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ANALYSIS AND TESTING OF RUPTURE OF STEAM GENERATOR TUBING WITH FLAWS**

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ABSTRACT

A high-temperature (300°C), high-pressure (18 MPa), and high-leak rate (1500 L/min) facility, and a room temperature, high-pressure (52 MPa) test facility were used to test flawed steam generator tubes. Single and multiple rectangular flaws were fabricated by electro-discharge machining on the outside surface of the tubes. This paper briefly reviews analytical methods for predicting ligament rupture and unstable burst of tubes with single and multiple rectangular flaws. Test data are presented to validate the failure models. The ligament rupture pressures of specimens with mutiple flaws predicted by an "equivalent rectangular crack" method agree fairly well with measured data.

KEYWORDS

Steam generator tubes, axial flaw, ligament rupture, unstable burst

INTRODUCTION

Although steam generator (SG) tubes of pressurized water reactors (PWRs) are designed conservatively by following the ASME Boiler and Pressure Vessels Code and are made of highly ductile alloys such as Alloy 600, stress corrosion cracks (SCCs) have been detected in the SG tubes of several PWRs. Since SG tubes form part of the primary pressure boundary, it is important to be able to predict crack growth, tube failure or rupture, and subsequent leak rates of SG tubes from crack morphology, as measured nondestructively during in-service inspection. This paper is concerned with tests and analytical prediction of ligament rupture pressure and unstable burst pressure of SG tubes with initially part-throughwall axial flaws.

BACKGROUND

Significant literature [1- 12] is available on testing and analytical models for ligament failure and unstable burst of tubes with part-throughwall and throughwall rectangular flaws. Well-

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established criteria exist for predicting ligament rupture and unstable burst pressures of tubes with relatively long rectangular flaws. Some modifications of these criteria have been made for short and deep flaws based on recent tests at ANL [7].

The critical pressures and crack sizes for the unstable failure (burst) of a thin-wall internally pressurized cylindrical shell with a single rectangular throughwall axial crack can be estimated with an equation originally proposed by Hahn et al. [1] and later modified by Erdogan [2]:

$$p_{cr} = \frac{p_b}{m} = \frac{\bar{\sigma} h}{mR}, \tag{1}$$

where p_b is unstable burst pressure of unflawed tube, $\bar{\sigma}$ is the flow stress, and m is a bulging factor that depends on crack length, tube radius (R), wall thickness (h), and Poisson's ratio (e.g., see Ref. 7).

A general failure criterion for predicting rupture of the through-thickness crack tip ligament in a pressurized tube with a single rectangular part-throughwall axial crack can be expressed as follows:

$$\sigma_{lig} = m_p \sigma = \bar{\sigma}, \tag{2}$$

where σ_{lig} is the average ligament stress, σ is the nominal hoop stress, and m_p is a ligament stress magnification factor that depends on axial crack length and depth [7].

Although we can currently predict with some confidence failure pressures of tubes with rectangular flaws, such a morphology is not characteristic of much of the cracking currently observed in SGs. Stress corrosion cracks (SCCs) in SG tubes are generally nonplanar, ligamented, and have highly complex geometry.

TESTS WITH MUTIPLE FLAWS

As a first step toward understanding the behavior of more complex cracks, tests were conducted on 22-mm (0.875 in.)-dia, 1.27-mm (0.05 in.)-wall thickness Alloy 600 tubes with two part-throughwall axial rectangular notches. The yield and ultimate tensile strengths of the tube material at room temperature are 300 MPa (43 ksi) and 675 MPa (98 ksi), respectively. Two different configurations of axial notches were tested (Figure 1). Each notch was either 6 mm (0.25 in.) or 13 mm (0.5 in.) long and 80% deep with a ligament width of either 0.25, 1.27, or 2.54 mm (0.01, 0.05, or 0.1 in.). Pressure tests were conducted at room temperature in two stages. In stage 1, the specimens were tested without a bladder until ligament rupture occurred and the pump could not keep up with the leak rate. In stage 2, a bladder and brass foil were inserted in a few of the specimens to cover the notches, and the specimens were pressurized until unstable burst occurred. The effect of the bladder and foil on the burst pressures has been found to be minimal. Two tests with initially 100% deep notches (without bladder) were conducted in a high-flow-rate blowdown test facility. During stage 1 testing, the pressure was increased to the maximum limit of the facility. One of the two tests was conducted at 282°C with high-temperature pressurized water. A summary of the test results is given in Table 1 where, unless otherwise noted, all notches are 80% deep and tested at room temperature. After stage 1 testing, all of the axial ligaments in type 2 specimens were ruptured while all of the 2.54 mm (0.1 in.) ligaments in type 4 specimens survived. On the other hand, the 1.27 mm (0.05 in.) circumferential ligament of type 4 specimens ruptured during stage 1 testing with notch lengths of 12.7 mm (0.5 in.) but survived with notch lengths of 6 mm (0.25 in.). The axial ligament in the specimen with 100% deep notches survived stage 1 testing at room temperature (T24), but failed at 282°C (T25).

ANALYSIS OF TESTS

Part-Throughwall Notches

A simple empirical method for predicting rupture pressure of a through-thickness notch tip ligament is based on defining an equivalent rectangular crack whose depth is obtained by equating the total area of the two notches to that of a single rectangular notch of the same total length. Predicted vs. observed ligament rupture pressures for type 2 and type 4 specimens tested at room temperature are shown in Figures 2a-b. Except for a single type 2 specimen with two 13-mm (0.5 in.)-long notches, the observed rupture pressures of through-thickness notch tip ligaments are close to those predicted by the equivalent rectangular crack method. Note that the method predicts a minimum ligament width beyond which the two notches behave as two independent notches. However, the method cannot predict the rupture pressure of the axial or circumferential ligament separating the two notches. The tests showed that although the axial ligaments for all type 2 specimens ruptured at the final pressure in stage 1, some of the circumferential ligaments of type 4 specimens survived. In cases where the ligament between the notches ruptured after stage 1 testing (e.g., Figure 3a), the final stage 2 unstable burst pressure can generally be predicted quite well by Eq. 1 for single cracks. In other cases (e.g., Figure 3b), the specimen is left with two throughwall notches with a ligament after stage 1 loading.

Throughwall Notches

Nonlinear finite-element analyses with shell elements (ABAQUS) were performed for a type 2 specimen with two 100% deep, 6-mm (0.25 in.)-long notches separated by an axial ligament of varying width. A plot of the variation of average ligament thickness with pressure for a 0.25-mm (0.01 in.)-wide ligament is shown in Figure 4a. The accelerated decrease in thickness at a pressure of 17 MPa (2.5 ksi) indicates a necking-like behavior. A corresponding test (T24) conducted at room temperature did not experience ligament rupture. However, the ligament of an identical specimen (T25) tested at 282°C did rupture at 15.5 MPa (2.25 ksi), indicating that the room-temperature test was close to ligament rupture (flow stress at 282°C is 10% lower than at room temperature). Variation of the calculated ligament rupture pressure with ligament width is shown in Figure 4b, which also includes ligament rupture pressures calculated by Lee et al. [13] with a flow stress criterion (i.e., average ligament stress = flow stress = average of yield and ultimate tensile strengths). It is evident that a rupture criterion based on flow stress significantly underestimates the ligament rupture pressure because failure of the ligament occurs by necking. A failure criterion based on ultimate tensile strength would be more appropriate.

Results from a similar analysis for a type 4 specimen (Figure 5a) shows a similar reduction in average ligament thickness with pressure as in Figure 4a for a type 2 specimen. Because the calculated ligament rupture pressure (45 MPa) is greater than the unstable burst pressure of the resulting 13-mm (0.5 in.)-long throughwall crack, the specimen is predicted to burst unstably at 45 MPa, which is reasonably close to the reported stage 2 burst pressure of specimen OM159 (Table 1). Note that in contrast to type 2 specimen, the ligament in the type 4 specimen is subjected to high shearing deformation (Figure 5b).

CONCLUSIONS

Tests were conducted on steam generator tubes with two part-throughwall axial flaws arranged in two different configurations. Rupture pressure of a through-thickness notch tip ligament can be predicted by an equivalent rectangular approach. Nonlinear finite-element analyses show that both the axial (type 2) and circumferential (type 4) ligaments between two axial throughwall notches fail by tensile necking. However, the type 4 ligament also experiences large shearing deformation. The calculated ligament rupture pressures are reasonably close to observed stage 2 burst pressures.

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TABLE 1
SUMMARY OF TEST RESULTS

Tube ID	Notch type	Notch length (mm)	Ligament width (mm)	Stage 1 pressure (MPa)	Stage 2 pressure (MPa)
OM161	4	6	0.25	28.3	-
OM162	4	6	1.27	31.4	32.5
OM159	4	6	2.54	34.8	38.3
OM150	4	13	0.25	19.0	-
OM151	4	13	1.27	23.0	-
OM152	4	13	2.54	23.5	18.9
OM153[1]	2	6	0.25	34.8	-
T24[2, 3]	2	6	0.25	17.2	-
T25[2, 4]	2	6	0.25	15.5	-
OM160	2	6	1.27	32.3	-
OM149	2	13	2.54	27.0	-

[1]Notches in this specimen were 70% deep.
[2]Notches in this specimen were 100% deep.
[3]Axial ligament did not rupture in this test.
[4]This test was conducted at 282°C.

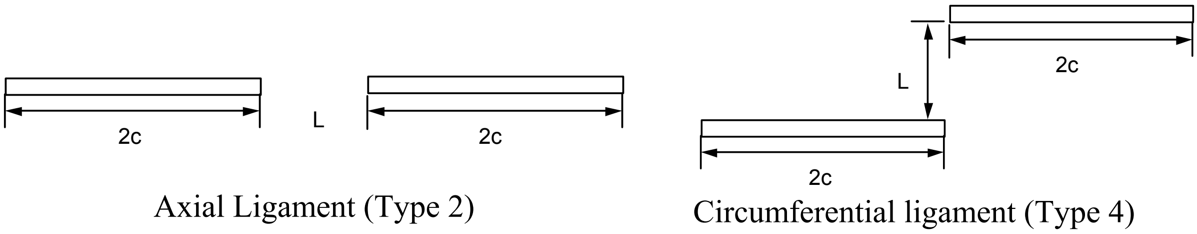

Figure 1: Type 2 and type 4 configurations of notches tested at ANL.

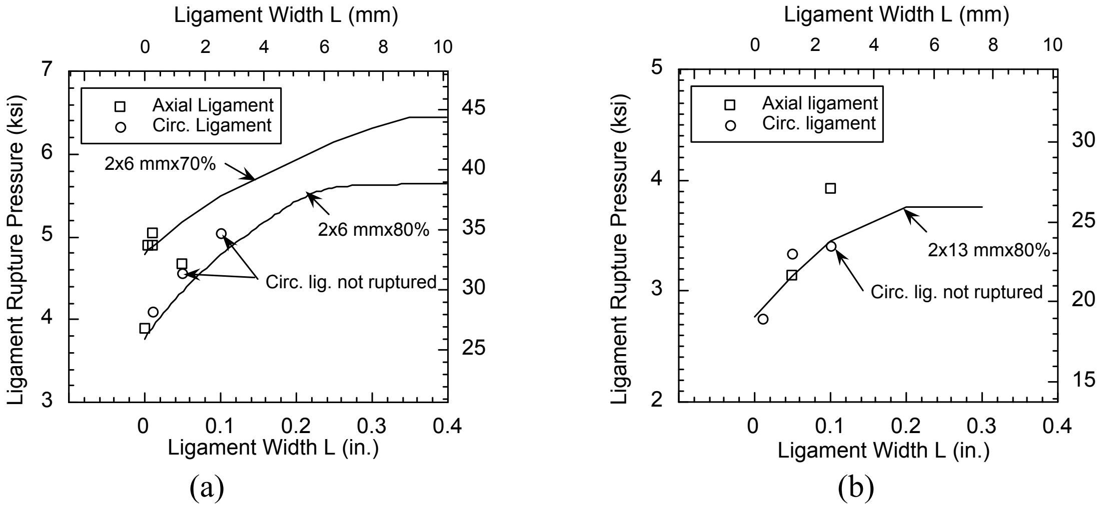

Figure 2: Predicted (lines) vs. observed (symbols) rupture pressures for through-thickness notch tip ligaments for type 2 (axial ligament) and type 4 (circumferential. ligament) specimens with (a) two 6 mm notches and (b) two 13 mm notches.

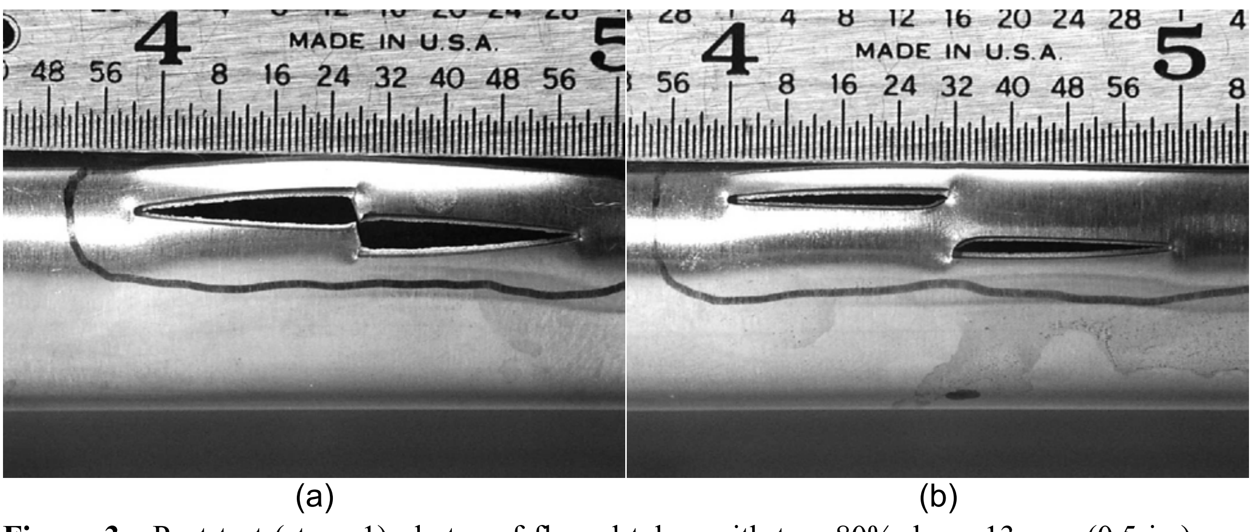

Figure 3: Post-test (stage 1) photos of flawed tubes with two 80% deep, 13-mm (0.5 in.)-long notches separated by a (a) 1.27-mm (0.05 in.)-wide and a (b) 2.54-mm (0.1 in.)-wide ligament.

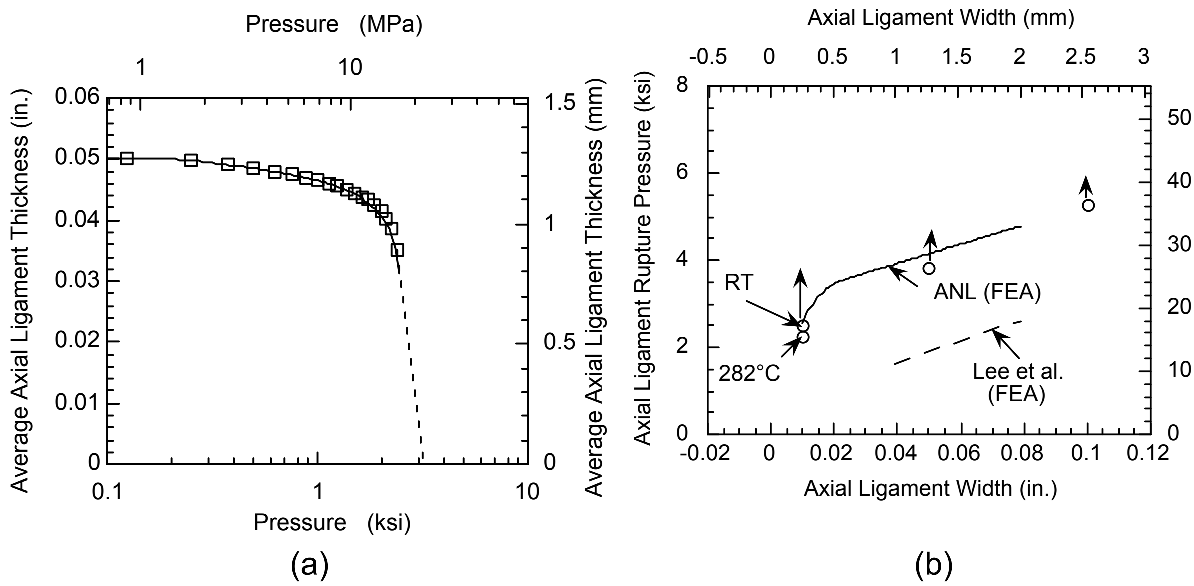

Figure 4: Results from FEA showing (a) variation of average axial ligament thickness with pressure for type 2 specimen with two 6-mm-long throughwall cracks separated by 0.25-mm-wide ligament, and (b) variation of ligament rupture pressure with axial ligament width for specimen with two 6-mm-long throughwall cracks. Symbols represent results from tests, with up arrow indicating no rupture of ligament. Dashed line is obtained from Ref. 13.

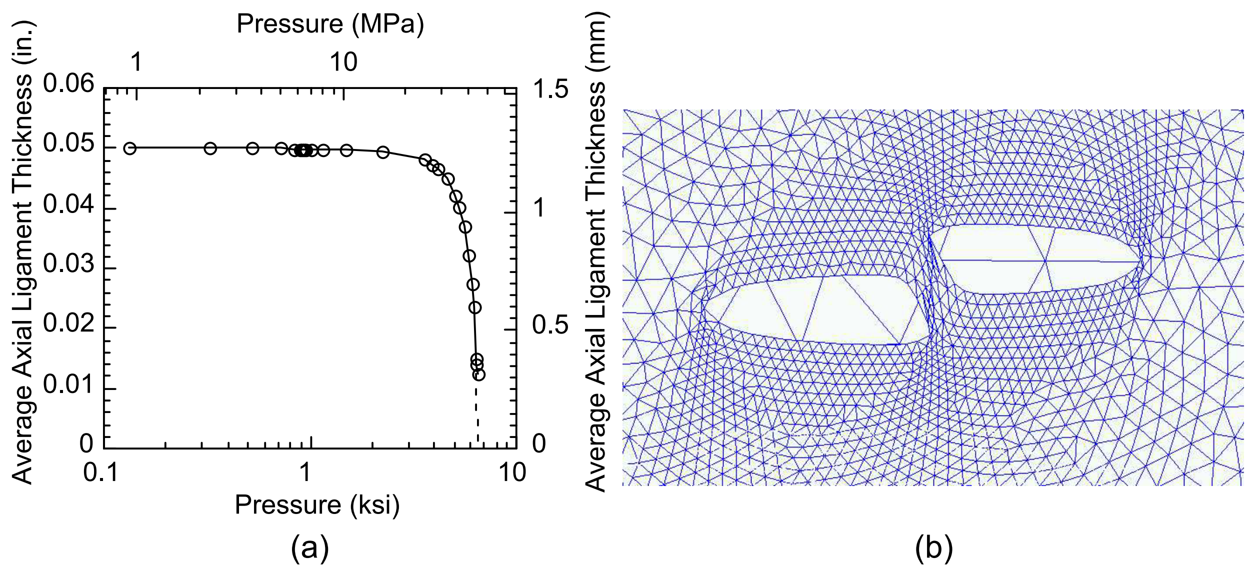

Figure 5: Results from FEA showing (a) variation of average axial ligament thickness with pressure and (b) deformed shape of type 4 specimen with two 6-mm-long throughwall cracks separated by 2.54-mm-wide ligament.