysis confirmed this conceptual perspective; the neutral axis is also uniform across the width despite the curvature). The stress gradient through the specimen remains constant. The consequence is that the stress on the tensile surface of the curved region would be expected to be slightly lower compared to that for the flat specimen at the centre of the specimen (as distance from the neutral axis is smaller) but would be higher towards the edges, with the distance from the neutral axis larger in this case. This is indeed observed clearly under elastic loading. With increasing stress above yield, the higher stresses towards the edges should cause that material to yield there first; i.e. there would be a greater plastic strain at the edges compared to the plastic strain at the centre of the specimen, where measurement is generally made.

The stress does not change too much through the specimen but is slightly elevated at a position halfway between the specimen edges and the centre line of the specimen. We consider that yielding towards the outer edges cause stress redistribution because of the reduced constraint with the stress maximum a balance between the effect of specimen thickness locally and local plasticity. For a flat specimen, there is also a tendency for a slightly lower stress at the edges when yielding occurs.

The distribution of stress and strain at the surface across the specimen would be expected to be an inherent function of the relative width of the specimen and the inner diameter of the pipe; the smaller the width for a fixed diameter the less significant should be gradients in stress and strain. To assess the impact of reducing the width, computations were performed at a width of 12 mm, the lower end of the recommended width-to-thickness ratio (1.5 to 5) in the draft standard. The data were plotted as before for both elastic loading and loading beyond yield (Figures 6 and 7). The results indicated only modest variation of both stress and strain across the specimen.

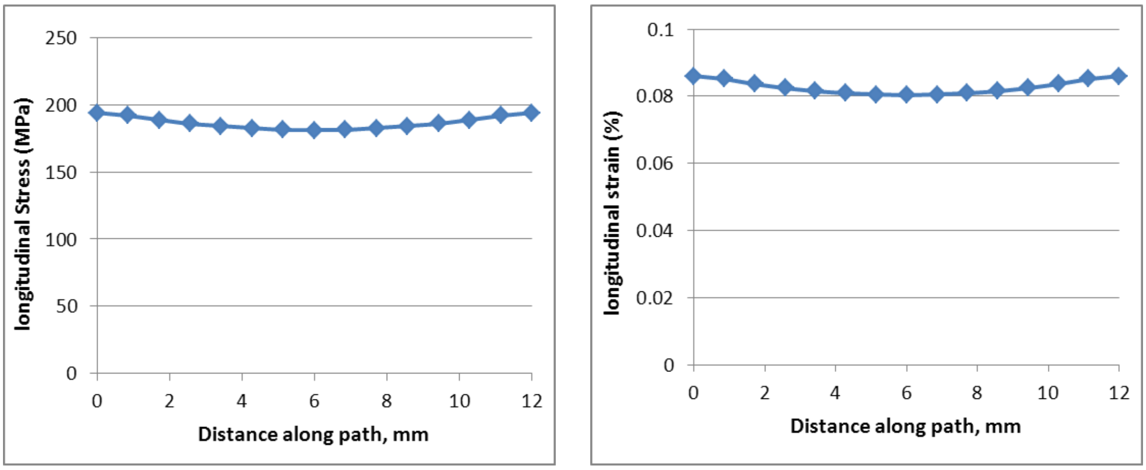


Figure 6. Stress and strain profile at the surface across the 12 mm width of the curved specimen, at mid-section, under purely elastic loading conditions.

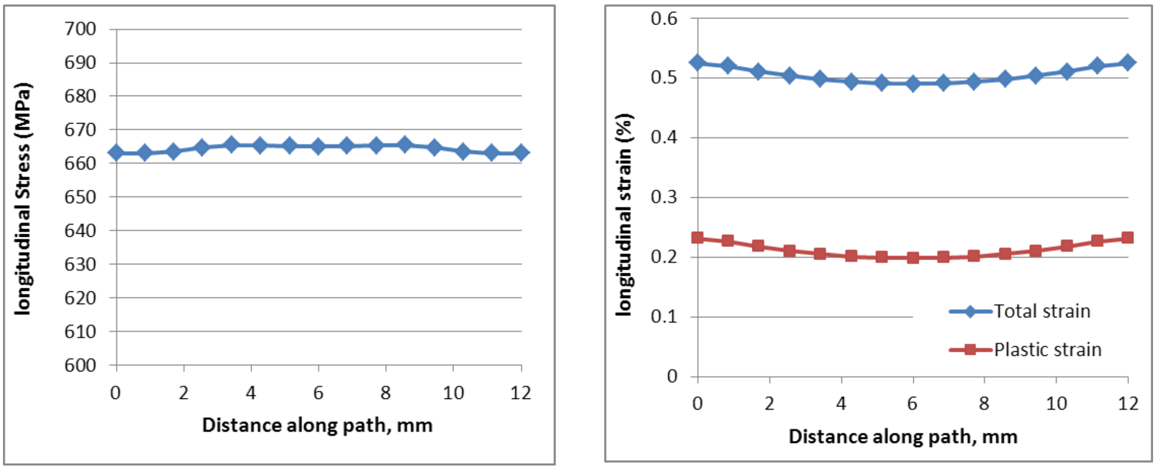


Figure 7. Stress and strain profile at the surface across the 12 mm width of the curved specimen, at mid-section at a plastic strain at centre close to 0.2%.

3. IMPLICATIONS

The results of this study are applicable primarily to testing of as-welded specimens, since otherwise flat specimens would be adopted. In that application the specimen is inherently curved laterally and the specimen is loaded to a total longitudinal strain corresponding to 0.2% plastic strain as determined by the first strain gauge fixed to the parent plate on either side of the weld filler. Clearly, avoiding use of an unnecessarily wide specimen is an advantage but in the case of the 20 mm wide specimen commonly used, are the results significant in assessing likelihood of failure? In testing, the specimen is deflected under constant displacement conditions and relaxation is exhausted prior to exposure so dynamic strain should not impact on the results. The question then is whether initiation and propagation of stress corrosion or sulphide stress corrosion cracks is driven by stress or a combination of prior plastic deformation and stress. The latter seems most likely in determining initiation. On that basis, the centre of the specimen would seem the least likely location for crack initiation for curved specimens. Preferential crack initiation at the specimen edges is well-established (e.g. Reference 2) but has been associated with the chamfered edges of the specimen, in this case in testing of flat specimens. Localisation of plastic strain could be an additional factor, though cracking just on the edge itself would probably be most associated with machining of the edges.

The results emphasise the need to report the specimen width in relation to the inner diameter of the pipe so that the possible influence of curvature could be recognised. The curvature of the specimen would tend to make the test somewhat more conservative but with the extent of that conservatism being dependent on specimen width. Minimising the effect of variations in strain and stress across curved specimens so that the material is stressed and strained as much as possible to the target value is clearly desirable and choosing a specimen width that is 1.5 times the thickness is recommended. Smaller widths can be adopted though challenges in ensuring alignment then become more significant.

Of course, full pipe testing removes all of these uncertainties but with a major cost penalty, which could be prohibitive in establishing pass-fail domain diagrams.

4. CONCLUSIONS

FE analysis of the stress and strain associated with specimens removed from pipework with one surface curved suggests that under elastic loading the stress and strain at the tensile surface become progressively greater towards the specimen edges where the specimen is thickest.

At deflections sufficient to induce yield, the strain is also greatest towards the specimen edges but the stress tends to be a maximum midway between the centre and the edges, reflecting stress relaxation and redistribution following yielding.

The magnitude of the effect will be a sensitive function of the specimen width to the inner diameter of the pipe. A width corresponding to 1.5 times the thickness is recommended.

5. RECOMMENDATIONS

Experimental work is recommended to measure the strain distribution across a curved specimen, using digital image correlation for example, to validate the FE computations. Since the stress does not show much variation across the curved specimen and the role of plastic strain as a critical factor in the location of cracking is yet not substantiated there would be value in assessing the impact by conducting sulphide stress corrosion cracking tests using specimens of varying width (same thickness) derived from a relative small bore pipe.

6. ACKNOWLEDGEMENTS

The authors appreciate the expert comments from Roger Morrell with respect to the mechanics of four point bend testing with curved specimens.

7. REFERENCES

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