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COALESCENCE CRITERION OF PART-THROUGH WALL CRACKS IN STEAM GENERATOR TUBES OF NUCLEAR POWER PLANTS

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ABSTRACT

In scheduling inspection and repair of nuclear power plants, it is important to predict failure pressure of cracked steam generator tubes. Nondestructive evaluation (NDE) of cracks often reveals two neighboring cracks. If two neighboring part-through cracks interact, the tube pressure, under which the ligament between the two cracks fails, could be much different than the critical burst pressure of an individual equivalent part-through crack. The ability to accurately predict the ligament failure pressure, called "coalescence pressure", is important. The coalescence criterion, established earlier for 100% through cracks using nonlinear finite element analyses [1-3], was extended to two part-through-wall axial collinear and offset cracks cases. The ligament failure is caused by local instability of the radial and axial ligaments. As a result of this local instability, the thickness of both radial and axial ligaments decreases abruptly at a certain tube pressure. Good correlation of finite element analysis with experiments (at Argonne National Laboratory's Energy Technology Division) was obtained. Correlation revealed that nonlinear FEM analyses are capable of predicting the coalescence pressure accurately for part-through-wall cracks. This failure criterion and FEA work have been extended to axial cracks of varying ligament width, crack length, and cases where cracks are offset by axial or circumferential ligaments. The study revealed that rupture of the radial ligament occurs at a pressure equal to the coalescence pressure in the case of axial ligament with collinear cracks. However, rupture pressure of the radial ligament is different from coalescence pressure in the case of circumferential ligament, and it depends on the length of the ligament relative to crack dimension.

INTRODUCTION

Safety is one of the most important factors in regular functioning of nuclear power plants. It becomes a more sensitive issue in pressurized water reactors (PWR) due to high-pressure application. Steam generator tubes account for more than 50 % of the primary pressure boundary surface of PWRs [4]. Right from the beginning, they have experienced in – service corrosive and mechanical degradation of various forms subsequently resulting in tube rupture. Resulting cracks may be through wall (TW) or part through wall (PTW) cracks. When cracks become large enough, the following failure modes can occur (a) the tubes either burst (fail mechanically), or (b) the crack opening area becomes sufficiently large to consider the leak rate unacceptable or (c) coalescence of neighboring cracks and / or rupture from existing conditions. These all affect the overall efficiency of the steam generator. Just to estimate the extent of damage, a single replacement of single steam generator costs around $100 to $200 million dollars [3].

In the maintenance cycle, it is important to predict the failure of tube. Typically it is based on nondestructive evaluation (NDE) testing of cracks. Rupture and leak rates for single crack configurations in steam generator tubes have been well established [5-11]. This kind of nondestructive testing may reveal and reports two neighboring but apparently independent cracks. Rupture of the ligament between two existing cracks (may be through-wall or part-through-wall type crack) occurs at much higher pressure value than the critical burst pressure of one crack with length equal to the sum of the two cracks and ligament. These conditions have been well established for 100 % through cracks by nonlinear finite element analysis techniques [2, 3].

Practically, the existing cracks may not be 100 % through wall (TW), and can be 70 %, 80 % or 90% part through wall thickness (PTW). It is essential to predict the pressure causing failure of the ligament between any two neighboring part through wall cracks and determine if the radial and axial or circumferential ligaments fail simultaneously, sequentially, or if the failure of one ligament leads to the failure of the other.

Preliminary nonlinear finite element studies of crack coalescence are quite capable of predicting coalescence criteria for 100 % through wall cracks [1-3] as opposed to the flow stress criterion used for single crack case [1,12]. The coalescence criterion established earlier is extended here for part through wall cracks in which the coalescence would require the axial (or circumferential) ligament to coalesce. Of equal importance is the prediction of the pressure that would cause the radial ligament to rupture. The two ligaments may coalesce simultaneously or in sequence depending on the crack configuration, ligament configuration and size. The radial ligament rupture starts when local instability exists in the crack resulting in a sudden uncontrollable reduction in radial ligament thickness. The thickness and pressure gradient becomes very high, and the ligament is no longer capable of resisting the applied tube pressure, and tube experiences complete failure, as shown below in Figure 1.

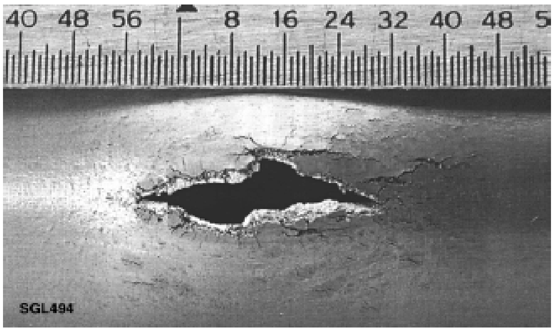


Figure 1 Typical rupture of a steam generator tube after crack coalescence.

NOMENCLATURE

Coalescence pressure (Pcoal): The pressure at which the reduction in the average thickness of the ligament (axial or circumferential) becomes unstable.

Radial rupture pressure (Pr): This is the pressure that causes rupture of the radial ligament.

Thax & Thc: the thickness of axial and circumferential ligaments respectively.

Thr: is the radial crack depth as percent of wall thickness.

Each case analyzed is identified as follows:

TW _ X _Y _Z
Where,
W– crack type (e.g. 2 for type 2 and 4 for type 4)
X – length of the crack notch
Y–length of the axial ligament
Z –radial crack depth as percent of wall thickness

MODELING

This paper investigates the coalescence criteria of part through wall cracks, which are axially and circumferentially offset and are termed as type 2 and type 4 cracks respectively. The numerical study considered 70%, 80% and 90% part through wall cracks with 21 mm tube inner diameter and 1.27 mm thickness. Tables 1 and 2 outline the crack/ligament dimensions and material properties respectively.

Table1 Analysis matrix (each case was investigated for 70%, 80% & 90% radial crack).

Specimen Type	No. of Notches	Notch Length mm (in)	Ligament Width mm (in)
Type 2	2	6.35 (0.25)	0.254 / 1.27 / 2.54 (0.01 / 0.05 / 0.1)
Type 2	2	12.7 (0.50)	0.254 / 1.27 / 2.54 (0.01 / 0.05 / 0.1)
Type 2	2	25.4 (1.00)	0.254 / 1.27 / 5.08 (0.01 / 0.05 / 0.2)
Type 4	2	6.35 (0.25)	0.254 / 1.27 / 2.54 (0.01 / 0.05 / 0.1)
Type 4	2	12.7 (0.50)	0.254 / 1.27 / 2.54 (0.01 / 0.05 / 0.1)
Type 4	2	25.4 (1.00)	0.254 / 1.27 / 5.08 (0.01 / 0.05 / 0.2)

Table 2 Tube material properties for Alloy 600.

Stress (MPa)	Plastic Strain (mm / mm)
300	0
512	0.09274
687	0.178865
840	0.2582
946	0.33177
1125	0.5
1700	1.05
Modulus of Elasticity =	200 GPa
Poisson's Ratio =	0.3

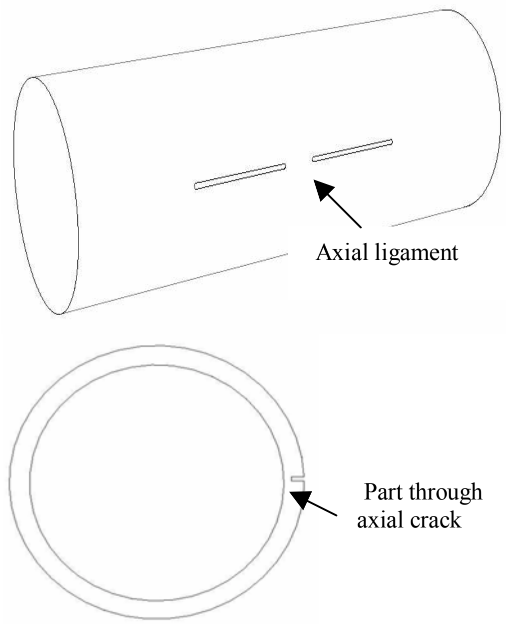
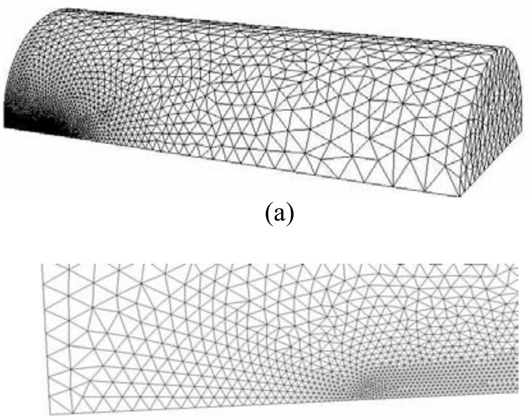


Figure 2 Type 2 crack.



(a)

(b)

Figure 3 (a) Quarter symmetry FEM with triangular shell elements, (b) crack region.

In type 2 model, two part through wall (PTW) cracks are axially offset as shown in Figure 2. The corresponding finite element model is quarter symmetry 3-D model, Figure 3. The elements used are triangular shell elements with five degrees of freedom with reduced integration. The radial ligament was modeled using shell elements of thickness corresponding to the thickness of the radial ligament.

The load was simulated by a pressure applied uniformly on the inner tube surface and on the end cap. The pressure is increased until ligament failure is observed by monitoring the reduction in thickness of both the radial and axial ligaments.

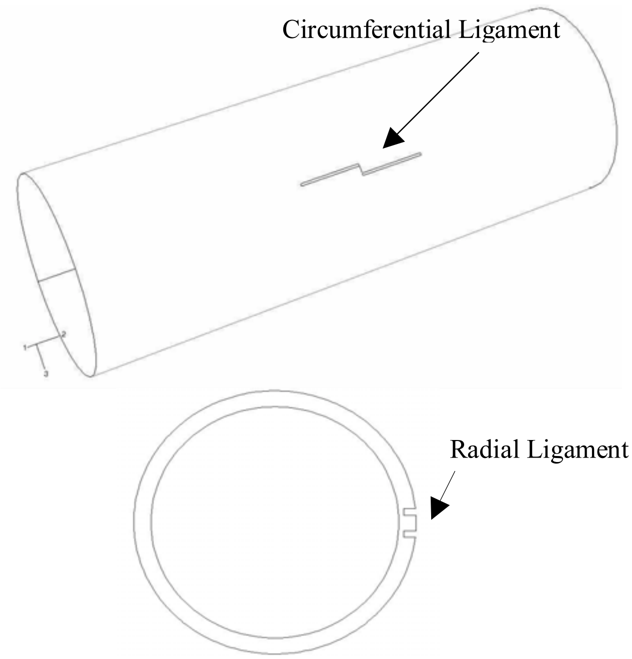


Figure 4 Type 4 crack.

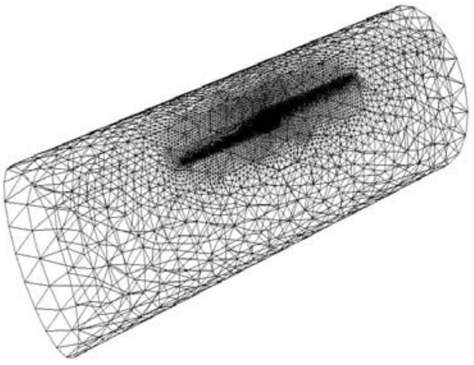


Figure 5 (a)

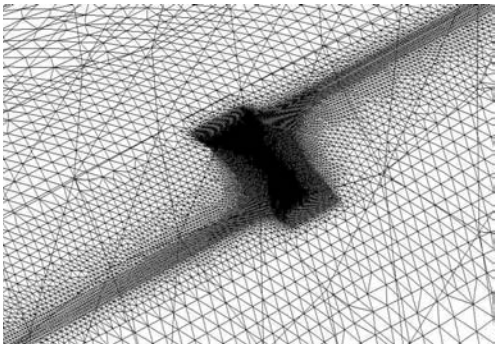


Figure 5 (b) FEM of circumferentially offset part through cracks – Type 4.

Figure 4 shows the type 4 crack configuration, and the corresponding finite element model (FEM) is shown in Figure 5 (a) and (b). This FEM is a full model, and consists of three-node reduced integration shell elements.

RESULTS

Results for type 2 cracks

The radial thickness was normalized relative to its starting value. Figure 6 shows the thickness of the radial ligament as function of tube pressure for three radial ligaments (70%, 80%, and 90%) for type 2 crack. Ligament thickness point of instability is specified as the point of intercept of two straight lines that represent the thickness/pressure gradient in two pressure regions, the first being the stable region, and the second being the instability region. The intercept point indicates the pressure at which significant thinning of the ligament thickness starts. In this case, the corresponding pressure value is the radial ligament rupture pressure (Pr).

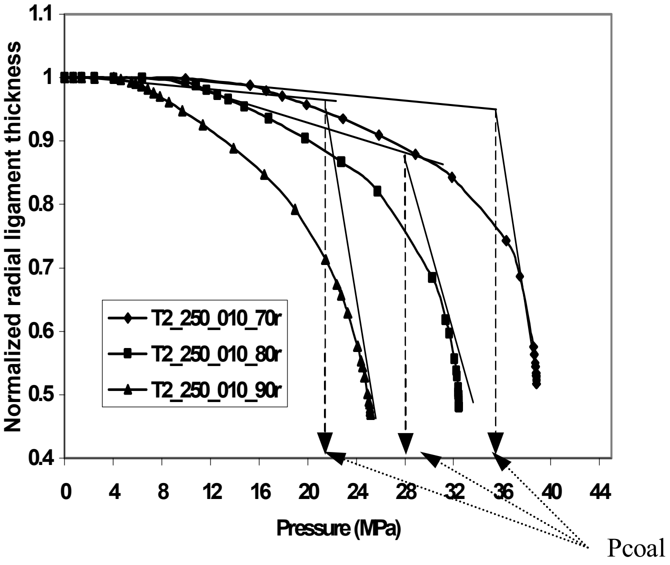


Figure 6 Normalized radial ligament thickness vs. pressure.

Figure 7 is similar to Figure 6 except it addresses the instability of the axial ligament. The figure shows the conditions under which the axial ligament becomes unstable. The axial thickness is normalized relative to its initial value of 1.27 mm. The pressure resulting in instability of the axial ligament is the coalescence pressure Pcoal. One can observe that in this situation, the coalescence pressure is practically equal to the radial rupture pressure. This means that both radial and axial ligaments do become unstable at the same pressure condition. Figure 8 shows the normalized radial and axial ligaments as function of pressure in order to ascertain this observation.

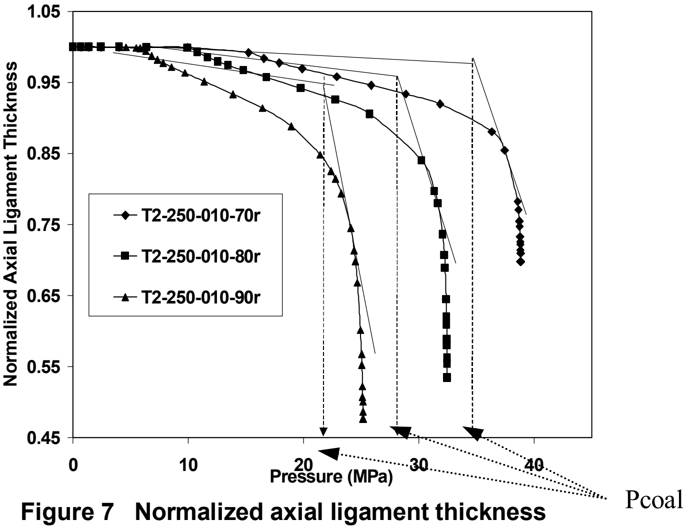


Figure 7 Normalized axial ligament thickness vs. pressure.

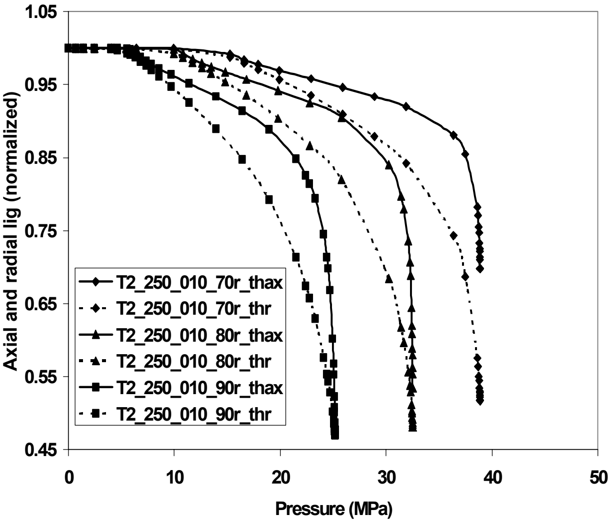


Figure 8 Thickness of axial and radial ligaments for different radial ligaments.

Plastic strain of the axial ligaments is presented in Figure 9 to show the extent of plastic damage at coalescence pressure conditions. The corresponding plastic strain ranges between 10% and 25%, which is quite significant. But more importantly, Figure 10 shows the unstable plastic formation beyond the coalescence pressure.

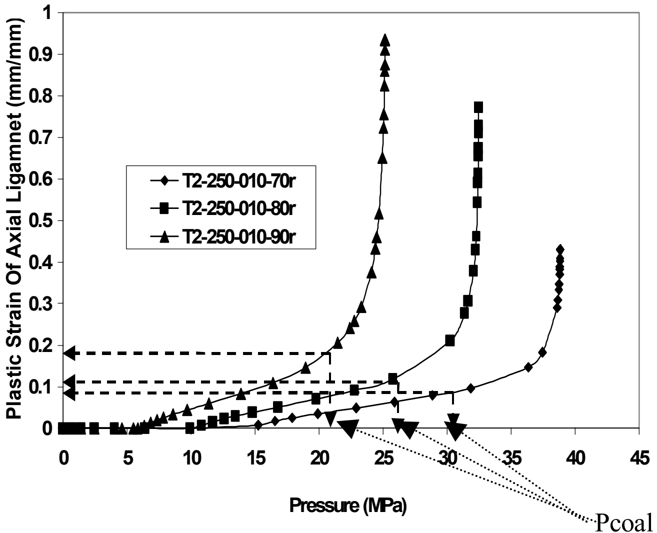


Figure 9 Plastic strain versus pressure for the axial ligament vs. pressure.

Table 3 shows the coalescence and radial rupture pressures for all the cases investigated. NA means that for 100% TW crack. Figure 10 illustrates the impact of the radial ligament on the coalescence pressure. The normalized pressure is the coalescence pressure normalized relative to that of 100% through wall crack case. These results show that the impact of radial crack is much more severe in the case of large cracks. For example, the 70% case of a 1 inch crack shows a coalescence pressure that is almost five fold that of 100% through crack. In contrast, a ¼ inch crack shows a coalescence pressure that is only 1.8 fold.

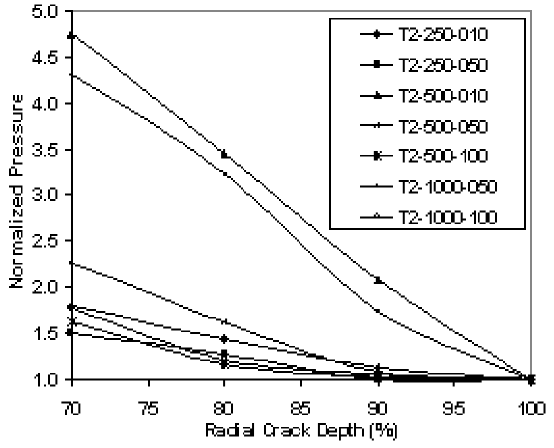


Figure 10 Normalized coalescence pressure vs. radial crack depth.

Table 3 Coalescence and rupture pressures for axial & radial ligaments respectively.

Type	Pressure (MPa)	
	Axial Ligament (Coalescence Pressure)	Radial Ligament (Rupture Pressure)
T2_250_010_70r	35.00	35.50
T2_250_010_80r	28.00	28.00
T2_250_010_90r	22.00	21.70
T2_250_010_100r	19.50	NA
T2_250_050_70r	36.00	35.50
T2_250_050_80r	30.50	29.50
T2_250_050_90r	24.00	23.00
T2_250_050_100r	24.00	NA
T2_500_010_70r	28.50	28.00
T2_500_010_80r	20.70	20.00
T2_500_010_90r	12.50	12.00
T2_500_010_100r	6.00	NA
T2_500_050_70r	30.00	30.00
T2_500_050_80r	21.50	21.90
T2_500_050_90r	14.30	14.50
T2_500_050_100r	13.25	NA
T2_500_100_70r	30.00	30.00
T2_500_100_80r	21.50	22.00
T2_500_100_90r	14.20	14.20
T2_500_100_100r	18.50	NA
T2_1000_010_70r	20.80	20.33
T2_1000_010_80r	15.93	15.11
T2_1000_010_90r	8.58	7.13
T2_1000_010_100r	0.20	NA
T2_1000_050_70r	22.43	22.53
T2_1000_050_80r	16.81	14.86
T2_1000_050_90r	9.05	8.15
T2_1000_050_100r	5.20	NA
T2_1000_100_70r	25.10	23.43
T2_1000_100_80r	17.17	16.25
T2_1000_100_90r	10.17	8.83
T2_1000_100_100r	14.20	NA
T2_1000_200_70r	26.90	24.75
T2_1000_200_80r	18.77	16.73
T2_1000_200_90r	10.63	8.85
T2_1000_200_100r	NA	NA
T2_2000_010_70r	19.62	19.74
T2_2000_010_80r	13.36	13.83
T2_2000_010_90r	7.13	6.58
T2_2000_050_70r	20.13	20.78
T2_2000_050_80r	13.77	14.36
T2_2000_050_90r	7.43	6.63
T2_2000_100_70r	20.81	23.50
T2_2000_100_80r	15.47	15.43
T2_2000_100_90r	8.58	7.60

Results for Type 4 Cracks

In the case of type 4 cracks, results reveal that the rupture of radial ligament occurs at a pressure different from the coalescence pressure. Figures 11 & 12 show the radial and circumferential thickness for three cases of a ¼ inch long crack at 70%, 80% and 90% radial crack depth.

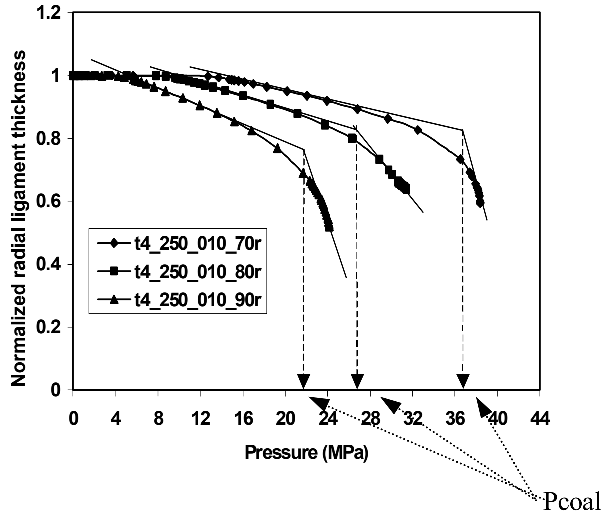


Figure 11 Normalized radial ligament thickness vs. pressure.

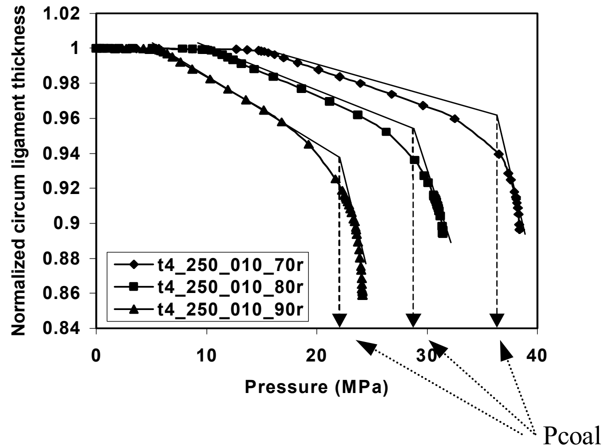


Figure 12 Normalized circumferential ligament thickness vs. pressure.

Figure 13 combines the normalized thickness profiles of the circumferential and radial ligaments to highlight the much faster deterioration of the radial thickness relative to the circumferential one. It is obvious that while the circumferential thickness drop is only in the 5-15% range, the corresponding radial ligament thickness drop is in the 35-50%.

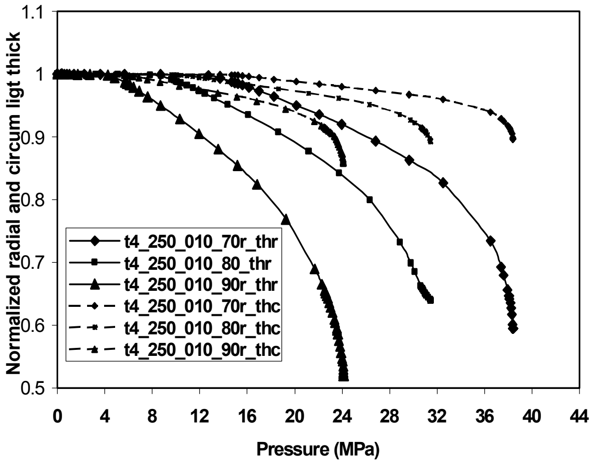


Fig 13 Normalized thickness of circumferential and radial ligaments for different crack depths vs. the pressure.

Figure 14 shows the level of plastic strain in the radial ligament. At rupture conditions, the plastic strain is in the range of 25%-45%. More importantly, the figure shows the instability beyond the rupture pressure point, thus confirming rupture.

The radial rupture pressure conditions for all the type 4 cases are listed in Table 4. The table shows rupture pressure normalized with respect to the coalescence pressure for a 100% through wall crack. This normalized pressure reveals whether radial ligament rupture occurs at a pressure equal to, below or higher than the coalescence pressure.

Figure 15 shows the effect of radial crack depth on the normalized radial rupture pressure.

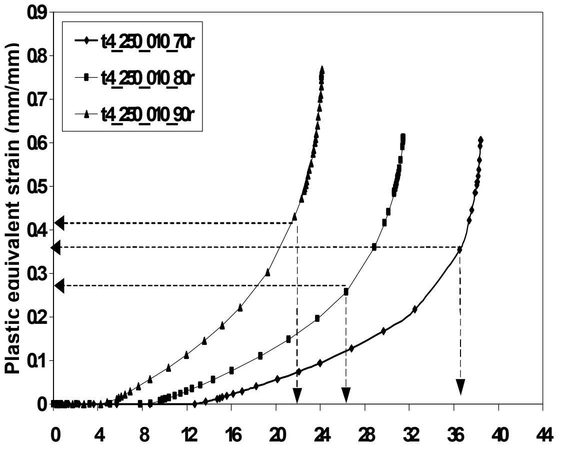


Figure 14 Plastic strain in the radial ligament.

Table 4 Coalescence and radial rupture pressures for type 4 cracks.

Type	Pressure (MPa)		Normalized Rupture Pressure
	Circumferential Ligament (Coalescence Pressure)	Radial Ligament (Rupture Pressure)	
T4_250_010_70r	NA	37.00	2.2
T4_250_010_80r	NA	27.00	1.6
T4_250_010_90r	NA	23.00	1.4
T4_250_010_100r	17.00	17.00	1.0
T4_250_050_70r	NA	39.50	1.1
T4_250_050_80r	NA	27.50	0.8
T4_250_050_90r	NA	25.00	0.7
T4_250_050_100r	35.00	35.00	1.0
T4_250_100_70r	NA	39.00	1.0
T4_250_100_80r	NA	33.50	0.9
T4_250_100_90r	NA	23.00	0.6
T4_250_100_100r	38.00	38.00	1.0
T4_500_010_70r	NA	32.50	3.6
T4_500_010_80r	NA	23.00	2.6
T4_500_010_90r	NA	11.75	1.3
T4_500_010_100r	9.00	9.00	1.0
T4_500_050_70r	NA	34.00	2.0
T4_500_050_80r	NA	22.50	1.3
T4_500_050_90r	NA	15.50	0.9
T4_500_050_100r	17.00	17.00	1.0
T4_500_100_70r	NA	34.00	1.3
T4_500_100_80r	NA	25.00	0.9
T4_500_100_90r	NA	15.50	0.6
T4_500_100_100r	27.00	27.00	1.0
T4_1000_010_70r	NA	30.00	10.0
T4_1000_010_80r	NA	20.50	6.8
T4_1000_010_90r	NA	10.00	3.3
T4_1000_010_100r	3.00	3.00	1.0
T4_1000_050_70r	NA	30.00	4.3
T4_1000_050_80r	NA	21.00	3.0
T4_1000_050_90r	NA	11.50	1.6
T4_1000_050_100r	7.00	7.00	1.0
T4_1000_200_70r	NA	31.00	NA
T4_1000_200_80r	NA	23.00	NA
T4_1000_200_90r	NA	13.30	NA
T4_1000_200_100r	NA	NO FAILURE	NA

In type 4 cracks, with a circumferential ligament, the radial rupture may occur at a pressure below coalescence pressure for cases where the circumferential ligament is relatively large relative to crack length (20% to 40% of crack notch length). This finding makes sense since larger circumferential ligaments allow for less interaction between the two axial cracks, and thus there is more likelihood for the radial ligament, which is subjected to hoop stress, to yield and rupture, without impacting the circumferential ligament much, Figure 15. In fact, it was already proven [2, 3] that circumferential ligaments require higher coalescence pressure than axial ligaments. A normalized rupture pressure less than 1 means that once radial ligament ruptures, the circumferential ligament will still be stable and would require higher-pressure condition for coalescence to ensue.

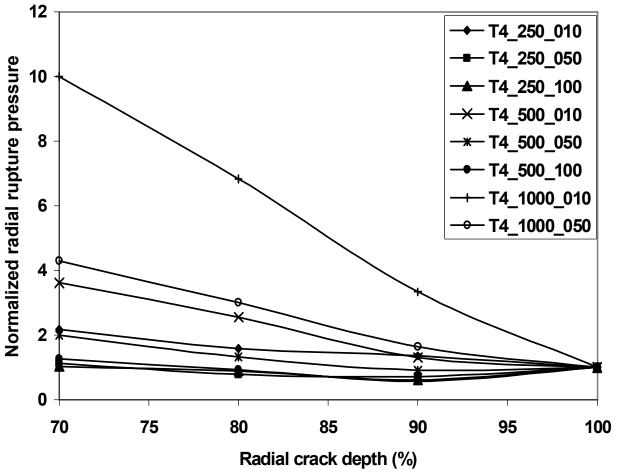


Figure 15 Normalized rupture pressure- type 4 cracks.

EXPERIMENTAL VERIFICATION:

Table 5 Coalescence pressure for axial ligament type 2 cracks (model vs. experiment).

Model	FEA Results		Experimental Result	% Difference
	Pcoal – axial ligament	Pr- rad. Ligament	Rupture Pressure	
T2_250_010_70r	35	35	34	3
T2_250_010_80r	27.2	27.9	27	0.7
T2_250_050_70r	35.5	36	37	4.
T2_250_050_80r	30.9	29.9	31	0.3
T2_500_010_80r	20.5	20.2	20	2.5
T2_500_050_80r	20.9	20.5	21.7	3.7
T2_500_100_80r	22	23	24	8.3

Some experimental data were made available from Argonne National Lab [13]. The experimental data includes crack length of 0.25 and 0.5 inches, for crack depth of 70% and 80% PTW. Table 5 shows the experimental results versus the finite element analysis results.

Table 5 shows a good match between the finite element prediction and the experimental results, with a maximum difference of about 8%.

OBSERVATIONS AND CONCLUSIONS

Nonlinear finite element model analyses of collinear cracks with axial and circumferential ligaments were conducted to predict pressures at which coalescence and radial rupture would occur for PTW cracks in steam generator tubing. Experimental results validate the finite element results for axial ligaments. The results show that radial rupture occurs simultaneously with axial coalescence if the ligament were axial. Once this pressure is reached, the cracks coalesce, with radial ligament rupture, leading to uncontrollable tube burst. The reason is that the coalescence pressure is higher than the burst pressure of a crack of a length that is the sum of the lengths of the two coalesced cracks and the ligament.

However, in the case circumferential ligament between two axial cracks, the size of the circumferential ligament relative to crack size determines which ligament ruptures first. If the circumferential ligament is relatively small, the radial rupture pressure exceeds that of coalescence of 100% TW case. But in the case of a relatively larger circumferential ligament, the radial rupture pressure becomes less than the 100% TW coalescence pressure. As a result, the cracks would leak but would not coalesce unless the pressure increases to the coalescence pressure level.

These results are essential components for predicting conditions of tube failure in steam generator tubes in nuclear power plants. These results enhance the interpretation of the tubing NDE inspection test data, and the prediction of leak rates that influence decisions of maintenance scheduling.

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