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Influence of Structural Defects on the Beneficial Effect of Autofrettage

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Abstract: A comprehensive numerical study has been carried out to investigate and to explore the impact of the presence of part through surface cracks of various size and orientation in a thick welded ferritic steel cylindrical vessel, on the beneficial effect of autofrettage loading. It is well known that autofrettage loading enhances the load carrying capacity of defect free pressure vessels. The results of this study suggest that in presence of cracks, the localised near crack tip residual stress fields interact with in service stresses and influence the enhancement in load carrying capacity of autofrettaged vessel. Furthermore it is concluded that depending on the crack/loading configuration the impact of crack presence on post-autofrettage performance of the vessel varies from noticeable in some cases to marginal in others to negligible for cases where the crack tip stress field is not significantly disturbed by the service loads.

Keywords: Autofrettage, surface part through cracks, pressure vessel, residual stress, FEM

1 Introduction

The beneficial effect of autofrettage loading i.e. enhancement in the load carrying capacity of pressurised defect free vessels is well established and widely addressed in literature. The majority of research conducted on the autofrettage process in recent years has focused on issues related to the effects of material behaviour including reverse loading response for the hardening rule (Bauschinger effect). For example Parker [2001], Perry and Aboudi [2003] and Perl and Perry [2006] investigated the role of Bauschinger effect and provided generalised three dimensional elastic-plastic stress and strain field solutions for an autofrettaged vessel. Hojjati [2007] provided analytical and FE models for autofrettaged strain hardening thick walled tubes. Geometry related studies were carried out by Abibi-Asl [2008],

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Adibi-Asl and Livieri [2007] and Parker [2008] who investigated autofrettage of spherical vessel and Mohammadi et al [2008] who explored residual stress fields induced by autofrettage in compound tubes for a range of geometries. An interesting study by Jahed [2006] considered the issue of "re-autofrettage".

The benefit of autofrettage is mainly due to the residual stresses arising from plastic deformation induced in the vessel that oppose the service load induced stresses and result in the critical stress levels being reached at a higher level of the applied service pressure. Typical residual stress distribution fields in a cylindrical vessel following autofrettage are shown in Figure 1.

The significance of influence of part through defects arising from manufacturing processes, mounting arrangements, installation procedures and maintenance that vary in shape, orientation, location and depth on the beneficial effect of autofrettage is less understood and needs to be systematically explored. The initial impact of presence of defects is that the residual stress fields in and around the defect plane will be affected and redistributed and hence would be different from the uncracked residual stress fields in the autofrettaged pipe. Treatment of residual stresses due to forming and welding in structural integrity assessment codes requires careful consideration to avoid misleading predictions of fracture. There exists very limited research work aimed to address redistribution of stresses due to autofrettage loading in presence of cracks. One such example is the work of Kapp and Crofton [1987]. They provided an analytical solution for stress field in an autofrettaged thick walled cylinder subjected to pressure load that included cracks. Recently a numerical study reported the effect of initial residual stress fields on cleavage fracture in a cylindrical vessel containing a surface hoop crack of finite size (Hadidi-Moud et al [2006]).The systematic numerical study reported here is aimed to provide an insight to the problem by considering various crack configurations.

In the following sections, the geometry, material and details of cracks are first described together with the finite element models that were created for the analysis of autofrettage. The results for normal to crack plane stresses are then presented and the impact of autofrettage is discussed. Finally important aspects of the impact of crack presence on the potential benefit of autofrettage are highlighted for all crack configurations

2 Description of Models

Using ABAQUS/CAE (V6.7) [2006], two thick walled cylinders of ferritic steel A533B were modelled and used in this study. The vessel geometry and crack details are shown in Table 1. The material data used in the analyses were taken from Smith et al [2004]. Eight configurations of part through cracks (5 mm through the pipe

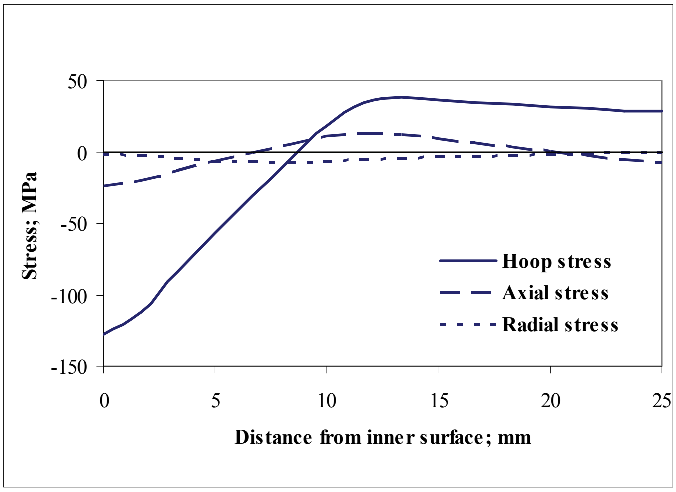


Figure 1: Typical residual stress distributions in autofrettaged uncracked cylinder

thickness at the deepest point) were introduced to the 25 mm thick pipe. These include finite (50 mm edge to edge on pipe surface) and fully extended cracks either in hoop or in the axial direction and in each case on the outer or the inner surface of the pipe. A 12 mm deep extended external axial crack was introduced into the 50 mm thick pipe. All crack configurations are shown in Figure 2 whereas Figure 3 shows the details of finite element model and mesh refinement in regions where various cracks were introduced in axial or hoop direction. The mesh refinement scheme used for the pipe in axial and hoop directions is shown in Figure 3.a and figures 3.b and 3.c show details of finite size part through cracks introduced on the inner side of the pipe wall in hoop and axial directions respectively.

To overcome the inaccuracy in stress data at the vicinity of crack fronts in a time efficient analysis, the sub-modelling technique available in ABAQUS/CAE was used. Only a very small region around the crack front zone was modelled allowing highly refined mesh at the tip region. The boundary conditions applied to the sub-model was obtained from an initial analysis of a course mesh model of the whole structures. The element size and type at tip region in the sub-model was reduced to level that resulted in achieving smooth stress gradient at the tip region as indication that the FE analysis would be offering reliable stress data.

Sufficient mesh refinement to provide reliable stress strain data was considered in the analyses based on verification of FE analysis results with analytical solutions for benchmark uncracked models. Furthermore, crack tip mesh refinement to sufficient

Table 1: Model details

Model	OD=2R_o, mm	Thickness; mm	ID=2R_i; mm	Length; mm	$K = \frac{R_o}{R_i}$	a/t
Short pipe*	200	25	150	100	1.33	0.2
Long pipe**	200	50	100	1000	2.00	0.24

*) all (eight) crack geometries **) extended axial crack on outer surface only

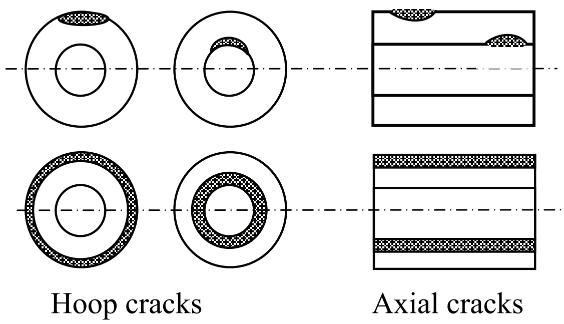
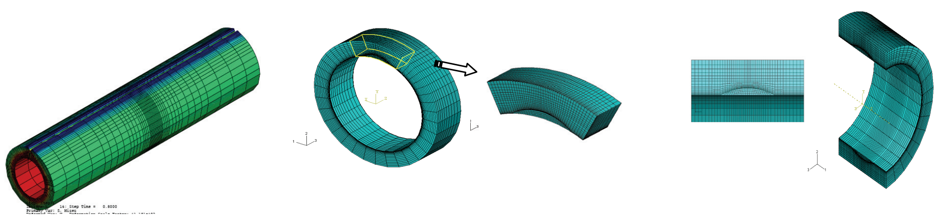


Figure 2: All crack configurations considered in the analyses



(a) (b) (c)

Figure 3: Details of finite element models and cracks: a) pipe model with locally refined mesh for introduction of cracks; b) finite part through hoop crack; c) finite part through axial crack

degree was achieved by use of sub-modelling option in ABAQUS/CAE.

3 Modelling Results

All results are discussed in the context of stress, residual stress and stress re-distributions at the crack front as well as the inner surface of the vessel. Normal to crack plane stresses have been plotted against through thickness distance from crack tip in the crack extension plane and compared to explore the impact of each crack configuration. Sub-modelling facility of ABAQUS/CAE was deployed to ensure that reliable stress evaluation at crack tip region was achieved in a time efficient fashion. In this section FE analyses are described and the results are discussed. Analytical solutions of autofrettage for elastic-perfectly plastic material available in literature were used for verification of FE simulations to ensure that appropriate mesh refinement and boundary conditions have been considered. However, details of analytical verification are not included in this paper.

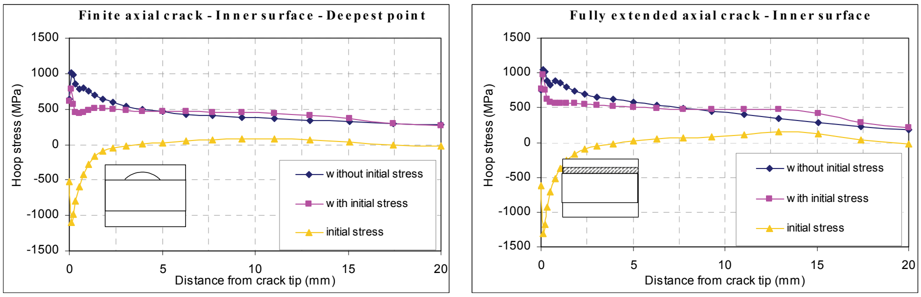
3.1 Results for 25 mm thick pipe

For the pipe with 25 mm wall thickness all crack configurations shown in figure 2 were simulated to understand how residual stress fields that develop in autofrettage process may be affected by presence of various part-through cracks in the pipe. An autofrettage pressure of 165 MPa and a service pressure of 125 MPa were used. Data for A533B steel used in these analyses was available from previous research (Smith et al [2004]). Through thickness stresses from the deepest point of the crack front were examined. Results for all axial cracks are shown in Figures 4a for inner surface finite and extended part through cracks and in Figure 4b for outer surface finite and extended part through cracks. Similarly, Figures 5a and 5b show the stress distributions for all hoop cracks for inner surface finite and extended part through cracks and for outer surface finite and extended part through cracks respectively.

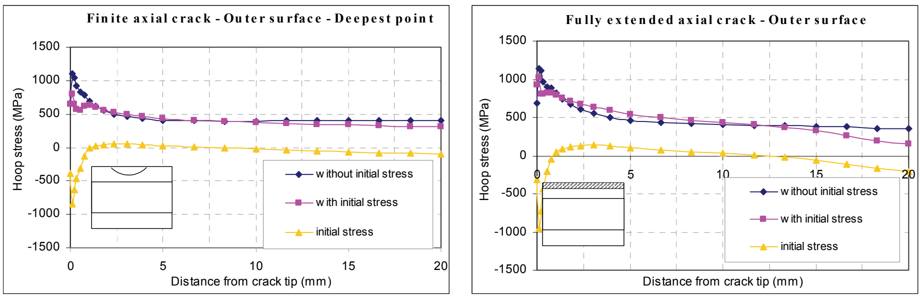
a) Axial cracks; hoop stress distributions

Comparison of distributions shown in Figure 4a for finite and fully extended axial cracks on the inner surface of the cylindrical vessel indicates that autofrettage loading leaves a compressive stress field normal to the crack plane at the crack tip region for both cases. The level of compressive stress for the case of fully extended crack (right) is higher that that of the finite axial crack (left). However following reloading the normal to crack plane stress level ahead of the crack tip shows a higher reduction for the finite crack i.e. extended crack represents a more critical situation. This finding is consistent with the general design practice in most integrity assessment codes. Procedures followed by some codes e.g. integrity codes developed in china and Japan replace the randomly distributed finite part through surface cracks of various depths with one fully extended crack of a depth equal to the deepest detected finite crack and consider this assumption to be conservative.

The above discussion is also valid for the case of outer surface axial cracks in figure 4b. as seen for the finite outer surface axial crack (left) crack tip compressive stress field is lower than that of fully extended crack but the result is a greater reduction in crack front stress compared with the case of fully extended crack. This again



(a)



(b)

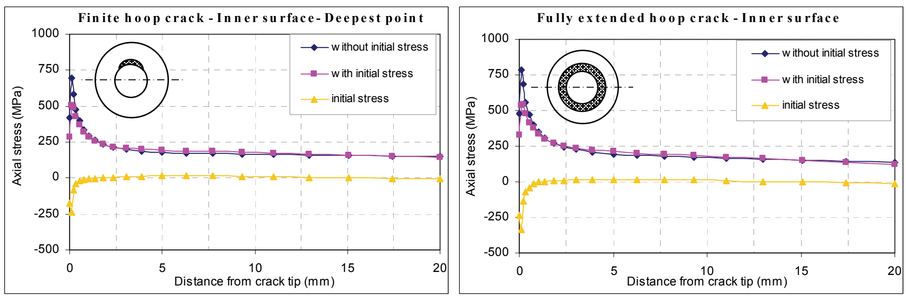
Figure 4: (a) Influence of autofrettage loading on crack plane stress distributions for inner surface axial cracks on 25 mm thick pipe; (b) Influence of autofrettage loading on crack plane stress distributions for outer surface axial cracks on 25 mm thick pipe

supports the design practice assumption as described above.

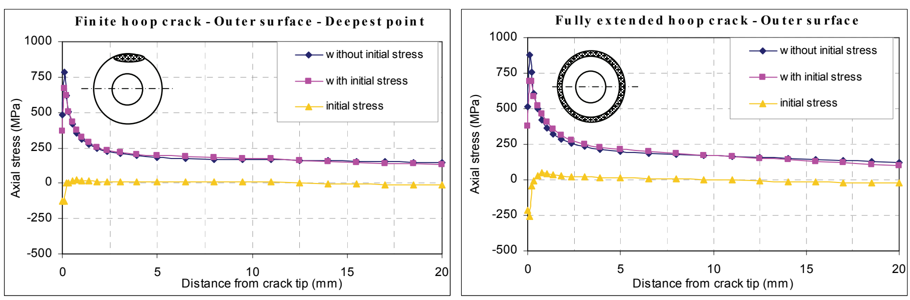
It is also noticeable from the comparison of Figures 4a and 4b that the compressive crack tip hoop stress field for the inner cracks (4a) is generally stronger than that of the outer surface cracks (4b). These figures also suggest that the subsequent impact of residual stress on reloading stresses is consistently more significant for the inner crack cases shown in Figure 4a.

b) Hoop cracks; axial stress distributions

Similar stress distributions in normal to crack plane direction are plotted in figures 5a and 5b. These figures summarise all hoop crack configurations, finite or fully extended on the inner surface (Figure 5a) or the outer surface (Figure 5b) and their corresponding normal to crack plane stresses (axial stresses for these cases). The results indicate that axial stress distributions show less sensitivity to stress redistributions for finite hoop cracks compared with the extended hoop cracks and this is the case for both inner and outer surface cracks. It should be noted that although the results are less affected in these cases it may be concluded that the fully extended cracks represent the higher stress fields consistent with the integrity assessment code recommendations.



(a)



(b)

Figure 5: (a) Influence of autofrettage loading on crack plane stress distributions for inner surface hoop cracks on 25 mm thick pipe; (b) Influence of autofrettage loading on crack plane stress distributions for outer surface hoop cracks on 25 mm thick pipe

Similar to the case of axial cracks the argument regarding the comparison of crack tip compressive residual stress regions corresponding to the inner and outer surface cracks and their subsequent impact on reloading stresses is also valid for the cases of hoop cracks. Comparing figures 5a and 5b it is seen that axial compressive crack tip residual stresses in Figure 5a are stronger that those in Figure 5b, so is their subsequent impact on reloading axial stress distributions.

3.2 *Results for 50 mm thick pipe*

For 50 mm thick pipe autofrettage load of 400 MPa was used and the applied service load was 320 MPa. Figure 5 shows that the extended axial crack on the outer surface disturbs the compressive hoop stress field on the inner surface of the pipe and as a result the benefit of autofrettage is almost wiped out across a region around the crack plane. Through thickness normal stress distribution is also shown in Figure 6. Interestingly in this case of a rather deeper crack into the exterior surface of the pipe, autofrettage has introduced tensile residual stress field in normal to crack plane at the tip region. As a result as Figure 6 (right) indicates the level of hoop stress on reloading at the tip region is higher that the stress at the same load level for the solution without considering autofrettage. This implies that for the case of fully extended external axial crack in the thick pipe with deep crack autofrettage not only is not beneficial to the vessel but also reduces the load carrying capacity on subsequent loading.

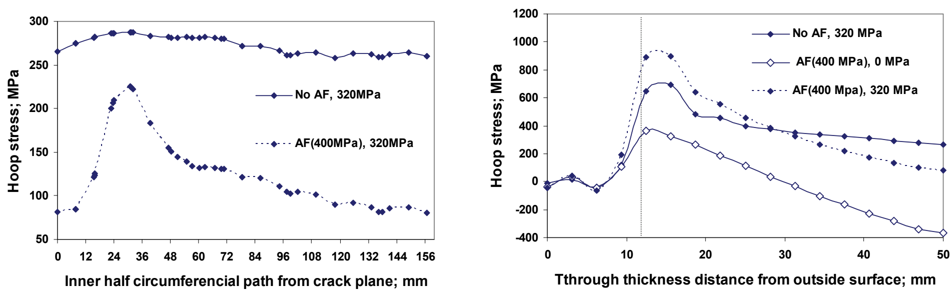


Figure 6: Influence of autofrettage on inner surface (left), and through thickness in crack plane (right) Hoop stress for 12 mm deep extended external axial crack on 50 mm thick pipe

4 Discussion and Conclusions

This numerical study explored the effect of autofrettage loading on the subsequent load carrying capacity of steel pressurized vessel for a range of cracks. For cracks on the outer surface regions of plasticity emerged from both the inner surface and the crack tip region whereas for internal cracks these plastic regions were submerged. In the case of extended axial cracks plastic regions eventually merged and plasticity extends from inner surface to the crack tip region. For finite length cracks residual stress distribution varied along the crack front. For hoop finite cracks on the outer surface crack edges (on the surface) experienced tensile normal stresses. The results of analyses presented in figures 4, 5 and 6 revealed that the residual stresses arising from autofrettage in both the inner surface of the pipe and at the crack tip zone were compressive, thus reduced stress levels on reloading were obtained. For axial cracks it was found that normal (hoop) stresses at the crack tip region were higher and increased with increasing the size of crack front, hence resulted in higher residual stresses.

Although experimental data to support and verify the conclusions were not available, the FE analysis results were validated by comparing the FE model data with the analytical solutions available in standard text books for simplified problem. The standard solutions were also used to achieve the sufficient mesh refinement in the modelling procedures to ensure reliable results.

Based on the case studies presented in this work the following recommendations were concluded: Firstly, care should be taken to avoid failure if autofrettage loading is to be used in presence of surface cracks. The crack tip stress field may limit the allowable autofrettage load, thus reducing the compressive residual stress field on the inner surface that in turn reduces, if not vanishing, the expected benefit of autofrettage. This is especially the case for external axial cracks. Secondly, although in most cases autofrettage loading results in lowering the crack front stresses on reloading, it should be noted that the level of stress generally remains higher compared with the case of uncracked pipe.

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