ASME STANDARDS TECHNOLOGY, LLC

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REFERENCE STRESS SOLUTIONS FOR THICK-WALL CYLINDERS

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FOREWORD

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EXECUTIVE SUMMARY

This report describes the analysis completed to obtain crack front maximum reference stress results for internal and external cracks in thick-walled cylinders. The crack models and analysis method compute the geometry factor that is used to compute the reference stress value for a given assessment pressure. The reference stress is needed to obtain the Lr ratio for the Failure Assessment Diagram (FAD) method to assess cracks for stability, which is described in Section 1. The geometry factor results are tabulated in the appendices of this report and in the Excel file attached to this report.

Three dimensional surface plots of nominal load and maximum geometry factor results are given for each crack case to show the results trend versus the cylinder geometry ratios. The results are reported as non-dimensional geometry factors that are tabulated in the report appendices for all cases. For use in crack assessments, the geometry factors would be used with a table look-up. For geometry and crack dimensions with intermediate ratios between the table values, interpolation would be used to obtain the geometry factor.

Cases Examined

The 523 thick-wall cylinder cases examined in this project include a range of geometry ratios for the cylinder thickness to radius ratio, crack depth to thickness ratio, crack length to crack depth ratio for the surface cracks, and four crack locations: axial internal, axial external, circumferential internal, and circumferential external. The crack shapes include surface cracks, axial full-width partial depth axial cracks, and circumferential 360° partial-depth cracks. The full-width and 360° crack shapes provide bounding solutions for the longest surface crack results so that the solutions presented here can be applied to longer surface cracks.

Methodology

Elastic-plastic Finite Element Analysis (FEA) was used to compute the crack front J-integral results versus increasing internal pressure. The J-integral results are used to obtain the nominal load using the Kr ratio intersection with the material-specific ratio, which is a function of the material's yield strength and elastic modulus. Using the nominal load, the geometry factor values were computed. The geometry factors are used to compute the reference stress and FAD Lr ratio. The J-integral nominal load methodology is described in Section 3.1 of this report. The stress-strain curve used for this project was initially examined using a range of yield strength to tensile strength ratios. The investigation revealed a dependency of the reference stress on the yield to tensile strength ratio. The investigation results led to the choice of a stress-strain curve with a yield to tensile strength ratio of 0.9, which is described in Section 3.2.

As the cylinder thickness increases, some shallow internal cracks had insufficient J-integral results to obtain the nominal load; the Kr ratio did not intersect with the material specific ratio. An alternative method of using the maximum converged pressure was used to obtain a nominal load so that the geometry factor could be computed for all the cases in this project. Section 3.3 discusses the maximum pressure approach and compares trends to the J-integral method.

Result Comparisons

The thick-wall cylinder reference stress results from this project were compared to the existing reference stress solution from API 579 in Section 3.4. The comparison shows similar reference stress result values for the radius to thickness ratio of 1.0, the thinnest cylinder geometry in this project. Since the thick-wall

cylinder hoop stress has a curved non-linear distribution through the thickness, and the current API 579 reference stress solution is in terms of a linear membrane plus bending stress, the thick-wall cylinder reference stress solutions better capture the actual hoop stress and thick-wall geometry to give an improved reference stress result to evaluate cracks in thick-wall cylinders.

Another result comparison was with the maximum collapse pressure of undamaged cylinders using the ASME Boiler Pressure Vessel Code Section VIII Division 3 pressure design equations. The cracked cylinder nominal load was less than the maximum collapse pressure of an undamaged cylinder, indicating the results capture the reduced maximum pressure of a cracked cylinder.

Software Automation

The crack meshes were created using Quest Integrity's FEACrack software, and the analyses were run using the Abaqus FEA software. Python scripts were used to update the geometry data and generate all 523 models by running the FEACrack software automatically, which removes human error from the crack mesh generation. The FEA results files were post-processed using FEACrack to extract the stress, deformation, and crack front J-integral results. The FEACrack post-processing module automatically computes the nominal load, geometry factor, and reference stress along the crack front and reports the maximum crack front reference stress results. A second Python script extracted these maximum crack front reference results from the output report text files to tabulate and plot the results for each model group.

Future Work

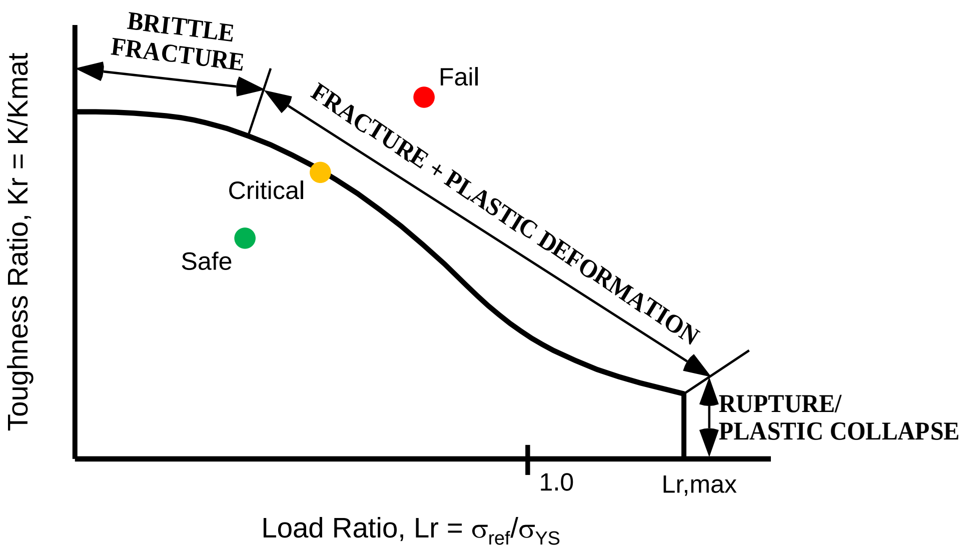
The tabular reference stress results can be reviewed and added to appropriate ASME standards, such as the API 579/ASME FFS-1 standard, to aid in evaluating cracked thick-wall cylinder components for high pressure applications. Since the reference stress was shown to have a dependence on the material yield strength to tensile strength ratio, some additional cases could be examined to determine if the trends in this report continue for thicker cylinder cases. A scalar multiplier as a function of the yield to tensile strength ratio could be developed that would be used to multiply the reference stress geometry factor solutions in this report, which were developed using a yield to tensile strength ratio of 0.9, to extend use of these solutions to smaller yield to tensile strength ratios.

To obtain a better overlap of the thick-wall cylinder reference stress solutions with the current reference stress solution in API 579, some thinner wall cylinder cases could be examined where the hoop stress distribution through the thickness is linear, which would match the stress distribution used in the current solution.

1 INTRODUCTION

Evaluating cylinders with cracks using the Failure Assessment Diagram (FAD) fracture mechanics methodology requires a reference stress solution to check for plastic collapse. An example FAD plot is shown in Figure 1-1. The Lr value on the FAD x-axis is the ratio of the reference stress to the yield strength. The Kr value on the FAD y-axis is the ratio of the crack front stress intensity to the toughness. To assess a cracked cylinder, the Lr,Kr point is computed using the cylinder dimensions, crack dimensions and orientation, and the applied loading. Assessment points below the FAD curve indicate a stable crack and are considered safe, where points outside the FAD curve predict an unstable crack that would cause a failure of the cylinder. An assessment point on the FAD curve is at the critical limit, and can be used to determine a critical crack size or a critical load, such as burst pressure. The shape of the FAD curve captures the interaction of the two material failure modes: brittle fracture and plastic collapse.

Figure 1-1: Failure Assessment Diagram example plot where the reference stress is used to determine the x-axis Lr assessment value.



The API 579/ASME FFS-1 2016 standard [1] provides reference stress solutions for cylinders with cracks for a limited range of diameter to thickness ratios for thinner wall cylinders. Reference stress solutions for thick-walled cylinders are not yet available in API 579, so additional solutions are needed to support thick-wall cylinder cases. Adding reference stress solutions for thick-walled cylinders would be beneficial to evaluate cracks in high pressure thick-wall vessels and piping.

Reference stress solutions can be determined using elastic-plastic Finite Element Analysis (FEA) of cracked cylinders. The crack front J-integral is computed for a range of increasing pressure values. The J-integral results are used to determine a nominal load and geometry factor that gives the reference stress using the methodology in API 579; refer to Section 3.1 in this report for more details. The non-dimensional geometry factor values are obtained for a range of cylinder and crack geometries and are tabulated in the appendices at the end of this report.

Two previous Standards Technology Publications [2][3] provided stress intensity K solutions for thick-walled cylinders. Stress intensity solutions are used to obtain the Kr value on the FAD y-axis. However,