Overview Of Structural Integrity Related Research On Alloy 800 Steam Generator Tubing Between 2006 And 2012

Xinjian Duan[1], Sandra Pagan[2] and Michael Kozluk[1],

[1]Candu Energy Inc., 2285 Speakman Drive, Mississauga, ON L5K 1B1

[2]Ontario Power Generation, 889 Brock Road, Pickering, ON L1W 3J2

ABSTRACT

Canadian utilities have been actively supporting structural integrity related research on Alloy 800 Steam Generator (SG) tubing through the Chemistry, Materials and Components (CM&C) research program of CANDU Owners Group (COG). The present paper summarizes the results from a variety of work packages funded under CM&C and Ontario Power Generation (OPG) between 2006 and 2012. The topics include:

- Revision of Canadian Industry Fitness-For-Service Guidelines for Steam Generator and Preheater Tubes
- Characterization of cold work and residual stresses in straight SG tubes
- Tension tests to characterize material stress-strain curves
- Tension test of SG tube with a circumferential slot
- Burst-pressure tests of defect-free archive and ex-service SG tubes
- Burst-pressure tests of SG tubes with different circumferential slot morphologies
- Development of advanced finite element method
- Residual stresses in hydraulically and mechanically expanded SG tube joints
- Validation of flaw models for structural integrity assessments of degraded SG tubes

These research results are being used by Candu Energy Inc. and the Canadian utilities to develop strategies to manage any emerging degradation mechanisms in Alloy 800 SG tubing in CANDU reactors to meet the requirements of the Canadian Industry's *Fitness-For-Service Guidelines for Steam Generator and Preheater Tubes*.

1. INTRODUCTION

Up until 2006, Stress Corrosion Cracking (SCC) in Alloy 800 Steam Generator (SG) tubing had not been reported in either Pressurized Water Reactors (PWR) or Pressurized Heavy Water Reactors (PHWR). However, ODSCC was confirmed by metallurgical examination of pulled Alloy 800 SG tubes between the upper and lower expansions in the tubesheet area from Biblis Unit A in 2006 [1]. Biblis A was designed by Siemens/KWU that has SG tubes with an OD of 22 mm and a wall thickness of 1.2 mm. The primary inlet and outlet temperature are 312.7°C and 283.4°C. The tube-to-tubesheet connection was realized by two mechanical roller expansion zones. Crack-like indications were also reported in Almaraz Unit 2 in 2009 at the top of tubesheet region and confirmed to be ODSCC in 2011 by metallurgical examination of pulled tubes [2]. Tube denting at the top of tubesheet region was also confirmed by metallurgical examination. The SGs in Almaraz Unit 2 was designed by Siemens and Framatome with tube

OD of 19.05 mm and a wall thickness of 1.09 mm. The tube-to-tubesheet connection was realized by full length hydraulic expansion followed by a mechanical kiss roller expansion. These European plant operating experience raised concern regarding the causes of ODSCC and whether similar degradation mechanisms could occur in the CANDU units with similar Alloy 800 SG tubes.

The present paper summarizes the proactive research on structural integrity of Alloy 800 tubing conducted between 2006 and 2012. This research was funded by the Steam Generator Integrity Working Group of CANDU Owners Group (COG) and Ontario Power Generation (OPG). The objectives of this work was to study the influencing factors on ODSCC and to develop flaw models for assessing the structural margins should flaws be detected.

2. FITNESS-FOR-SERVICE GUIDELINES

Fitness-For-Service Guidelines for Steam Generator and Preheater Tubes (in short FFSG) was originally developed by OPG in late 1990s. Since that time, it has undergone several revisions to address comments from independent 3rd party reviewers, which were commissioned by Canadian Nuclear Safety Commission (CNSC). The FFSG is now a Canadian Industry document and is being maintained by Candu Energy with funding from Chemistry, Materials and Components (CM&C) research program of COG. The FFSG is similar to the EPRI (Electric Power Research Institute) Guidelines used by the PWR community in the USA. A brief comparison between Canadian FFSG and EPRI Guidelines [3] is summarized in Table 1.

3. CHARACTERIZATION OF ALLOY 800 TUBING

Three factors must all be present for the initiation and propagation of ODSCC: susceptible material, high tensile stress (including both operating stress and residual stress), and aggressive chemical environment (usually associated with the concentration cells associated with the formation of deposits and off-normal chemistry). Because of the European OPEX, it is plausible that CANDU Alloy 800 SG tubing material could crack in-service; though the CANDU Alloy 800 SG tubing is at significantly lower risk of cracking because of the lower service temperature. The present paper focuses on the first two factors: Alloy 800 tubing material and residual stresses in tubes after expansion into the tubesheet.

The susceptibility of Alloy 800 to Primary Water Stress Corrosion Cracking (PWSCC) is believed to be low on the inside surface based on the general understanding that PWSCC of Alloy 800 is not credible in typical CANDU primary heat transport environments [4], laboratory data, and field experience that PWSCC has also not been observed in any European Alloy 800 SGs in PWR primary environments.

3.1 Characterization of Alloy 800 tubing

Alloy 800 tubing used to fabricate CANDU SGs has been produced to meet the requirements of SB-163 [5] for nickel-chromium-iron alloy UNS N08800 tubing. There are several compositional and thermally processed varieties over the years. The modified Alloy 800 material specification, which is being used for CANDU replacement steam generators, is believed to offer the better performance. Table 2 compares chemical compositions specified in SB-163 used for Darlington, CANDU 6 plants and that being used for replacement steam generators.

CANDU Alloy 800 SG tubing was specified to be seamless, cold finished, cold drawn, annealed and OD ground. After incoming inspection of the tubes, the pilgering production process involved the following manufacturing steps: pilgering followed by degreasing, hydrogen annealing, straightening, OD polishing, cutting and deburring, and hydrotesting. Table 3 shows the through-thickness distribution of microhardness after burst testing of a defect-free section of an ex-service Darlington straight SG tube [6]. The plastic deformation associated with testing causes a substantial increase in the measured hardness values. There is an apparent cold worked layer at the tube OD, see the measured high microhardness near the OD surface in Table 3.

3.2 Residual stresses in as-fabricated straight tubes

The Alloy 800 tubing used in the Siemens SGs was cold drawn by about 4% to increase mechanical properties and resistance to caustic induced SCC [7]. This extra cold work (compared with the manufacturing practice of Alloy 800 tubing at Darlington and CANDU-6 plants) results in higher residual stresses in the as-fabricated straight tube. Figure 1 compares the measured residual stresses in prototypical Biblis A tube [1] CANDU archival tube at two positions. The distribution of residual stresses is similar: there is a compressive stress layer on the OD that is several hundred microns deep; followed by the tensile residual stresses; and the residual hoop stress is greater than residual axial stress. However, the magnitude of residual stresses in Alloy 800 Biblis A tubes is substantially higher than in the archival CANDU tube over a large extent of wall thickness; there is a maximum residual hoop stress of 335 MPa in the Biblis A tubes and a maximum residual hoop stress of 207 MPa in the CANDU archival tube. The newly measured lower residual stresses in CANDU SG straight tube are consistent with the independent previous measurements of Norsand production tubes, which was documented in a proprietary AECL report.

3.3 Residual stresses in expanded tubes

Figure 2 compares the predicted first (largest) principal residual stress values on the OD surface in hydraulically and mechanically expanded non-stress-relieved CANDU Alloy 800 SG tubes. These predicted values, which include both the baseline and a number of sensitivity studies, were obtained from the Finite Element Analysis (FEA). The best estimate values are 91 MPa and 206 MPa for hydraulically and mechanically expanded SG tubes, respectively. The ASME Code specified yield strength at room temperature is 207 MPa. From only stress point of view, when the residual stress is greater than yield strength, the susceptibility to SCC is high. It is noted that the actual yield strength at room temperature is usually significantly greater than ASME Code specified yield strength. The mechanically expanded tube without stress relief heat treatment is more susceptible to ODSCC than the hydraulically expanded tubes.

The two highest values in Figure 2 correspond to the case where a 10% cold work is assumed in a 0.2 mm deep layer at the OD surface on both the hydraulically and mechanically expanded tubes. For such a postulated scenario, hydraulically expanded tube also has a high susceptibility to ODSCC.

3.4 Residual stresses in U-bend

Figure 3 compares the measured axial residual stresses in one tight-radius U-bend (bend radius of 121 mm) and one large radius U-bend (bend radius of 1092 mm) on both the OD surface and 0.12 mm below the OD surface [8]. There is a large gradient of residual stress near the OD surface in Figure 3, which is associated with the cold worked layer. Bend radius has little effect on the magnitude of residual stress. This is different from the tubing in PWR SGs where residual stress in the smallest U-bend (bend radius of 57 mm) is significantly higher than the large radius bend. Further work is required to confirm this observation (bend radius has little effect on the magnitude of residual stress for CANDU U-bend) because this could have significant impact to the life cycle management.

4. BURST PRESSURE TESTS

The predominant load for recirculating CANDU SGs tubes is internal pressure. Only in the sections of tubes directly above the tubesheet and in tubes that are “locked” into secondary support structures, there are bending moments or axial forces sufficiently large that they need to be considered when assessing the structural integrity of either circumferential or axial cracks.

4.1 Defect-free tubes

Figure 4 compares the burst-pressure test results of the two Darlington defect-free ex-service tubes with six Alloy 800 archive defect-free tubes from the OPG Steam Generator Tube Testing Project (SGTTP) [6]. All of the tests were conducted at 288°C. The ex-service tubes were in service for more than 10 EPFY (Effective Full-Power Years) and were both manufactured by the same tube supplier (Norsand) as the archive Alloy 800 tubing used in the SGTTP. Very consistent failure pressures are observed for both ex-service tubes (× symbols) and archive tubes (○ symbols). These test results provide a convincing case that the tensile properties of Alloy 800 tubing have not been degraded by service.

4.2 Tubes with axial cracking

Figure 5 plots the measured failure pressure versus axial EDM slot depth of ~74%tw. The tests were performed at 288°C. The length of EDM slot is ~25 mm. Three specimens have an axial slot fabricated on the inside surface and three specimens have an axial slot fabricated on the outside surface. Based on the unpublished FEA model, which has been validated against the test data in Figure 5, it can be concluded that, for an axial crack less than 25 mm long and less than 70%tw deep, the failure pressure is greater than 3 times the maximum pressure differential for Level A transients for Darlington SG; therefore satisfying the FFSG structural integrity requirements.

4.3 Tubes with circumferential cracking

Figure 6 shows the measured failure pressure versus 360° uniform deep (>80%tw) EDM slot depth and the observed failure modes. Complete severance was observed for all of the tests. The scatter of the test data is primarily caused by the varied EDM slot width, which varies from 0.1 mm to 0.3 mm. Based on the unpublished FEA model, which has been validated against the test data in Figure 6, for slot depth less than 78%tw, all failure pressure is greater than three times the maximum pressure differential for Level A transients for Darlington SG; therefore satisfying the FFSG structural integrity requirements.

5. VERIFICATION AND VALIDATION OF FINITE ELEMENT MODELS

Efforts have also been expended to develop advanced finite element modeling methods to provide an alternative approach for assessing the structural integrity of degraded SG tubing.

Figure 7 shows the results from a tension test of a piece of Alloy 800 SG tube with a circumferential through-wall EDM slot. The images captured during the test were analyzed by ARAMIS, commercial software for calculating the strain based on digital imaging correlation technique. Figure 8 compares the load-displacement curve and Figure 9 compares the strain distribution at the EDM slot tip. Excellent agreement is observed [11].

6. CONCLUSIONS

Hydraulically and mechanically expanded Alloy 800 SG tubing in CANDU SGs satisfy two of the three factors for the occurrence of ODSCC: susceptible material and high (residual) tensile stress. Good secondary chemistry control during all phases of plant operation and routine deposit removal to limit deposit build-up are therefore key actions to avoid ODSCC.

There are significant differences in the Alloy 800 tubing used in CANDU SGs and those used in European PWR SGs. The European Alloy 800 tubing has much higher residual stresses in both the as-fabricated straight tube and the tubes after mechanical expansion. Also, the operating stress in European Alloy 800 tube is larger because of higher operating pressure and higher tube radius to wall thickness ratio.

Advanced finite element modeling technique has been developed and validated for use in simulating the structural response of Alloy 800 SG tubes with through-wall and surface cracks. It can be applied with confidence to assess the structural margins of Alloy 800 tubing with any emerging degradation mechanisms.

7. REFERENCES

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Table 1. Comparison between Canadian FFSG and EPRI Guidelines.

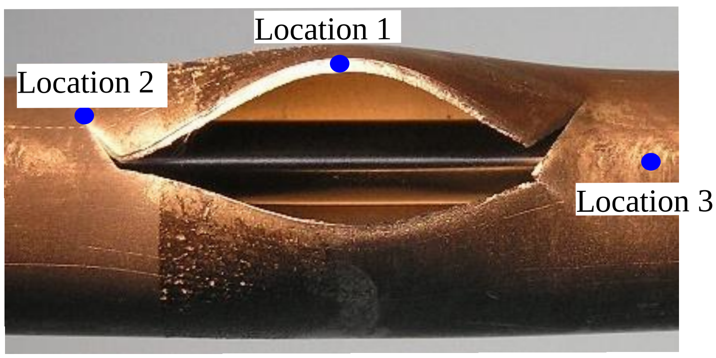
Items	Canadian FFSG	EPRI Guidelines
Tube materials	Monel 400, Alloy 600 and Alloy 800	Alloy 600 and Alloy 690
SG type	Recirculating	Recirculating and once through
Structural criteria	3 times pressure differential for Level A and 1.5 times pressure differential for Level D	3 times pressure differential for normal operation and 1.4 times pressure differential for limiting design basis accident
Leakage criteria	Operational leakage limit 10 kg/h to 20 kg/h for the unit Consequential leakage based on site dose limit (7-10 kg/s)	150 gpd (25 kg/h) through any one SG during normal operation 1 gpm (241 kg/h) per SG under accident conditions
Condition Monitoring Assessment (CMA)	Analysis or in-situ testing or pulling tubes	Analysis or in-situ testing or pulling tubes
Operational Assessment (OA)	If CMA fails, OA to be performed before unit restart and accepted by the regulator; If CMA passes, OA to be performed within 90 days after the restart	If CMA fails, an evaluation to be performed prior to Mode 4 If CMA passes, OA to be performed within 90 days after Mode 4

Table 2. Specified chemical composition for Alloy 800 tubing.

Composition (%)	ASME Requirements [5]	Darlington and CANDU-6	Modified Alloy 800
C	0.05-0.10	0.03 max.	0.03 max.
Si	1.0 max	0.75 max.	0.75 max.
Mn	1.5 max.	1.0 max.	1.0 max.
S	0.015 max	0.015 max.	0.015 max.
Cr	19.0-23.0	21.0-23.0	21.0-23.0
Ni	30.0-35.0	32.5-35.0	32.5-35.0
Fe	39.5 min	Balance	Balance
Cu	0.75 max	0.75 max.	0.75 max.
Al	0.15-0.60	0.15-0.45	0.15-0.45
Ti	0.15-0.60	0.35 min.	0.35-0.60
Ti/C	--	12 min.	12 min.
Ti/C + N		8 min.	8 min.

Table 3. Through-thickness Vicker's hardness measurements (200 g load).of ex-service Darlington SG tube.

Through-Wall Thickness Measurement	Location #1	Location #2	Location #3	Undeformed
1 (ID)	271	283	235	179
2	254	279	234	168
3	256	282	237	170
4	268	263	223	170
5	264	267	226	183
6 (OD)	251	275	237	185
Average	**261**	**275**	**232**	**176**



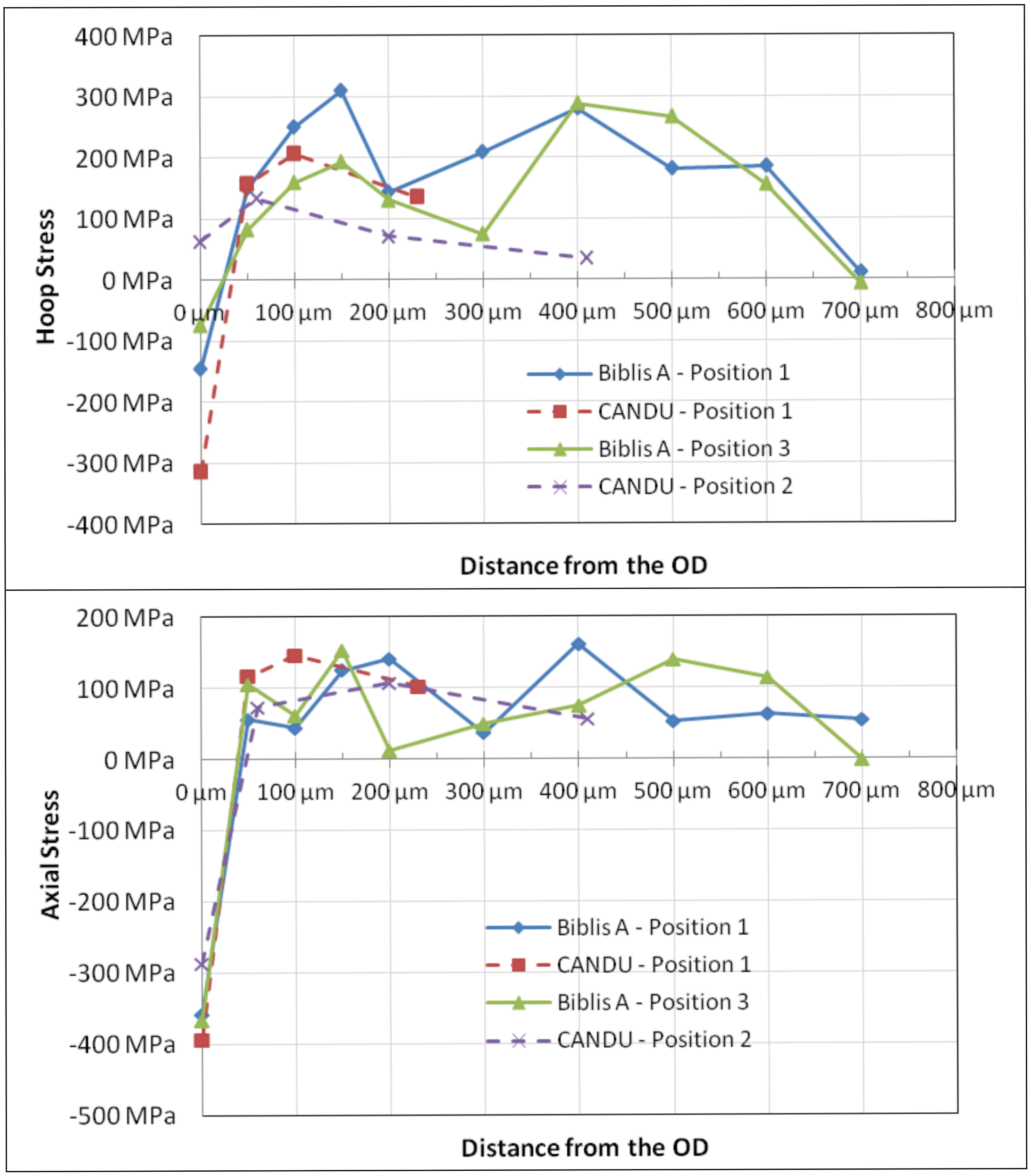


Figure 1. Comparison of residual stresses in as-received Alloy 800 SG tube [1].

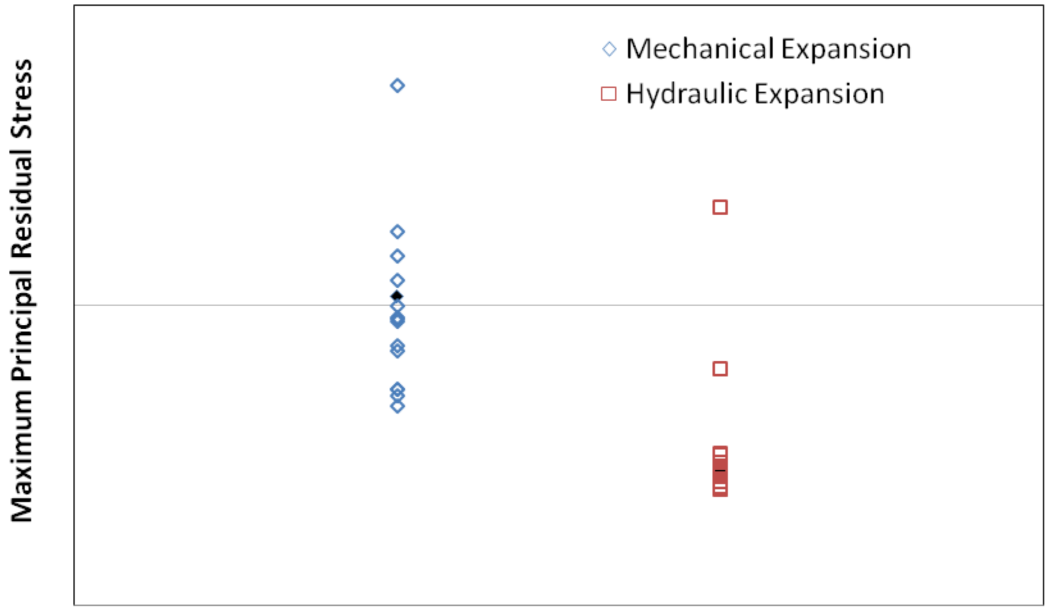


Figure 2. Predicted residual stress in expanded CANDU Alloy 800 SG tubes.

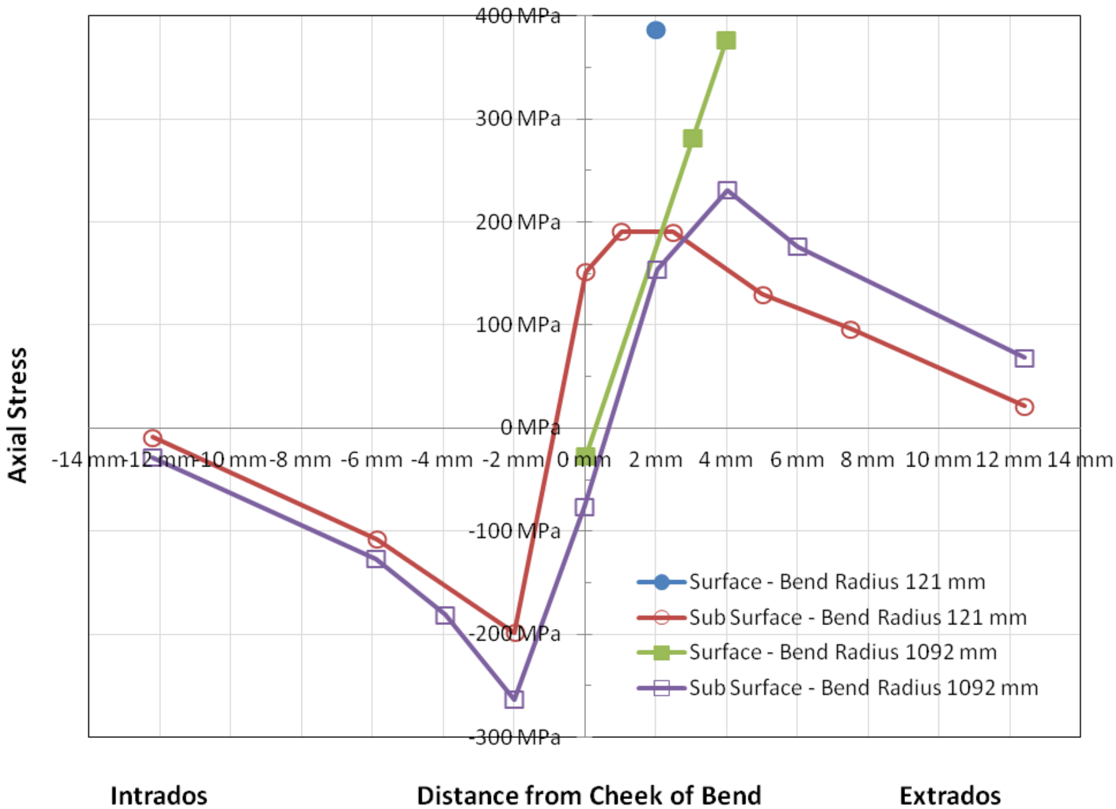


Figure 3. Comparison of residual stresses in prototypical CANDU-6 U-bends [8].

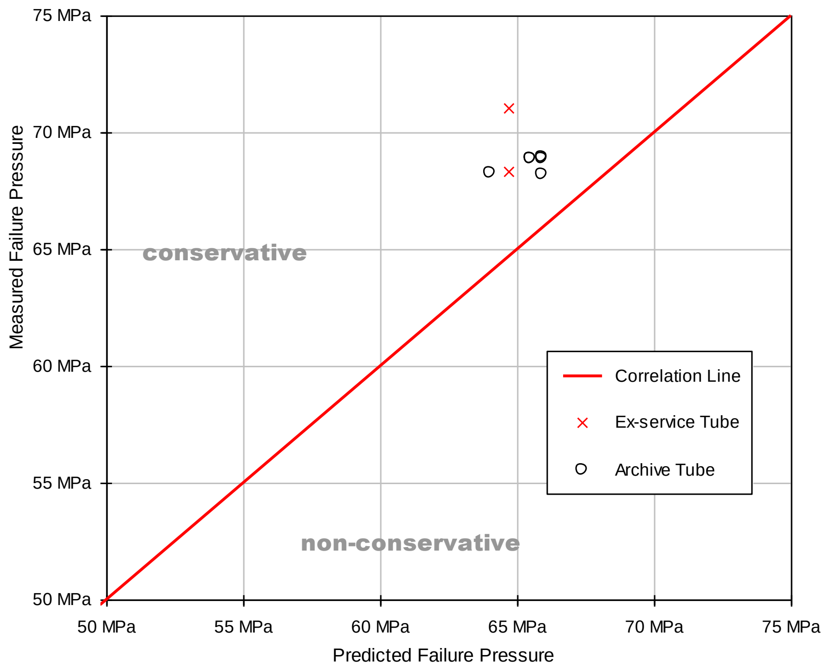


Figure 4. Burst pressure of archive and ex-service Alloy 800 SG tubes [6].

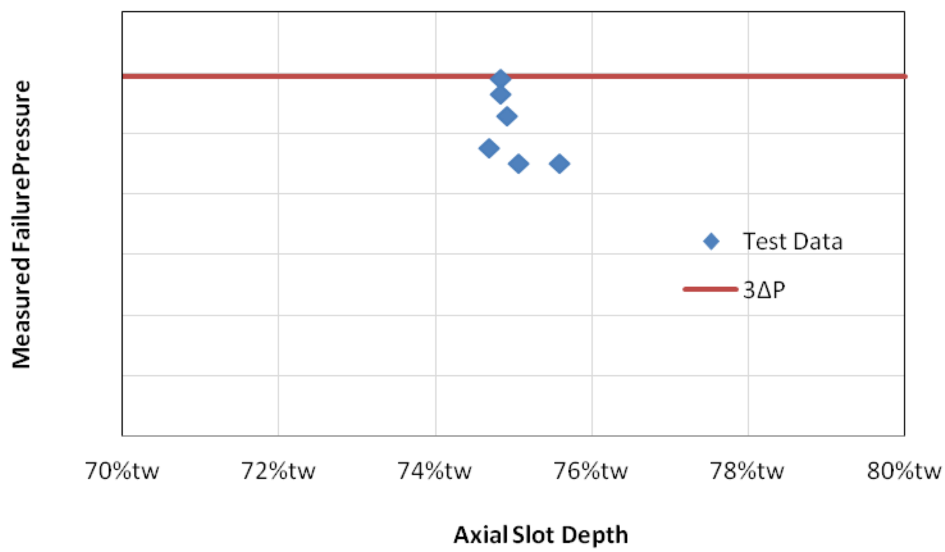


Figure 5. Burst pressure test of Alloy 800 tubes with axial EDM slot.

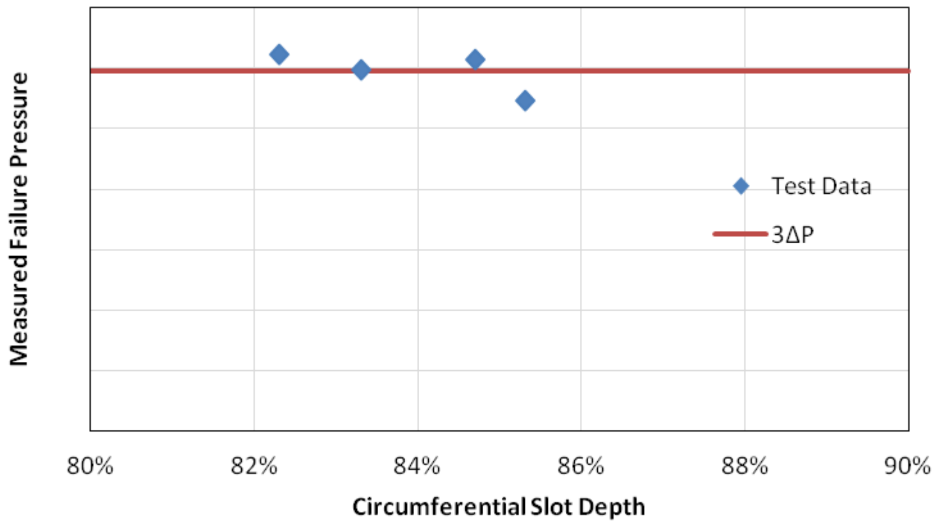


Figure 6. Burst pressure test of Alloy 800 tubes with circumferential EDM slot.

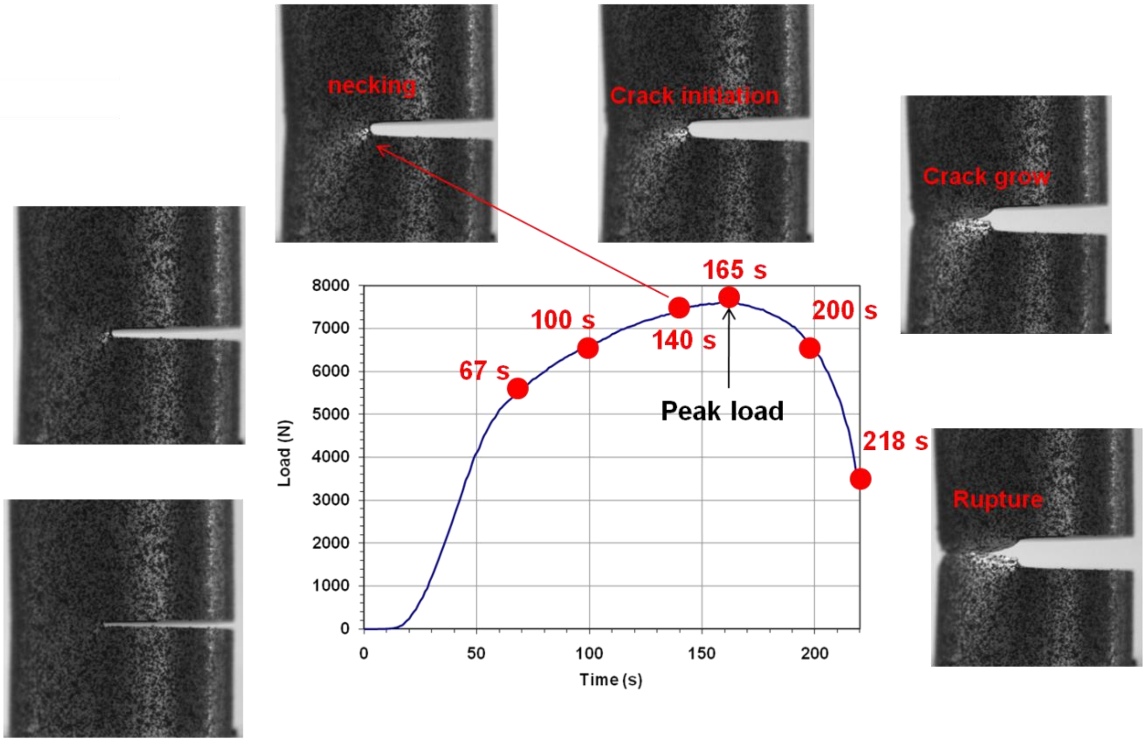


Figure 7. Deformation of Alloy 800 tubes with circumferential through-wall EDM flaw under uniaxial tension.

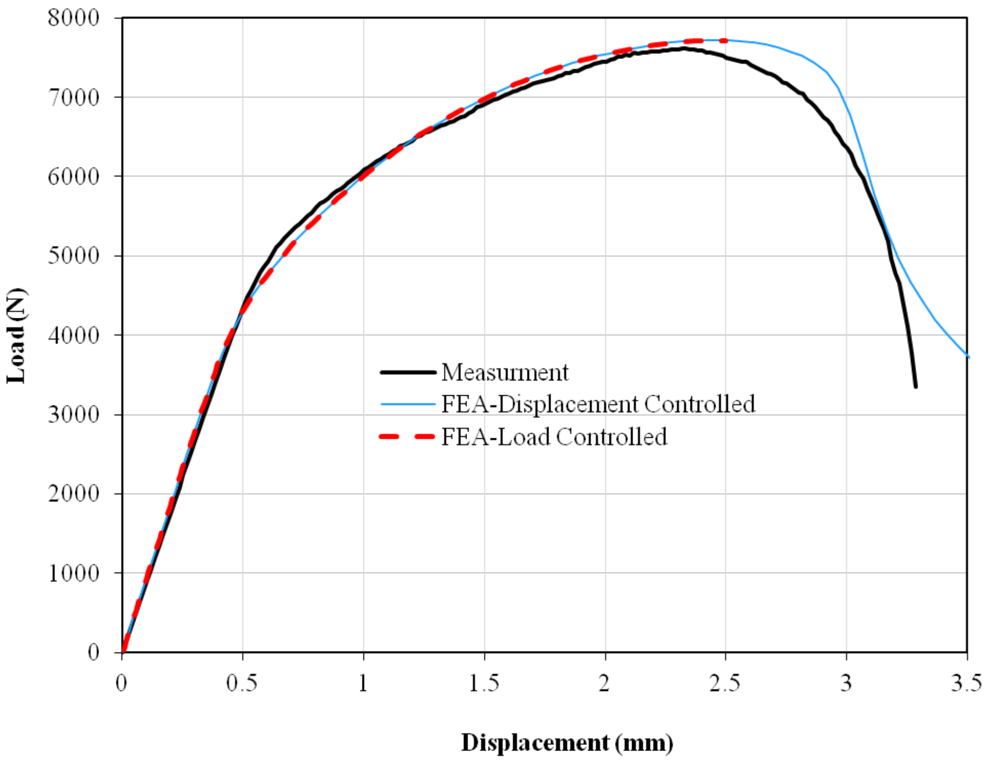


Figure 8. Comparison between the load-displacement curve.

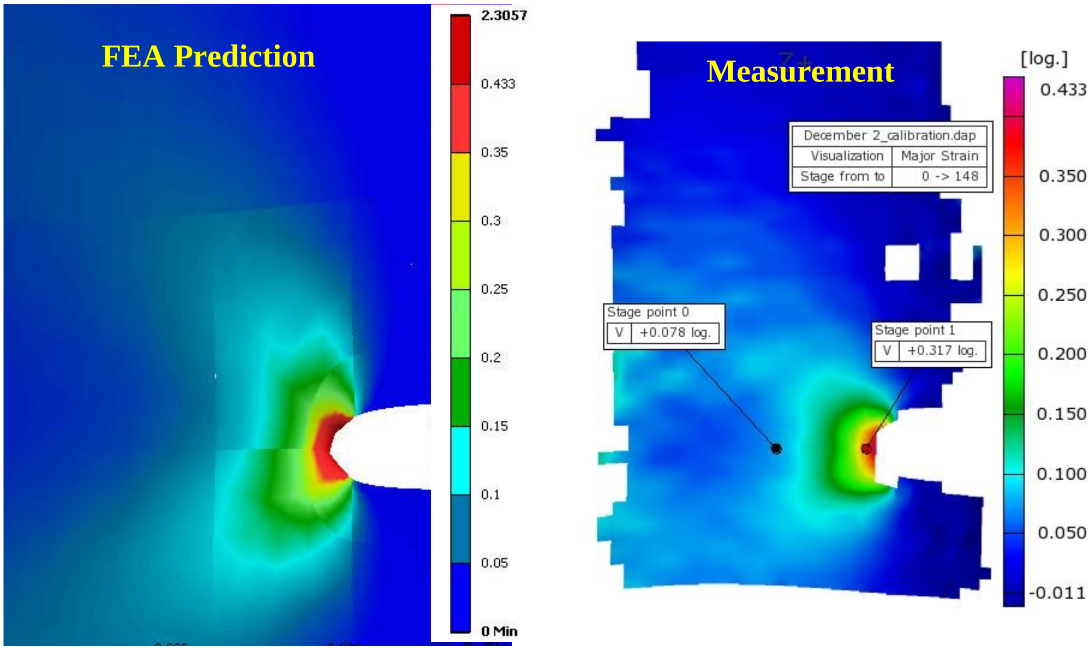


Figure 9. Comparison between FEA predictions and experimental measurements.