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Interaction of Mechanical Loading with Residual Stresses in Pressure Vessels

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Abstract. Assessment of the integrity of structures such as reactor pressure vessels is a critical issue in relevant industries. In a full integrity assessment, the presence of initial residual stresses (RS) needs to be taken into account. An initial RS field is introduced into a type 316 stainless steel cylindrical vessel with no defects and to one with a partial circumferential crack on its outer surface. Relaxation of RS following several proof load cycles, in form of internal pressure, applied to the vessel is explored using finite element simulations. It is found that the proof loading process generally relaxes the RS and is proved to be beneficial to both cracked and un-cracked vessels with or without the presence of initial RS. Interaction of residual stresses with warm pre-stressing is further investigated using A533B steel at room and low temperature subjected to axial loading. The results are compared with similar analyses but with no introduction of an initial RS field to explore the interaction effects on fracture resistance, as well as the role of partial crack on the RS distribution / redistribution. The differences are discussed and illustrated.

Introduction

It is a normal practice in industry that autofrettage enhances the subsequent resistance of a pressure vessel to fracture. Welding is an essential element in the fabrication of components in pressure vessel and piping technology. Due to the importance of reliability in performance, especially when the components are used in sensitive applications such as nuclear industry the conventional integrity assessment codes and standards are receiving continuous attention for appropriate revisions. Welding processes often leave residual stresses in the fabricated components and significant effort is made to minimize their impact on the performance and integrity of such structures. This issue becomes more complicated when adding the likelihood of generation of cracks in these structure origination from various possible mechanisms on one hand and the singularity problem associated with the crack tip response to loading on the other hand. As a result the industrial codes need to establish very cautious measures in the standard procedures to be followed.

This work attempts to simulate some aspects of this framework and concentrates on a specific case study using geometry and crack configuration adopted from a study carried out by British energy.

Two different materials are used in this study and residual stresses are artificially introduced to cracked as well as un-cracked problem and effects of warm pre-stressing together with the RS fields is studied from the point of view of stress re-distributions in relation with the relaxation. This study followed the trends used by authors in a previous work on laboratory scale generation of RS fields in standard fracture mechanics specimens [1]. Also studied is the prediction of fracture distributions for various cases using a local approach to cleavage fracture previously adopted by the authors [2, 3, 4].

The analyses are subdivided to those looking at stress state, mostly using type 316H stainless steel, and those looking on the interaction effect of subsequent fracture, using A533B response at room and low temperature [5].

The finite element models

The case used in current study is a pipe with outside diameter of 432.0mm and a wall thickness of 19.6mm. An arc type partial circumferential crack, 5mm deep and 50mm long was introduced on the outer surface of the pipe in the hoop direction. Three-dimensional finite element models one for the pipe without any defect and one for the pipe with the described crack were produced using Type 316H stainless steel. All analyses for this steel used room temperature response whereas the FE model with crack was also used with A533B steel using material response at room as well as very low temperature. ABAQUS/CAE v6.3 was used as the FE tool throughout this work. The element type used for all analyses was C3D8R, 8-nodded linear brick 3D elements with reduced integration, containing one integration point at the center of the element only. This allowed significant reduction in problem size and thus sufficient mesh refinement at the crack tip region, yet providing reliable results from the FE simulations.

For type 316H stainless steel models a whole pipe was modeled and the crack was inserted into the pipe by artificial simulation, introducing additional nodes coincident with the desired crack face nodes and integrating them into the model to represent free surfaces. Details of pipe geometry, crack and the mesh are shown in Fig. 1. In case of type A533B steel, only half of the specimen was modeled and the symmetry planes allowed the crack introduction by simply changing the boundary conditions on the plane of symmetry normal to the pipe axis through the crack face.

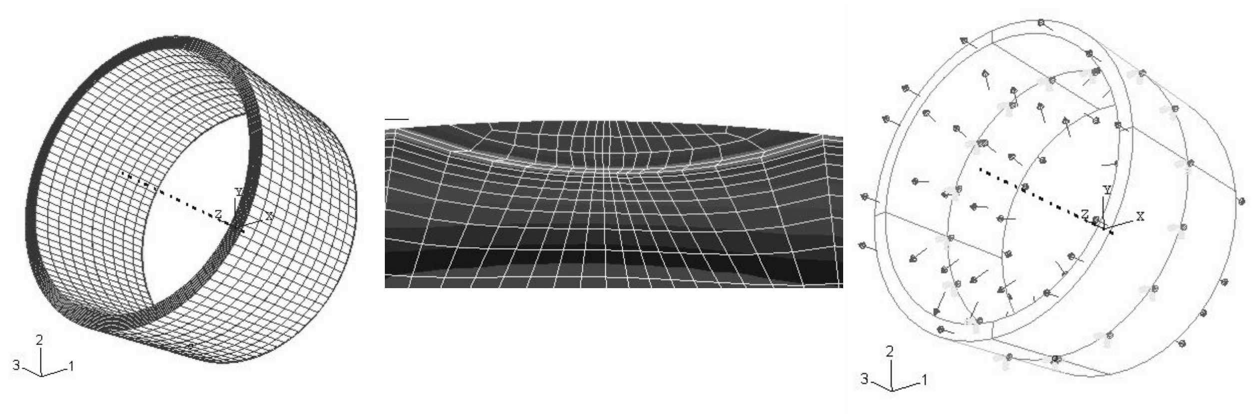

Fig. 1 Geometry,FE model and boundary conditions

Description of analyses

Type 316H stainless steel pipe model. All models in the final step of analysis were incrementally loaded to fracture by a combination of internal pressure and its corresponding axial loading component to simulate a pressurised vessel. Fig. 1 also shows the boundary conditions and the loading. From each configuration (with and without crack) the following analyses were performed:

1) Loading to fracture with no presence of initial residual stresses.
2) Proof loading to various levels followed by unloading and re-loading to fracture.
3) Introducing initial residual stress field and subsequent loading to fracture.
4) Introducing initial residual stress field, then proof loading to various levels followed by unloading and reloading to fracture.

Analyses of types 1 and 2 are normal practice in autofrettage study of pressure vessels and were only performed to explore the require level of proof loading to get the autofrettage effect. This was necessary both to estimate the required load levels that are high enough to introduce some plasticity and at the same time not to high to result in the spread of complete plasticity in the wall through the thickness, as this will not produce any autofrettage benefit. In particular, for this case study, the thickness to radius ratio is small (~0.1) and there is a rather narrow zone for appropriate autofrettage loads. Results of these analyses are only used as self-equilibrated stress status to establish the initial RS field for other analyses and are not presented in this work.

Type 3 analyses were performed to investigate the influence of residual stresses that are initially present, i.e. due to fabrication processes, on the stress-state during in service conditions. The last series of analyses, type 4, would provide information to explore the interaction of mechanical loading, with the initial RS field in the vessel as well as the role of initial RS field in the proof load effect in terms of enhancement of the fracture resistance of the vessel. The remaining of this work mainly focuses on stress distributions and re-distributions through out these analyses.

The material model for all the reported analyses is kinematic-hardening response based on the elastic-plastic stress strain response of the stainless steel as provided in other research. It should be noted however that the material model was purely used for FE simulation and does not necessarily reflect the through material response. This is not a crucial issue as no experimental data are included in present work.

All the analyses presented here assume that, in case of surface crack, the crack was present prior to all loading stages and various loading cycles were applied to cylinder with crack inserted on the outer surface as described before.

Type A533B steel. To further explore the interaction of RS and mechanical loading in cracked component, a different type of fracture loading was applied to the same geometry / crack configuretion as described above. Application of axial loading, would subject the outer surface hoop type partial crack to the opening mode of fracture. Subsequently, the stresses normal to the crack face would rapidly increase on reloading, indicating a completely different response from the un-cracked model (unlike the previous case for 316H stainless steel). The material properties of A533B steel, often used in the fabrication of pressure vessels, were available from previous research at both room temperature and –170C. Using this material, it was possible to also study the effect of residual stress and proof loading on cleavage fracture. For A533B steel analyses all other features of the FE model remained unchanged. The loading cycles included initial RS field followed by fracture loading at low temperature, either directly or after proof loading and unloading at room temperature. These analyses were termed ISCF (initial stress cool fracture) and ISLUCF (initial stress load unload cool fracture) respectively. Analyses using AR and LUCF load cycles were also performed to provide data for comparison.

Introduction of initial RS field

Type 316H stainless steel pipe model. The initial residual stress field for all the analyses that used 316H stainless steel was generated from the results of type 1 and 2 analyses. Incremental application of internal pressure alongside the corresponding axial loading allowed identification of the appropriate load level to cause some plasticity in the cylinder (but not fully extended through the pipe wall thickness). Loading to this level followed by unloading resulted in formation of residual stresses. This RS field, naturally self-equilibrated, was used to generate the desired RS field of significant level in the opposite direction to those resulting from autofrettage (i.e. reducing the subsequent load carrying capacity rather than being beneficial). This was achieved by simply up-scaling of all stress components, thus increasing in level by an order of magnitude and changing the sign, to reverse the subsequent effect. The self equilibrated RS distributions are shown in Fig. 2. The above procedure was similarly used for both models with or without crack inserted. It should be noticed that in the present study different RS fields were used as initial conditions. For the un-cracked problem the RS was adopted from the autofrettage of an un-cracked cylinder, hence a global residual stress field was used. For the interaction studies of the cylinder with surface crack on the other hand, the RS was generated from stress data from autofrettage of a pre-cracked model.

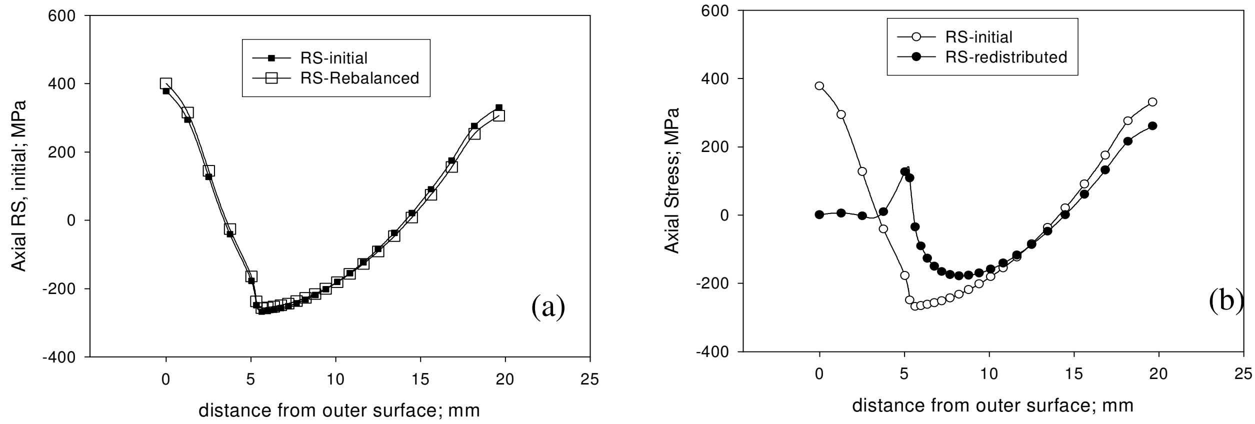

Fig. 2 Initial RS introduced and self equilibrated; (a) un-cracked and (b) cracked

Type A533B steel. For the analyses that used this material model the initial RS field was generated from the autofrettage data of the un-cracked pipe following the procedures described above. For the cracked problem the same global RS was introduced as initial conditions and then redistributed following the crack insertion. Thus the equilibrated RS field for the cracked problem in this case is different in nature from that used for 316H stainless steel problem. This is shown in Fig. 2.

Analysis of results

Type 316H stainless steel. Although an extensive simulation scheme was carried out for the present configuration, here only the results of un-cracked and cracked models with initial RS field, are presented in detail.

Un-cracked cylinder with prescribed RS field was subjected to various proof load levels applied as internal pressures from 5 to 45MPa together with their corresponding axial loads. A series of analyses were performed with increments of 5MPa and the redistribution of RS due to each load-unload cycle was monitored. The result was the relaxation of initial stress field with the level of relaxation increasing with increasing level of subsequent proof loading. This is shown graphically in Fig. 3 for Mises stresses. Hoop, axial and radial stress distributions were plotted and the significance of hoop and axial stresses compared with the radial stresses was obvious as expected.

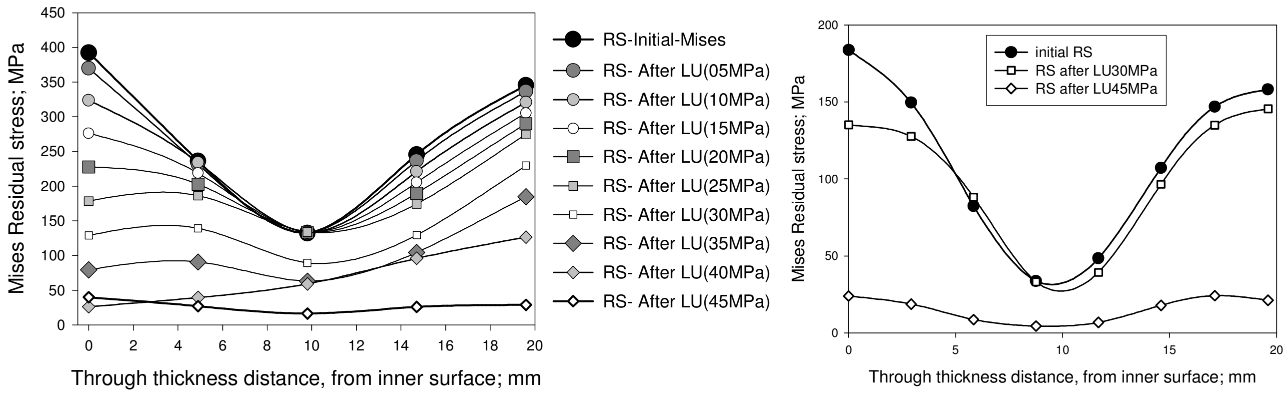

Fig. 3 Residual stress relaxatin for un-cracked and cracked problem for 316H models

Type A533B steel. Whereas the analyses for 316H stainless steel were used to illustrate the residual stress relaxation, A533B analyses results were further examined to predict the effect of interaction on final fracture using the local stress based Approach developed by the authors [2, 3]. The stress distribution / re-distributions for a number of load cycles are shown in Fig. 4. Residual stress distribution and Local approach predictions for various load cycles for cracked problem for A533B model. Predictions of local approach for fracture distributions corresponding to the above load cycles are also presented in Fig. 4.

These are discussed in the next section whereas Further studies on this issue are currently underway. Stress intensity, K, in all cases was obtained using the approximate analytical solution for the crack configuration [6].

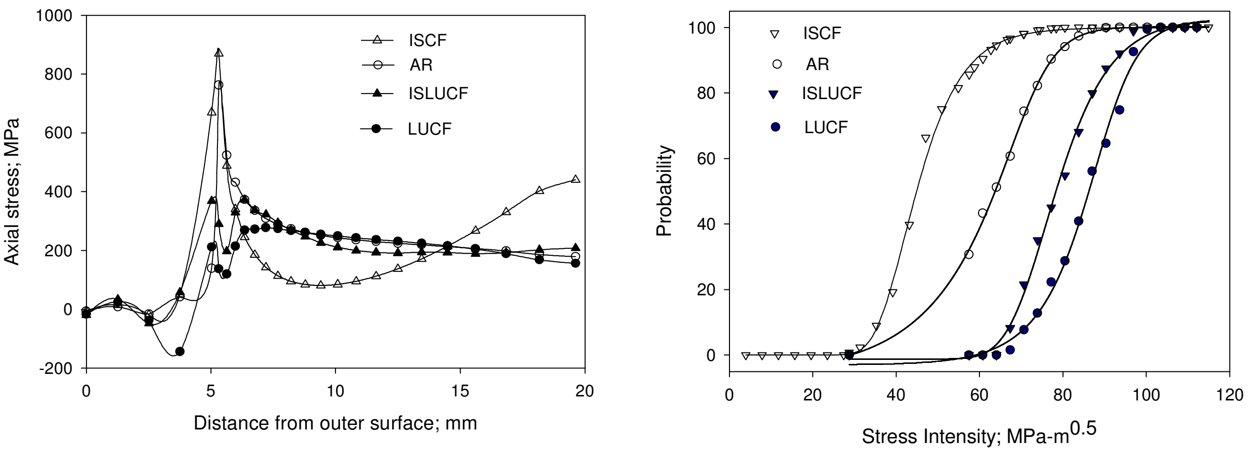

Fig. 4 Residual stress distribution and Local approach predictions for various load cycles for cracked problem for A533B model

Discussion

The A533B ferritic steel for which the material response was available at both room and low temperatures was used to explore how a "global" residual stress field is redistributed due to the crack appearance, and to examine the effect of RS on the stress state at the crack front region. Axial loading of the pipe allowed the crack opening to be dominated by mode-I.

As confirmed by the analyses presented in this work, structural defects will only interact with the residual stresses and subsequently will affect the failure conditions if the stress-state at the crack tip region has a significant contribution to triggering the failure conditions. In other words the crack tip zone is responsible for fracture only when it experiences the highest stress conditions. Whereas for the A533B analyses this was the case, for the analyses performed for the other steel the crack tip region did not dominate the fracture conditions, mainly due to the crack position and its relation to the loading used (internal pressure). This can be seen from the figures comparing the relaxation of RS for 316H problems and from the results obtained for the A533B analyses.

There are some other features affecting the interaction. One to mention is the sequence of RS introduction and crack insertion. Another is the nature of RS field at the crack tip in terms of magnitude of various stress components as well as the extent of the RS field. It is also important to investigate the relation of the RS field with the stresses arising from subsequent loading that are corresponding to the type of fracture loading that the model is subjected to.

An extensive simulation programme looking at various features of the interaction problem is currently in progress.

Concluding remarks

The initial RS field introduced to an un-cracked pipe was relaxed by means of subsequent load-unload cycles at room temperature. The level of relaxation depended on the load level used in the LU cycle, the higher the LU level, the higher the relaxation level. This statement is true provided that the LU cycle is high enough to interact with the initial RS.

In the case of the vessel containing crack and initial RS, similar conclusions are valid provided that the LU cycles does not specifically disturb the stress state at the crack tip. This was the case where the cracked vessel with the prescribed initial RS field was subjected to internal pressure.

Interaction of RS with mechanical loading would dominate the fracture condition of the cracked vessel if the stresses arising from LU cycles and or those due to final fracture loading subject the crack to opening fracture mode due to increasing stresses at the crack front. This was seen in the case of analyses that used A533B material and axial loading was used for both the LU and final fracture loading.

For the analyses presented here the impact of initial RS on the fracture condition was observed by indication of significant reduction if fracture resistance distribution resulted for the application of the local approach. LUCF loading with no initial RS resulted in significant increase in predicted fracture resistance as expected.

When initial RS of the global type was combined with Axial LU cycles the predicted fracture distribution depended on the significance of initial RS.

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