"Inherent Safety Factors in the API Girth Weld Defect Tolerance Analysis – Part II"

by

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ABSTRACT

The 2007 API 1104 standard for pipeline construction includes a new Appendix A for "Alternative Acceptance Standards for Girth Welds". Conservatism exists from two factors. The largest conservatism is from a new empirical limit-load solution. This conservatism came from not screening out the low toughness material test data. Properly screening the data shows a margin of $4/\pi$ to $(4/\pi)^2$ on failure stress. The new API 1104 Appendix A limit-load solution is so conservative, that both elastic-plastic fracture mechanics (EPFM) approaches are not needed. An additional conservatism of about 1.1 is due to an increase in the effective flow stress for pipes under pressure and bending. Hence for pipe under pressure and bending, the inherent margins in the API analysis are 1.40 to 1.86 on failure stress. Finally, the API Option 1 procedure was based on larger diameter pipe results (i.e., ~30-inch diameter), so they will be even more conservatism for smaller diameter pipes.

INTRODUCTION

The 2007 Edition of the API 1104 standard for pipeline construction included a new Appendix A for "Alternative Acceptance Standards for Girth Welds". The approach in this new Appendix A replaced criteria that were developed in the late 1970's. The new criteria include a limit-load solution, simplified graphs for elastic-plastic fracture toughness considerations, and a much more detailed failure-assessment-diagram (FAD) approach for the elastic-plastic fracture analyses of girth weld defects. The criteria are stress-based criteria, not strain-based criteria. In 1979, a paper by Wilkowski and Eiber was presented at the American Welding Society Pipeline II Conference with the same title [1], hence this paper, although 30 years later, is Part II.

SUMMARY

In this paper, some of the inherent conservatisms in the new 2007 Appendix A criteria are discussed. One of the largest contributors to the conservatism is the limit-load solution that was used. That solution was based on empirically bounding all the full-scale line-pipe girth-weld defect fracture tests that could be found, and having a correction factor developed relative to the existing Miller limit-load solution. As pointed out in a recent DOE/PRCI publication [2], that data included all of the test data,

and did not screen out the low toughness material test data that were not actually limit-load failures, i.e., even brittle fracture girth weld tests were bounded by the empirical limit-load correction. When properly screening out the non-limit-load failures, it was shown that there was a safety factor of at least $4/\pi$ on the failure stress. However, even those results are not consistent with limit-load solutions in other international circumferentially surface-cracked pipe defect acceptance criteria [3,4] where there is an additional $4/\pi$ degree of conservatism in the new API limit-load solution. When combined together this gives an inherent safety factor of up to 1.62 on the failure stress. In fact, the limit-load solution used in the new API 1104 Appendix A criteria was so conservative, that it bounded all the pipe test data that had CTOD values down to 0.05 mm (0.002 inch), so that in reality the simplified EPFM approach in Option 1 graphs were not needed, and the FAD curve approach in Option 2 was also not needed, see Figure 1.

There is an additional contribution to increase the conservatism for pipes under pressure and bending loads. The limit-load solution and EPFM corrections were all based on pipe tests under pure bending. Full-scale pipe test data from other industries [5,6] shows that the EPFM and limit-load solutions are more conservative for combined pressure and bending loads. The effects of hoop stress on strain-based criteria are part of on-going research efforts, where it is agreed upon that the hoop stress *reduces* the strain capacity of flawed pipes [2]. Interestingly, the hoop stress *raises* the load capacity of flawed pipes for stress-based analysis. This comes about from an increase in the effective flow stress of the material under biaxial loading, where the von Mises yield surface criterion can be used to determine the increased flow stress. Finite element (FE) analysis illustrating this effect is shown in Figure 2. In this example, FE analyses were conducted with and without hoop stress in the pipes, which showed an increase in the maximum load-capacity. A simple von Mises correction was also made for the hoop stress effect to the non-hoop stress pipe case, and that agreed excellently with the FE results with hoop stress. From this work, it can be shown that for pipes with hoop stress loading of 60% to 80% SMYS, the flow stress will be raised by about 10 to 15 percent, which increases the axial load-carrying capacity by that amount.

DISCUSSION

For pipes under hoop stress and bending loads, the inherent margins in the API analysis is a combination of the above two conservatisms and would be a factor of 1.40 to 1.86 on the axial failure stress. For pipe being loaded under high bending stresses during construction with no internal pressure (i.e., lowering pipe into a ditch, or offshore pipe laying), the hoop stress effects on increased margins do not exist. Furthermore, in the sag bend region of the pipeline for deep-water pipe laying, the external pressure can be detrimental for stress-based criteria and possibly beneficial for strain-based criteria. These efforts show that it is important to have consistency in the understanding of stress-based and strain-based girth weld defect acceptance criteria. Finally, the Option 1 approach is based on larger diameter pipes, which will add additional conservatism to the above factors. Simplified EPFM correction factors as a function of pipe diameter exist in other industries for more than 20 years and could be adapted to an API criterion as well.

REFERENCES

[1] G. M. Wilkowski and R. J. Eiber, "Inherent Safety Factors in the API Girth Weld Defect Tolerance Analysis," presented at the American Welding Society Pipeline II Conference, Houston, Texas, February 12-14, 1979.

[2] Wilkowski, G. Rudland, D., Shim, D. J., Brust, F. W., and Babu, S., "Advanced Integration of Multi-Scale Mechanics and Welding Process Simulation in Weld Integrity Assessment," DOE Award Number: DE-FC36-04GO14040, published October 2008.

[3] ASME Boiler and Pressure Vessel Code, Section XI, Rules for In-service Inspection of Nuclear Power Plant Components, 2007 Edition, July 2007.

[4] API RP 579, "Fitness-for-Service," First Edition, January 2002.
Wilkowski, G., Olson, R., and Scott, P., "State-of-the-Art Report on Piping Fracture Mechanics," U.S. Nuclear Regulatory Commission report NUREG/CR-6540, BMI-2196, February 1998.

[5] Wilkowski, G. M., Olson, R. J., and Scott, P. M., "State-of-the-Art Report on Piping Fracture Mechanics," U.S. Nuclear Regulatory Commission report NUREG/CR-6540, BMI-2196, February 1998.
[6] Krishnaswamy, P., Scott, P., Mohan, R., Rahman, S., Choi, Y. H., Brust F., Kilinski, T., Ghadiali, N., Marschall, C., and Wilkowski, G., "Fracture Behavior of Circumferential Short-Surface-Cracked Pipe," NUREG/CR-6298, November 1995.

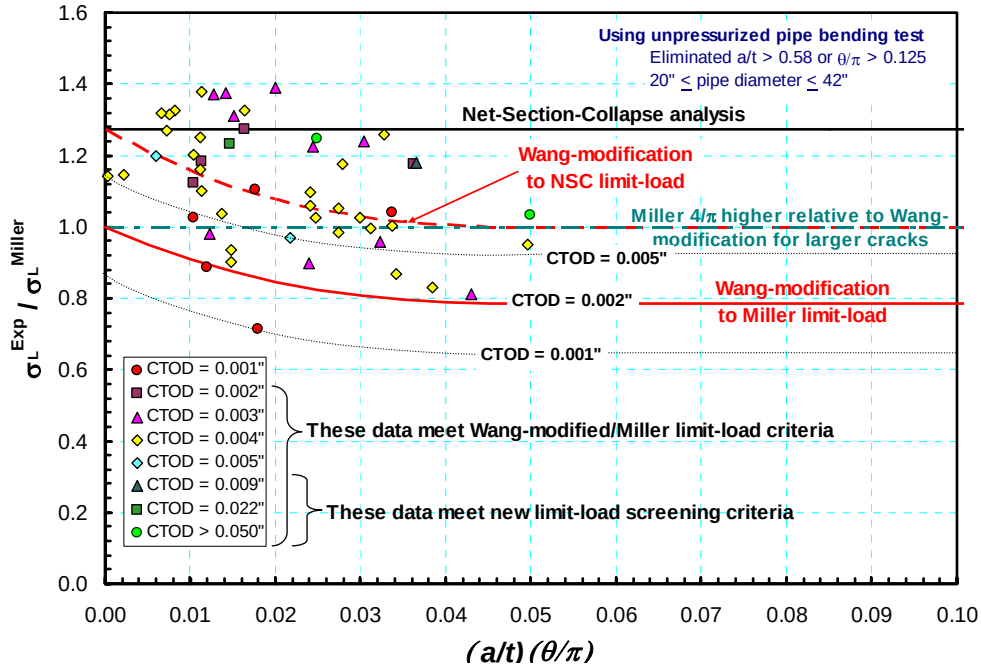

Figure 1 Comparison of full-scale line-pipe girthweld fracture tests to 2007 API 1104 Appendix A limit-load solution (Wang-modification of Miller limit-load)

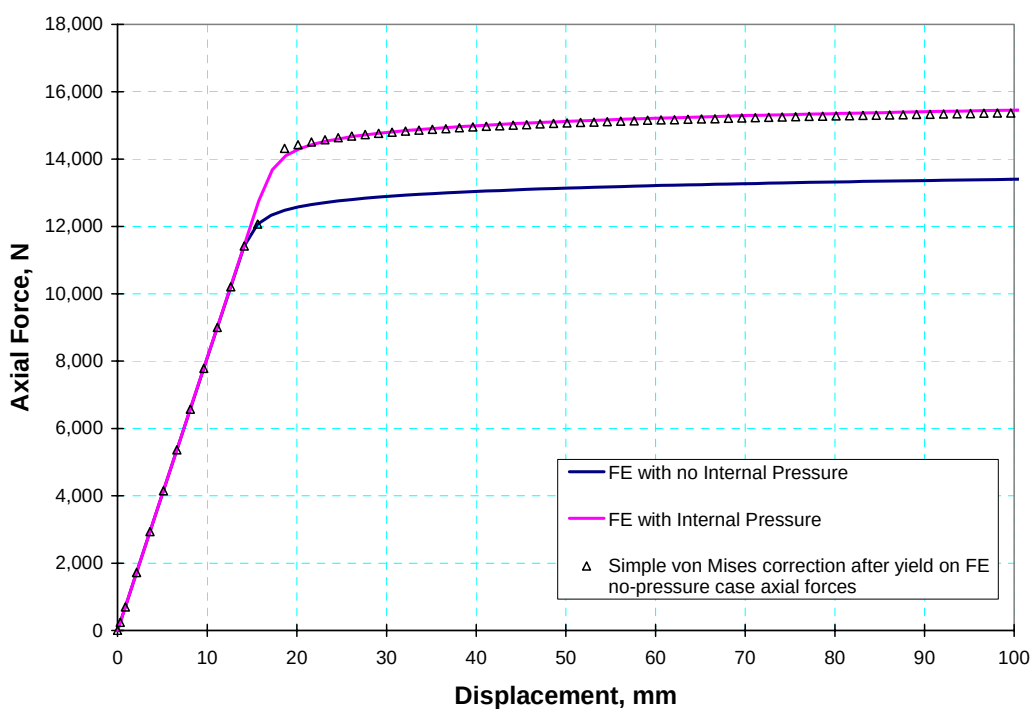

Figure 2 Illustration of hoop stress effect on axial load-carrying capacity for 36-inch diameter by 0.5-inch thick X100 pipe with hoop stress of 60% SMYS and circumferential flaw 3-mm deep and 25-mm long