Fracture Mechanics Evaluation of a Highly Redundant Reactor Pressure Vessel Internal Structure

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ABSTRACT

Reactor pressure vessel (RPV) internal structures are potentially susceptible to embrittlement and stress corrosion cracking due to neutron irradiation. Linear elastic fracture mechanics methods coupled with a detailed finite element analysis have been used to assess the significance of cracking in a particular RPV internal component. The component analyzed is the Boiling Water Reactor (BWR) top guide structure which consists of a series of intersecting beams. This study shows that rather large cracks would be required for top guide failure and progressive beam failure would be possible only if the top guide fracture toughness were significantly degraded or there were many large beam cracks in the immediate vicinity of the first beam to fail.

KEYWORDS

Core structures; neutron irradiation; embrittlement; stress corrosion cracking; finite element analysis; critical crack size; failure modes.

INTRODUCTION

Reactor pressure vessel (RPV) stainless steel internal structures are potentially susceptible to stress corrosion cracking due to a combination of neutron irradiation and the light water reactor (LWR) water environment. As both neutron irradiation and high stress are believed to cause cracking, this cracking has been called Irradiation Assisted Stress Corrosion Cracking (IASCC). In addition to concerns for IASCC, stainless steel experiences a loss in fracture toughness when irradiated above 1 x 10^{21} (>1 MeV). Consequently, while neutron irradiation and the LWR water environment may conspire to cause cracking of RPV stainless steel internal structures, neutron irradiation also makes the material less flaw tolerant. One internal structure that sees a relatively high neutron irradiation fluence and could experience high loads during a postulated earthquake is the Boiling Water Reactor (BWR) top guide. The integrity of the BWR top guide structure has recently been studied as part of an Electric Power Research Institute (EPRI) research program (Gerber, et al., 1986, Gerber, Kuo, 1988).

Figure 1 shows a schematic of the BWR pressure vessel with a sketch of sections of the top guide structure. In the BWR models 2 through 5, the top guide is formed by a series of Type 304 stainless steel beams joined at right angles by means of vertical slots with beams welded to a peripheral ring. Each opening between beams provides lateral support and guidance for four fuel assemblies. While normal operating loads on the top guide structure are small, an earthquake would result in relatively large lateral loads to the top guide beams due to motion of the fuel assemblies.

Estimates for current peak fluence levels for the BWR top guide structures range from 2×10^{21} to 5×10^{21} n/cm^2 (E > 1MeV) with end-of-life peak cumulative fluences on the order of 1×10^{22} n/cm^2 (E > 1MeV). Using 1×10^{22} n/cm^2 (E > 1MeV) as the end-of-life fluence at the bottom-center of the top guide, typical end-of-life fluences at the top-center, bottom-periphery and top-periphery are estimated to be 1×10^{21} n/cm^2, 2×10^{21} n/cm^2 and 2×10^{20} n/cm^2 (E > 1MeV), respectively (Gerber, et al., 1986). These values are noted in Fig. 1.

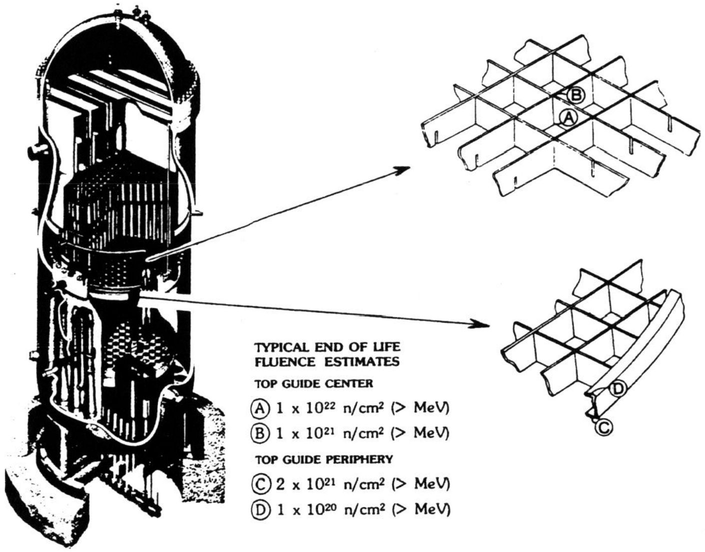

Fig. 1. Schematic of BWR Top Guide Structure With Typical End-of-Life Fluence Estimates

The top guide modeling process includes development of a finite element model of the top guide and shroud, calculation of top guide seismic reaction loads, calculation of crack tip stress intensity factors for different crack orientations and locations in the top guide, and comparison of stress intensity factors with expected material toughness for these locations. In this manner the critical crack size for a particular crack orientation and location was determined. This modeling technique was also used to study the possibility of progress beam failure.

The specific top guide configuration evaluated here is the BWR model 4 design installed in Browns Ferry Units 1, 2 and 3. This design is for a 251 inch diameter pressure vessel. Beam height and thickness are 13.00 inches and 0.36 inch, respectively, and total seismic lateral load was estimated to be 346 kip (Gerber, et al., 1986).

Figure 2 shows a schematic of three crack orientations evaluated at beam intersections. A Type 1 crack is shown growing downward from the slot in a top slotted beam while a Type 2 crack is growing upward from the slot in a bottom slotted beam. A Type 3 crack is also growing upward but from the notch on the bottom side of a top slotted beam.

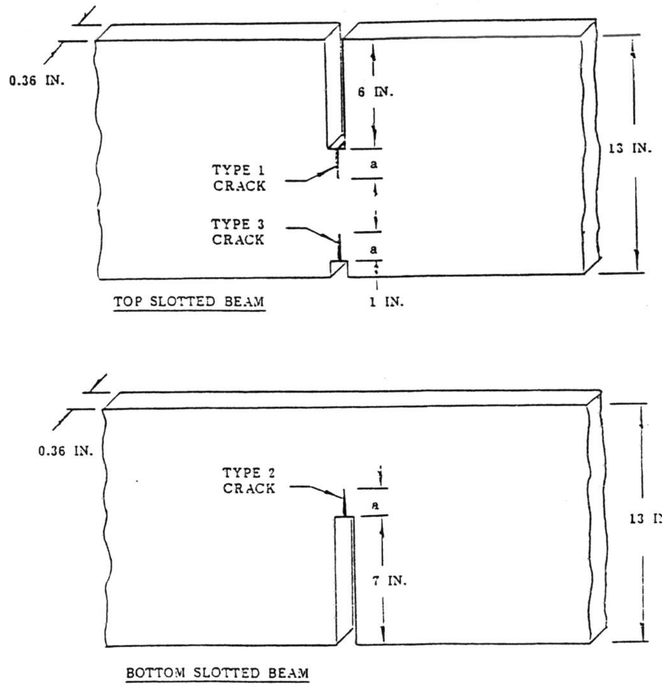

Fig. 2. Top Guide Beam Crack Types and Locations

FINITE ELEMENT ANALYSIS

The BWR top guide structure was originally modeled with the ABAQUS (Gerber, et al., 1986, Hibbitt et al., 1982) finite element code and subsequent studies with the SUPERSAP (Gerber, Kuo, 1988, Algor Inc., 1986) code. In both cases, the top guide beams were represented as two-node, cubic-interpolated beam elements. Because of the slot construction, the two perpendicular beams were allowed to rotate relative to each other in the plane of the top guide.

Top guide beam slots are machined with a close tolerance which suggests the possibility of binding between the beam elements. While it is not clear this binding would occur, it was felt prudent to include in the model differences in beam flexibility to account for the possibility. For top slotted beams, where binding is a possibility, the beam was modeled as a full 13 inch deep beam without a notch. On the other hand, bottom slotted beams were modeled as having a depth equal to the ligament at the notch. These reduced section beams were modeled as having a 6.0 inch depth, with the neutral axis at the top of the beam.

The modeling of the shroud on which the top guide sits was included in the analysis in order to obtain an accurate boundary condition around the peripheral ring. Flat plate elements with a thickness of 2 inches were used to model the shroud. Because the structure is symmetric, only half of it was modeled. The complete top guide and shroud model included 232 beam elements, 50 shell elements and 224 nodes. A schematic of the top guide finite element model is shown in Fig. 3.

Seismic lateral loads were applied as concentrated nodal point forces and moments. The force at a node was computed by summing one-half the load per cell for each cell that ties to that node. Similarly, a moment that twists the bottom of the beam in the direction of the horizontal force was applied at the node. Its magnitude is equal to the horizontal force at the node times a moment arm equal to the distance from the neutral axis to the bottom of the beam.

Top guide beam loads were calculated for two seismic loading conditions. In one case the load was applied normal to the top slotted beams (Case 1) and in the second case the seismic load was applied normal to the bottom slotted beams (Case 2). Due to symmetry and anti-symmetry features of the applied loading, only one quarter of the top guide is needed to present the results of the two loading cases. For any seismic load from an arbitrary seismic direction, the resulting nodal forces and moments can be calculated by

$$\text{Combined loads} = [\text{Case 1 loads}] \times \cos\theta + [\text{Case 2 loads}] \times \sin\theta \qquad (1)$$

where:

θ = angle between the Case 1 direction and the applied seismic direction

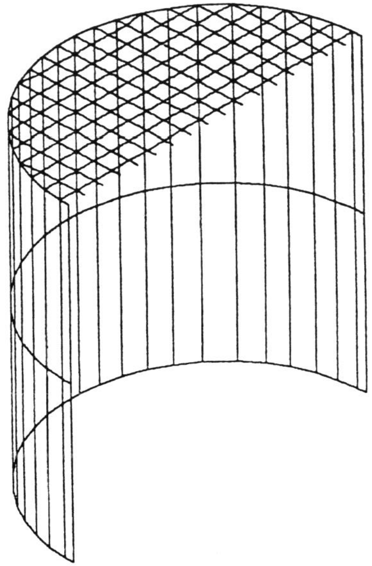

Fig. 3. Top Guide Finite Element Model

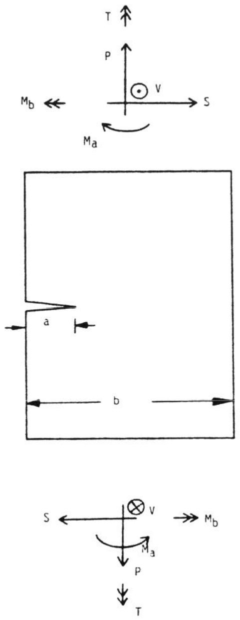

Fig. 4. Single Edge Crack Plate Model

FRACTURE MECHANICS ANALYSIS

As illustrated in Fig. 2, three types of cracks are considered in this report. Type 1 cracks emanate from the bottom of the slot in top-slotted beams, Type 2 cracks emanate from the bottom of the slot in bottom-slotted beams, and Type 3 cracks start from the notch in the lower edge of top-slotted beams. As a result of simultaneous existence of forces and moments in three directions, all three fracture modes (Mode I, Mode II and Mode III) are involved in each one of the three crack types.

In this analysis, the three crack types have been modeled as a single edge crack plate, as shown in Fig. 4, subjected to three forces and three moments. Stress intensity factors for the single edge crack plate are calculated by the following expressions derived from (Gerber, et al, 1986, Sih, 1973, and Tada, et al, 1973).

$$K_I = \sqrt{\pi a}\left[\left(\frac{P}{bt} + \frac{6M_b}{b\,t^2}\right)F_{IA} + \frac{6M_a}{b^2\,t}F_{IB}\right] \qquad (2)$$

$$K_{II} = \sqrt{\pi a}\,\frac{S}{bt}\,F_{II} \qquad (3)$$

$$K_{III} = \sqrt{\pi a}\left[\frac{V}{bt}F_{IIIA} + \frac{3T}{bt^2}F_{IIIB}\right] \qquad (4)$$

where:

- P, S, V = forces defined in Fig. 4
- M_a, M_b, T = moments defined in Fig. 4
- a = crack length
- b = plate width
- t = plate thickness

and

$$F_{IA} = \sqrt{\frac{2b}{a\pi}\tan\left(\frac{a\pi}{2b}\right)}\left[0.752 + 2.02(a/b) + 0.37\left(1-\sin\frac{a\pi}{2b}\right)^3\right]/\cos\left(\frac{a\pi}{2b}\right) \quad (5)$$

$$F_{IB} = \sqrt{\frac{2b}{a\pi}\tan\left(\frac{a\pi}{2b}\right)}\left[0.923 + 0.199\left(1-\sin\frac{a\pi}{2b}\right)^4\right]/\cos\frac{a\pi}{2b} \quad (6)$$

$$F_{II} = \left[1.122 - 0.561(a/b) + 0.085(a/b)^2 + 0.180(a/b)^3\right]/\sqrt{1-(a/b)} \quad (7)$$

$$F_{IIIA} = \sqrt{\frac{2b}{\pi a}\tan\frac{\pi a}{2b}} \quad (8)$$

$$F_{IIIB} = 1.7624 - 3.047(a/b) + 3.3997(a/b)^2 \quad (9)$$

The Mode I, II, and III crack tip stress intensities can be combined given the applied J–integral for comparison with the material toughness J_{Ic} or K_{Ic}.

$$J = \frac{1-\nu^2}{E}\left(K_I^2 + K_{II}^2\right) + \frac{1+\nu}{E}K_{III}^2 \quad (10)$$

and $$J_{Ic} = \frac{K_{Ic}^2}{E} \quad (11)$$

A review and assessment of irradiated stainless steel mechanical properties was carried out as part of the original EPRI top guide integrity study. While much of this data is not for temperatures and neutron energy spectrum different from BWR conditions, it was felt that a toughness of 224 ksi$\sqrt{in}$ at a fluence of 10^{21}n/cm^2(>1MeV) and 63 ksi$\sqrt{in}$ at a fluence of 10^{22}n/cm^2(>1MeV) would be representative. A linear relationship between toughness and the log of fluence was assumed.

As noted in Fig. 1, there is a fall–off in fluence as one moves from the bottom to the top of a top guide beam and from the center of the top guide to the periphery. In this study, it was assumed that radial distribution of fluence would have a parabolic shape. Using the end–of–life fluences noted in Fig. 1,

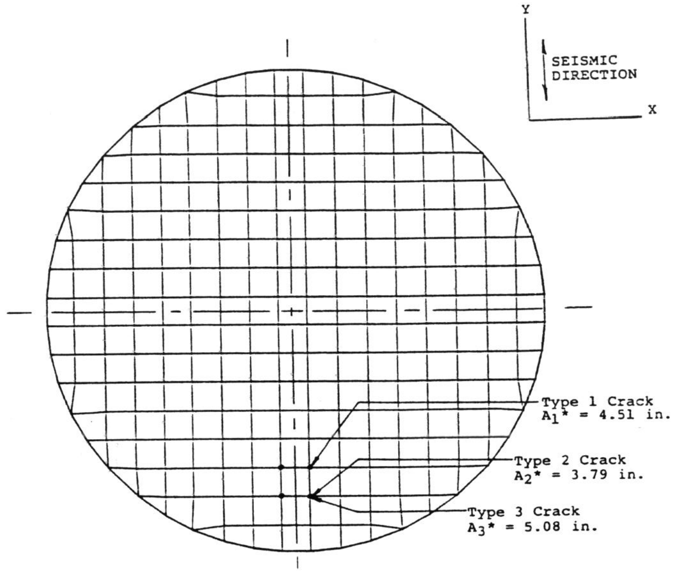

Fig. 5. Comparison of Critical Crack Size and K_{eff} from Previous and Present Top Guide Analysis

$$f_{top} = 1 \times 10^{21} - 9 \times 10^{20}\left[\frac{r}{R}\right]^2 \quad (12)$$

$$f_{bottom} = 1 \times 10^{22} - 8 \times 10^{21}\left[\frac{r}{R}\right]^2 \quad (13)$$

where f_{top} is the fluence in n/cm^2 at the top edge of the beams, f_{bottom} is the fluence at the bottom edge, R is the radius of the top guide and r is the distance from the center.

Further, using the relationship between fluence and fracture toughness,

$$(K_{Ic})_{top} = 224 - 161 \log\left[f_{top}/1 \times 10^{21}\right] \quad (14)$$

$$(K_{Ic})_{bottom} = 224 - 161 \log\left[f_{bottom}/1 \times 10^{21}\right] \quad (15)$$

where $(K_{Ic})_{top}$ is the fracture toughness in ksi$\sqrt{in}$ at the top edge of the beams and $(K_{Ic})_{bottom}$ is the fracture toughness at the bottom edge. Assuming that fracture toughness varies linearly with beam depth, the fracture toughness at any position in a beam is given by

$$K_{Ic} = (K_{Ic})_{bottom} + \left[(K_{Ic})_{top} - (K_{Ic})_{bottom}\right] \frac{d}{13} \qquad (16)$$

where d is the distance in inches from the bottom edge of the beam.

Figure 5 shows positions and notes the size of each type of crack which would be expected to first become critical during a seismic event. Note that the first beams to break are quite near the periphery and that the locations where the different types of cracks would first be expected to be critical are quite close together.

PROGRESSIVE BEAM FAILURE

In the event that a seismic event causes one beam to fail, the possibility exists that progressive beam failure, due to load redistribution to neighboring beams, could result. This "domino" type failure mode, if should be shown to be credible, could result in disruption of the core arrangement and impair scrammability.

Progressive beam failure was investigated using the finite element and fracture mechanics models described earlier. Two scenarios were considered. In the first case it was assumed that every beam in the top guide had a crack of the type and size which would be critical at the highest stress intersection. As indicated in Fig. 6, this is a Type 2 crack with length of 3.79 inches. Assuming failure of the first pair of beams, the beams in finite element model were cut and the finite element analysis was rerun to calculate new beam loads. The model was then explored to see if the effective stress intensity factor for any cracks (recall each beam is assumed to have a 3.79 inch, Type 2 crack) exceeds the fracture toughness. If they did, these beams were cut and process repeated.

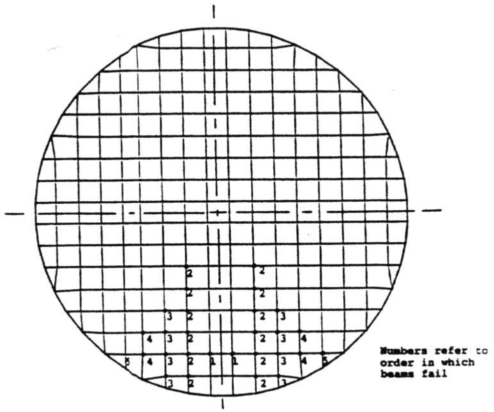

Fig. 6. The Order of Beam Failures Assuming All Beams Contain a Type 2 Crack 3.79 Inches Long

Figure 6 shows the pattern of beam failures which develops. The numbers at the beam intersections indicate the order in which beams break. Note that with the assumptions that all beams contain a large crack, a number of beams would be expected to fail with one load application. Failure does appear to progress in an orderly manner but a relatively large area of the core could be disrupted. Similar failure patterns develop if one starts with either a critical Type 1 or Type 3 crack and one assumes this size and type of crack exists at each beam intersection.

The assumption that a large crack exists at each beam intersection is quite conservative. To gain additional perspective on the possibility of progressive beam failure, a second failure scenario was explored. In this case, cracks were assumed to be present only at the beam intersections at which the analysis had shown they would first be critical. Beams at these locations (which due to symmetry occur in pairs) were assumed to break. These beams were cut and the finite element analysis was rerun to calculate new beam loads. Using these loads, the fracture mechanics analysis program was used to find the size crack required to cause the next pair of beams to fail. It could be reasoned that if the size of defect required for second and subsequent failures is nearly the same size as the defect required to produce the first failure, progressive beam failure would be credible only if there were a pervasive beam cracking mechanism. On the other hand, if subsequent failures require only very small defects or no defects at all, progressive beam failure is a possible failure mode.

Figure 7 shows the results for the case where the first beam failure is due to a Type 1 crack. This is a crack growing downward from a top slotted beam oriented normal to the seismic direction. The crack size required for this failure is 4.51 inches. Note that

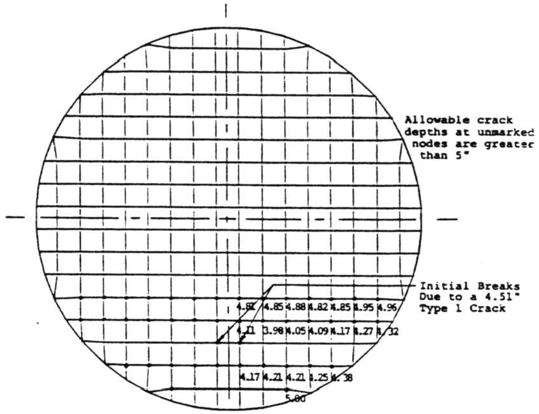

Fig. 7. Size of Type 1 Crack Required to Produce a Second Beam Failure Assuming the First Break Occurs at a Beam With a Type 1 Crack of 4.51 Inches

the Type 1 crack required for the next failure is almost as large as the crack required for the first failure (3.98 inches versus 4.51 inches). Critical crack depths for unmarked beam intersections are greater than 5 inches. Similar behavior was found for Type 2 and 3 cracks.

DISCUSSION

A systematic study of the integrity of the BWR top guide core support structure has been carried out. A finite element model of the top guide structure was used to calculate beam loads due to an earthquake. This model realistically modeled the beam joints, including uncoupled rotation in one direction, and included both the peripheral ring and the shroud. With these features the model showed that seismic loads are rather uniformly distributed among the top guide beam elements. While beam stresses tend to be highest at joints near the periphery, they are not that much higher than stresses at joints near the center of the top guide.

Linear elastic fracture mechanics methods have been used to calculate top guide critical crack sizes. Material–toughness gradients were assumed in both the radial (top guide center to periphery) and axial (bottom to top of beam) directions. This combination of realistic estimates of top guide beam stress and material–toughness gradients leads to large critical crack sizes. This analysis shows that the first beams to fail are near the periphery and smallest critical crack size is 3.79 inches long. This is a crack which has grown upward from the slot in a bottom slotted beam.

Analysis of multiple top guide beam failure shows that progressive beam failure is not a likely failure mode. That is, unless the top guide has large cracks at most beam intersections near where the first failure occurs, the failure of a first beam would not result in additional beam failures due to load redistribution. Given the generally random nature of stress corrosion cracking, progressive beam failure is not likely.

In addition to these encouraging results, it is important to point out some conservative assumptions used in the analysis. First, the analysis is based on the use of K_{Ic} data and does not recognize the additional capability resulting from stable crack extension. Second, beam slots and notch are treated as cracks in the stress intensity calculations. If a crack is assumed to be present, the slot or notch depth is added to the crack length to define an effective crack length. In reality, slots and notches are blunt and will be less structurally significant than an equivalent length crack. Third, a number of conservative assumptions have been employed in the finite element analysis. These include boundary conditions at the beam intersections as well as the fuel to beam interface. And fourth, the top guide analyzed is of a particular design. Other designs, particularly for smaller diameter pressure vessels, would be expected to have lower beam loads. In addition, the loading condition analyzed is for a particular design basis earthquake. The loads come from conservative models of the pressure vessel and fuel coupled to conservative models of the building, basement and soil. Normal operation top guide loads are insignificant in comparison.

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