Load and Displacement Capacity of Steam Generator Tubes with Circumferential Defects

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ABSTRACT

An experimental program has been carried out to determine the load and displacement capacity of circumferentially notched Inconel 600 steam generator tubes. Comparison of experimental results with analytical methods shows good agreement.

INTRODUCTION

Most light water reactor steam generator tubes are fabricated from Inconel 600 material. During service, tube sustain a primary to secondary pressure differential. In addition, tubes may be subjected to axial loads during cooldown transients.

A number of investigators have studied the rupture behavior of axial defects in tubes with internal pressure (Burke and Ware, 1980; Hernalsteen, 1981; Clark and Bickford, 1984). In addition, analytical methods first developed for predicting behavior of circumferential defects in ductile piping materials have been used for predicting the rupture behavior of circumferential cracks in Inconel 600 tubes under axial load (Lang et al., 1985; Griesbach et al., 1985). But, experimental data for tubes with circumferential defects under axial load have, until recently, not been available.

To fill this information gap, a series of laboratory experiments were conducted to measure the load and displacement capacity of Inconel 600 tubes with circumferential defects. Results of those experiments along with comparison of experimental results with analytical predictions are summarized in this paper.

TUBE RUPTURE EXPERIMENTS

Figure 1 shows a schematic of the experimental arrangement. A 10,000 pound capacity Instron screw–type test machine was used to perform the tests. Test sections, which were approximately 12 inches long, were gripped at each end and loaded with a constant cross head speed of 0.1 inch/minute. Tube load was monitored with a load cell and tube strain was measured with an extensometer spanning a gauge length which included the notch. All tests were conducted in a room temperature air environment.

Circumferentially oriented notches were made in the tube inside surface using electro–discharge machining (EDM). Notches were located at the tube mid–span. Prior to testing, plastic replicas of notches were made and measured to accurately determine notch depth, width and length. Nominal tube dimensions were diameter of 0.625 inch and wall thickness of 0.035 inch.

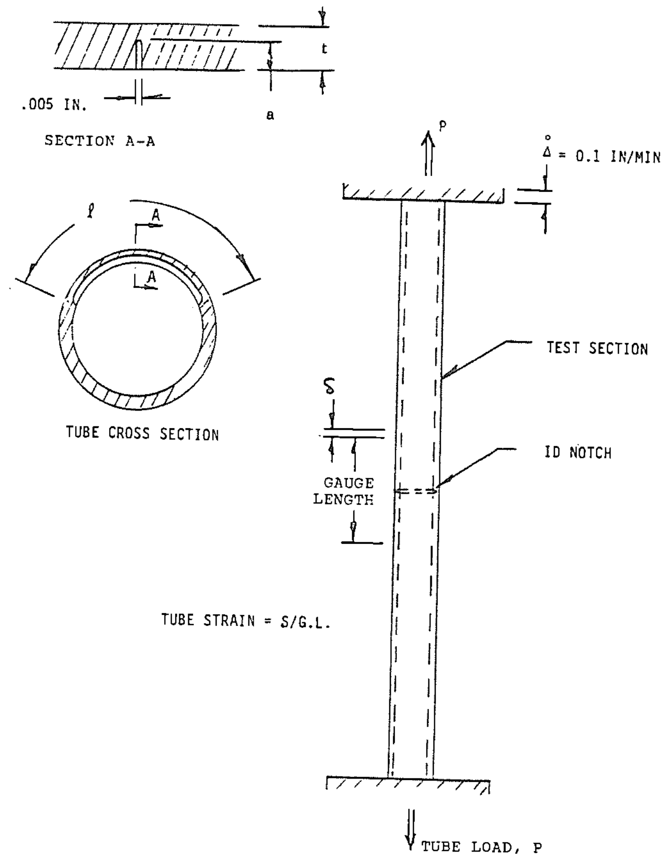

Figure 1. Lehigh Notch Tube Test Experimental Arrangement

A total of ten tests were conducted. Table 1 gives notch depth as a fraction of wall thickness and notch length as a fraction of circumference. Note that eight test specimens had part–through–wall notches. In two of these, the notch extended completely around the circumference. One test involved a through–wall notch and one test specimen was unnotched.

Notched tube experimental results are summarized in Table 1. Included in Table 1 are 0.2 off–set load, maximum load and load at ligament break–through. In all tests the tube maximum load is above the 0.2% off–set load. Note that for part–through–wall notched tests, maximum load occurs at ligament break–through.

The load displacement behavior for both unnotched and notched tubes were similar. Following general yielding, significant tube displacement is required before tube rupture occurs.

Also shown in Table 1 are gauge sections strains at tube failure. Percent strain over 1 inch and 2 inch gauge lengths as measured on the notch side and back side of the specimen are given. Large plastic strains were measured.

Table 1

SUMMARY OF NOTCHED TUBE EXPERIMENTAL RESULTS

Test No.	Notch Depth (a/t)	Notch Length (ℓ/c)	0.2% Off-Set Load (lb.)	Maximum Load (lb.)	Ligament Break-Thru Load (lb.)	Strain at Failure: Notch Side 1" Gauge %	Strain at Failure: Notch Side 2" Gauge %	Strain at Failure: Back Side 1" Gauge	Strain at Failure: Back Side 2" Gauge %
1	.42	.49	3010	4320	4320	15.0	9.0	12.1	9.3
2	.53	.49	2940	3870	3870	13.0	7.0	11.0	6.0
3	.45	.25	3260	4380	4380	16.0	8.9	12.7	10.9
4	.58	.37	2945	3635	3635	15.0	7.0	10.0	6.0
5	.69	.31	2720	3155	3155	15.0	7.0	10.0	6.0
6	.100	.21	2155	3360	N/A	18.0	8.0	11.0	7.0
7	.39	1.00	3155	4710	4710	8.0	5.0	8.0	5.0
8	.36	1.00	3150	4725	4725	7.2	6.1	6.3	5.5
9	.42	.74	2975	4460	4460	9.7	6.2	9.9	7.1
10	0 (unnotched)	0	3350	7140	N/A	28.0	29.0	28.0	29.0

PREDICTION OF FAILURE LOADS

Development of engineering methods for predicting the load carrying capacity of components with defects requires identifying the appropriate failure mechanism and using the analysis method associated with that mechanism to determine the relationship between defect size and load. Results from experimental and analytical studies indicate that ductile materials, such as wrought austenitic stainless steels, will reach limit load and fail due to large plastic strains at the smallest or net section. Consequently, limit load or net section collapse (NSC) based analysis methods are appropriate for estimating load carrying capacity for these materials.

NSC methods for assessing the structural margin of piping containing circumferential defects are due to the work of S. Ranganath and co–workers (Ranganath and Metta, 1983). These methods have also been incorporated into Section XI of the ASME Boiler and Pressure Vessel Code (ASME, 1983; Norris et al.,1986).

Figure 2 shows a schematic of a circumferentially oriented defect in a tube. The defect size is defined by a depth a, and a length, 2θ. The relationship between the collapse load and defect size is obtained by requiring force and moment equilibrium of the tube section.

For $(\theta+\beta) \leq \pi$

$$\beta = \frac{[\pi - \theta(a/t)] - (P_m/\sigma_f)\pi}{2} \tag{1}$$

$$P_b = \frac{2\sigma_f}{\pi}\ (2\ \sin\beta - (a/t)\sin\theta) \tag{2}$$

For $(\sigma + \beta) > \pi$

$$\beta = \pi \frac{[1-(a/t) - (P_m/\sigma_f)]}{2-(a/t)} \tag{3}$$

$$P_b = \frac{2\sigma_f}{\pi}\ (2-(a/t)\ \sin\beta) \tag{4}$$

P_m and P_b in the above equations are the applied primary membrane and bending stresses, respectively. For the notched tube experiments, P_m equals the tube test load divided by the cross section area and P_b equals zero. σ_f is the material flow stress.

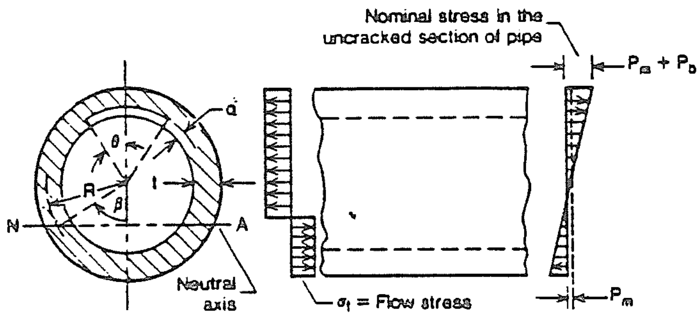

Figure 2 Schematic of Tube Cross Section and Parameters Used in Net Section Collapse (NSC) Equations

The NSC equations (1) through (4) assume that the tube is free to bend due to the presence of defect asymmetry. This bending produces a shift in the neutral axis measured by the angle β shown in Figure 2. This shift produces some bending stress at the net section even though the applied bending load is zero. For the net section neutral axis shift to occur, the application of the load must be remote from the section containing the defect or the load must be applied through pinned end conditions.

The length of tubes in the notched tube experiments was not long and the end loading condition was not pinned. On the other hand, appreciable tube bending was observed in tubes with asymmetric notches. Consequently, in the NSC predictions which follow, one of two assumptions was employed. One assumption was that the tubes behaved like a "long" tube and shift of neutral axis is unrestrained. The second assumption was that the tubes behaved like a "short" tube, shift of the neutral axis is prevented by moments developed in the grips and β is zero.

Table 2 compares the measured notched tube load capacities with NSC predictions. The material flow stress was assumed equal to the average of the yield and ultimate strength as measured in the unnotched tube test. Predictions based on both long and short tube assumptions are shown.

Table 2

Comparison of Experimental Results with Net Section Collapse Predictions with Flow Stress Equal to 1/2 (Yield + Ultimate)

Test No.	Notch Depth (%T.W.)	Notch Length (% Circ)	Tube Load Capacity (lbs)	NSC Pred.* Long Tube (lbs)	NSC Pred.* Short Tube (lbs)
1	42	49	4320	3459	4166
2	53	49	3870	2988	3883
3	45	25	4380	4121	4655
4	58	37	3635	3220	4119
5	69	31	3155	3157	4123
6	100	21	3360	3104	4144
7	39	100	4710	3199	3199
8	36	100	4725	3357	3357
9	42	74	4460	3102	3615
10	0 (unnotched)	0	7140	5245	5245

* Based on flow stress equal to 1/2 (Yield + Ultimate) = 78,753 psi

Figure 3 contains a comparison of NSC predictive capability against experimental results for notch depths which are roughly 40% and 50% of the wall thickness. Predictions are the average of the predictions for long and short tubes. Tube load capacity is shown as a function of circumferential extent ranging from unnotched to notched 360°. In all cases, the measured notched tube load capacity exceeds predicted capacity. For very short or long notches, measured capacity significantly exceeds predictions.

SUMMARY OF RESULTS

Axial load to failure tests with Inconel 600 tubes containing circumferential notches show that tubes fail in a ductile manner after significant plastic deformation. Although notches reduce the tube load and displacement capacity, the shape of the load displacement curve for notched and unnotched tubes is similar. Maximum tube load occurs at ligament break–through with additional displacement required to cause tube rupture.

Net section collapse predictions show reasonably good agreement with measured maximum tube loads. Predictions are more conservative for part–through–wall than for through–wall notches. Predictions for both short and long notches show the most conservatism.

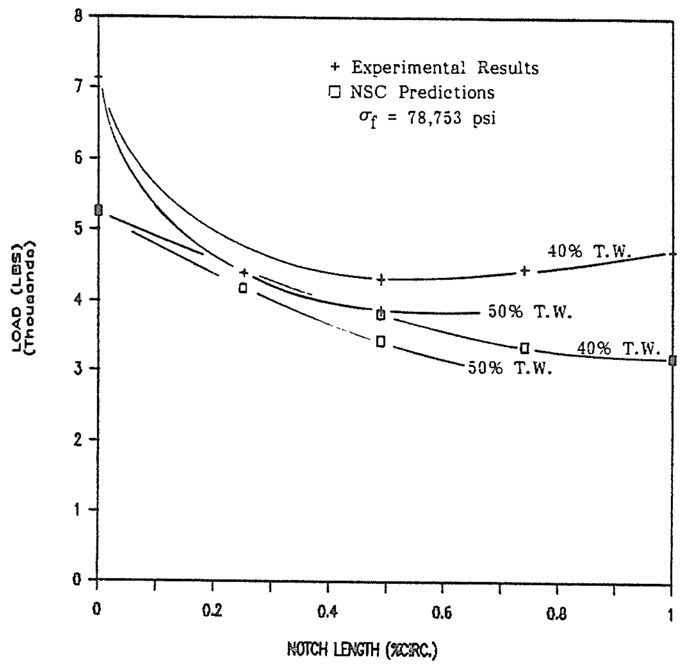

Figure 3. Comparison of Measured Tube Maximum Load Capacities with Average NSC Predictions Based on $\sigma_f(\sigma_y + \sigma_u)/2$.

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