Structural Integrity Evaluation of Fuel Test Loop Submerged in Water Subjected to Postulated Pipe Rupture

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ABSTRACT : The structural integrity of the fuel test loop (FTL), in a Korean experimental reactor is evaluated when the FTL, submerged in a water environment, is subjected to a postulated pipe rupture. The analyses are performed for static analysis and dynamic analysis, imposing the thrust force history at the postulated pipe rupture section. Through analysis the following results are found: 1) A double ended guillotine can not be expected based on the toughness of the material.

1. Introduction

Battelle Northwest Research Institution[1] performed the structural integrity evaluation of the fuel test loop (FTL), Korea multipurpose research reactor (KMRR). The purpose of [1] is to construct a model to evaluate the effects on environments of the thrust force and jet impingement caused by a postulated pipe rupture at Korea Atomic Research Institute (KAERI) - KMRR - FTL. The final purpose of [1] is to evaluate the structural integrity, using the leak before break (LBB) concept. Through the results of LBB analysis, [1] concluded that the dynamic analysis may not be required. However, KAERI recognized that the leakage detection of 1GPM or 10GPM is difficult, since the FTL is submerged in water and the pipe size, 2.5in. sch. 160, is too small to apply LBB concepts. The purpose of this paper is to regenerate, 1) Battelle Research Institution's static model and to compare the results obtained by Battelle and the present analysis, 2) to determine the rupture section from the results of the static analysis and ASME section III, and 3) to perform the dynamic analysis of a ruptured pipe subjected to the prescribed thrust history. The employed assumptions are, 1) LBB concepts are not applied, 2) water-hammer, creep, erosion and corrosion are not considered in the analysis, 3) initial and steady state thrust forces are used directly from the results obtained from Battelle [1], 4) the entire FTL is submerged in the pool and the effects caused by the FTL rupture on the environment are ignored. This can be justified from the energy balance, i.e., the

temperature of the pool is increased from 72°F to 95°F due to the postulated pipe rupture. Also, the ejection of pool water caused by the rupture is not considered in the analysis. The calculations regarding thrust force history and jet impingement are performed by Battelle Research Institution using [2].

2. Static Analysis

2.1 Data for the analysis

The FTL is made from austenitic stainless steel(301, 309, 319, 321 and 237). Design pressure 2500psi, temperature 622°F, saturation pressure 1813psi (622.4°F). Nominal pipe size 2½in. Sch. 160, outside diameter, 2.875(Do)in, wall thickness, 0.375in and inside diameter, 2.125in, Young's modulus, 25.028×10^6 (662°F), poisson's ratio, 0.2642, density of pipe, 500 lb/ft³, linear expansion coefficient, $9.8834 \times 10^{-6}/^\circ\text{F}$, diameter of the insulation, 3.9in, density of the insulation, 0.11918 lb/in³, thickness of covering insulation 0.05in, SIF of the elbow, $0.9/h^{2/3} = 0.9655$, $h=tR/r_m^2 = 0.375 \times 3.75/1.25^2 = 0.9$ in, $R=3.75$ in, $r_m=(Do - t)/2=1.25$ in.

2.2 Model of static and seismic analysis

The node number and loop lay out are shown in Fig. 1. Node number 210, 120 and 10 are fixed in all three directions. Node number 90 and 170 are fixed in the x and y direction, respectively, while the z direction is free. The static analysis is performed using the input data with the boundary conditions.

In order to perform the seismic analysis, modal analysis is required. Modal analysis is performed using the identical input data with those of Battelle and ANSYS computer code. The analysis shows the lowest mode is 6.0Hz and the second mode is 7.8Hz. The significant response in the first mode shows between nodes 210 and 170.

The length between node 210 and node 170 is 15.3ft and it contains two elbows. The length between node 210 and node 175 is 11.4ft. The line density of the pipe is obtained by summing the weights of the steel covered insulation material, 0.180 lb/in, insulation, 0.017 lb/in, added mass, 0.453 lb/in, water in the pipe, 0.0823 lb/in, and the pipe, 0.854 lb/in. The line

Fig. 1 The model for both static and dynamic analysis

density of the composite pipe is approximately 1.586 lb/in. The density of the pipe is 503lb./ft³ assuming the outside diameter of the insulation, 3.9in, and the inside diameter of the insulation material is 2.875in. If the first mode (6.0Hz) corresponds to the cantilever beam, the natural frequency can be found using the formula, $\omega_n = (\lambda^2 / l^2) (EI / \rho A)^{1/2}$, where $\lambda = 1.875$, l = beam length 11.4ft, ρ : equivalent beam density 501 lb/ft³, E : Young's modulus, 26.7×10^6 psi, I : sectional moment of inertia of pipe 37.64/16 in⁴. If these values are used in the formula of ω_n calculation, $\omega_n = 32.0$ rad/sec = 5.0Hz. This value is approximately 6Hz, obtained through the computer. Similarly, the distance between nodes 120 and 105 in Fig. 1 is 9.84ft. The second mode frequency, 7.83Hz, can be approximately found using data given in the ω_n calculation. The value obtained from the ω_n formula is 6.76Hz. Through these rough estimations, the model established for the mode analysis is justified.

The input ground acceleration in the x and y direction were obtained from the Korea Atomic Research Institution. The maximum OBE ground acceleration in the x and y directions are both 1.92g, and 1.02g in the z direction. The minimum value in the x, y and z directions is 0.1g. The imposed frequency range is 100Hz to 0.6Hz.

The ground acceleration spectrum for SSE is found by $1.5 \times$ OBE ground acceleration spectrum. These spectrum are imposed at the anchor points, nodes 210, 120, 90, 170 and 10. The stress values at each element for each node are calculated and the final stresses are obtained by SRSS(square root of square summation) method. This calculation is performed automatically by ANSYS computer code.

The results of seismic analysis are combined with the results obtained from static analysis. The algebraic combinations of the maximum effective stress are, 1) Dead weight stress (DW), 2) Pressure stress (P), 3) Thermal stress (T), 4) DW+P, 5) DW+P+T, 6) DW+P+S₁+S₃ (S₁: stress due to SSE in the x direction, S₂: stress due to SSE in the y direction), 7) DW+P+S₂+S₃ (S₃: stress due to SSE in the z direction), 8) S₁, S₂ and S₃ for SSE, 9) similar stress combinations for OBE. The total stresses of algebraic combinations are sixteen, including both OBE and SSE and the effective stress can be found for each stress analysis.

The rupture sections are determined by using the criteria, class 2 of NUREG - 0800(standard review plan), $\sigma_a \leq 0.8 (1.8 S_h + S_a)$. σ is the effective stress, which should be less than the allowable stress σ_a , S_h : allowable stress at 622.4°F(16.57ksi), S_a : allowable expansion stress $S_a = f(1.25 S_c + 0.25 S_h)$, f : stress reduction factor, if full temperature cycle during the life of the plant is less than 7000, then $f=1.0$, S_c : allowable stress at 70°F(20ksi). The allowable effective stress σ_a is found from eq.(2), $S_a = 29.14$ ksi, and allowable effective stress $\sigma_a = 47.2$ ksi.

If the maximum effective stress obtained through the various stress combinations is found to be greater than the value $\sigma_a = 47.2$ ksi, a pipe rupture is postulated at that section. The results show that stresses in all pipe sections are less than the allowable stress, $\sigma_a = 47.2$ ksi, and the postulated pipe sections can not be determined

by NUREG-0800. Therefore, pipe rupture is postulated at the weakest sections, which correspond to the connecting sections of the pipes. Through the comparisons of Battelle and the present analysis, Battelle's analysis is found to be consistent with the present model and justifies the present static model and analysis as reasonable.

3. Dynamic Model

3.1 Thrust force generation

Thrust force applied at the rupture section is required. The initial thrust force will decrease rapidly due to the decrease of pressure in the pipe and it will reach a steady state. Eventually, the thrust force will be zero. The main response of the pipe is a transient response caused by the initial and steady thrust force. The initial, steady state thrust force and time required to for steady state thrust force can be found from Battelle's result or [2]. The schematic diagram of the thrust history is given in Fig. 2.

Fig. 2 Approximate force history applied at the broken sections

3.2 Determination of damping

The FTL consists of steel pipe, insulation material, and thin steel covered by insulation material and water. The damping in the air is assumed to be 2%(damping ratio). The damping force is considered at 7.83Hz(the second mode of unbroken loop) and equivalent line density including steel pipe, insulation material, steel covered with insulation material, added mass and water in the pipe is found to be approximately 501 lb/ft^3 . In order to obtain a smaller damping ratio for conservative analysis, the pipe is considered to be solid pipe with a 4in diameter corresponding to the outside diameter of the insulation. The mass of the pipe with 17.5ft length and 4in diameter solid pipe is given as $m = 1.98 \text{ lbf} - \text{sec}^2 / \text{in}$.

The damping factor in the air is obtained by assuming a single degree of freedom, $C = 3.92 \text{ lbf} - \text{sec} / \text{in}$.

The other damping factor is associated with damping of the fluid. The drag force is obtained from the equation, $F_D = C_D \rho A |\bar{v}| V / 2g$, and $C_f = C_D \rho A |\bar{v}| / 2g$.

The damping factor C_f is obtained if the initial velocity of the beam is known. The initial beam velocity is found from the energy conservation law. If 8900 lbf is applied statically to the free end with $\ell=17.5$ ft, the work done in the beam is given by $P\delta/2 = P^2\ell^3/6EI = m\bar{v}^2/2$, the velocity $\bar{v}$ is found as $\bar{v}=117$ ft/sec.

The damping coefficient C_f is given as $C_f=660.2$ lb-sec/ft. Damping force is considered as a parallel connected dashpot model and C_f is obtained by summing C and C_r . The value of C_f is $C_f=59$ lbf-sec/in. The damping ratio ζ is $\zeta = C_f/2m\omega_n \sim 0.3$, ($\omega_n=7.83\times 2\pi$).

The Rayleigh damping values are obtained for four cases, 1) broken loop, $m=0.704$ lbm, frequency range, 1.946Hz~30Hz, $\zeta=1.576$, $\ell=14.3$ ft, 2) unbroken loop $m=1.98$ lbm, frequency range, 6.3Hz~30Hz, $\zeta=0.3$, $\ell=17.5$ ft, 3) $m=1.98$ lbm, frequency range, 1.946Hz~30Hz, $\zeta=0.3$, $\ell=17.5$ ft, 4) no damping, $\zeta=0.0$.

4. The Dynamic Responses of the Final Dynamic Model

The dynamic model is that nodes 120, 210 and 10 are fixed in the three directions, while nodes 90 and 170 are restrained in the y and x directions, respectively, and those points are not restrained in the z-direction. Node 186 has the restraints in the x and z directions, and node 112 is constrained in the y and z directions in the final model. The thrust force history given in Fig. 2 is applied independently at the postulated rapture sections, nodes 60, 140, 110, 111, 200 and 201 in Fig. 1 with Raleigh damping values α and β for four cases.

The displacements and velocities responses at the each broken section are found. The effective stresses at each fixed node, caused by each broken section, are found. The typical displacement response at the broken section, node 60, are given in Figs. 3 to 6. The effective stress responses at the fixed node 112, caused by the broken section, node 60, is given in Fig. 7. The dynamic responses at six broken sections and the effective stress responses at the fixed nodes, caused by each six broken sections, are summarized in Table 1.

5. Structural Integrity Evaluation

The dynamic responses at fixed nodes caused by each broken section are summarized in Table 1 and the straight distances between the fixed node and the broken node are summarized in Table 2. The mean value of the effective stress denotes the mean value of the stress of $\zeta=1.576$ and $\zeta=0$. From table 1, the effective stress at each fixed node exceeds yielding stress 18ksi(650°F) and the ultimate strength, $\sigma_u=61.6$ ksi of SA304-376, except nodes 112 and 170.

Table 1 The dynamic responses at fixed and broken nodes
(final dynamic model)

Broken node	Fixed node	Effective stress		Velocity at broken node in/sec	Displacement
		Max.	Mean		
60	112	70	45	node 60, Max 150	Max 11"
	90	110	75		
140	186	140	100	node 140, Max 220	Max 20"
	170	200	125		
110	90	200	125	node 110, Mean 20	Mean 10"
111	90	210	155	node 111, Mean 260	Mean 18"
200	170	32	24	node 200, Mean 30	Mean 1.5"
201	170	34	20	node 201, Mean 50	Mean 6"

Table 2 The straight distance between fixed and broken nodes, mass.
(final dynamic model)

Fixed node	Node	Broken node	ℓ (in)	$m=1.586(\text{lbf/in}) \times \ell / g$
170	175	200	46	0.19
		201		
90	105	110	49	0.20
		111		
90	76	60	83	0.34
170	165	140	89	0.37

The bending moment for the yielding stress is given by $M_{yp} = \sigma_y I / c = 2.95 \times 10^4 \text{ lb-in}$. The bending moment for the plastic hinge, M_{ult} is given by $M_{ult} / M_{yp} = 16r_i(r_o^3 - r_i^3) / 3\pi(r_o^4 - r_i^4) = 1.07$ ($d_o = 2.875 \text{ in}$, and $d_i = 2.125 \text{ in}$).

The stress for the plastic hinge, is $\sigma_h = 1.07 \times 18 = 19.3 \text{ ksi}$. This result ignores the strain hardening effect. The next step is to compare total energy caused by thrust force with the energy it can absorb. The strain hardening exponent of SA 304-373 is assumed to be $m=0.2$, and ultimate strength, $61.6 \text{ ksi}(650^\circ\text{F})$. The stress-strain law of the material is $\sigma = K \epsilon^m$. The strain at the instability point of ductile material, ϵ_u , is given by $\epsilon_u \sim 0.2$. The material constant, K , is found from $\sigma_u = 61.6 \times 10^3 = K(0.2)^{0.2}$ and $K = 85000$. The toughness of pipe can be found from the relationship, $T = K(\epsilon_u)^{1+m} / 1+m = 10270 \text{ lb-in/in}^3$. The applied energy associated with the broken section can be found. When the node 60 is broken, the thrust force will be in the direction of z . However, the force in the x and y direction is assumed to be half of mean thrust force $P = 0.25(8900 + 5500) = 3600 \text{ lbf}$. The work done by thrust force, $U_1 = P \delta / 2 = 3600 \times 11 / 2 = 1.98 \times 10^4 \text{ lb-in}$, where 11 in is the displacement at node 60 as shown in table 1. The bending stress at fixed node 90 is found to be 110 ksi in table 1. The bending moment at node 90 is given by, $M = \sigma I / c = 1.80 \times 10^5 \text{ lb-in}$. The energy due to bending moment is, $U_2 = M^2 l / 2EI = 2.42 \times 10^4 \text{ lb-in}$, where the maximum length, 89 in , in table 2, is used conservatively. The total energy applied in the broken loop is $U_t = U_1 + U_2 = 4.4 \times 10^4 \text{ lb-in}$. The total toughness of the pipe is $T_t = T \times \pi(2.875^2 - 2.125^2) l / 4 = 3.0 \times 10^4 \text{ lb-in}$.

The applied energy $U_1=4.4\times10^4$ can be absorbed by the material within 2in. Therefore, fixed node 90 cannot be broken. If the node 140 is broken, the stress at the fixed node 170 is given as 200ksi and $\delta=20$ in table 1. A similar calculation is performed. The applied energy due to the thrust force is $U_1=3.6\times10^4$ lb-in. The applied energy due to the bending moment is $U_2=8.0\times10^4$ lb-in. The total applied energy is $U_1+U_2=12\times10^4$ lb-in. The energy, 12×10^4 lb-in, can be absorbed within the pipe length $l=12\times10^4/3\times10^4=4$ in. Therefore, node 170 can not be broken. Furthermore, the fixed points are not fixed exactly and partial energy can be released at the points. Therefore, even though the stress at the fixed points exceeds the ultimate strength, a double ended guillotine can not be expected.

Fig. 3 Response at broken section
(node 60, final dynamic model)
 $\alpha=36.191$, $\beta=0.01571$, $\zeta=1.576$

Fig. 4 Response at broken section
(node 60, final dynamic model)
 $\alpha=19.63$, $\beta=0.00263$, $\zeta=0.3$
 $f=6.3\text{Hz}\sim30\text{Hz}$

Fig. 5 Response at broken section
(node 60, final dynamic model)
 $\alpha=6.9512$, $\beta=0.002987$, $\zeta=0.3$
 $f=1.95\text{Hz}\sim30\text{Hz}$

Fig. 6 Response at broken section
(node 60, final dynamic model)
 $\alpha=0$, $\beta=0$, $\zeta=0$

Fig. 7 Stress response at fixed node 112(broken section 60)
(final dynamic model) definition of cases(Refer 3.2 in the text)

6. Conclusion

The static and seismic analysis using a static model of the fuel test loop(FTL), Korean multipurpose research reactor(KMRR), is performed and the results are compared with the results obtained by Battelle Northwest Research Institution. Dynamic analysis under the condition of a postulated FTL loop rupture is performed.

Six postulated rupture sections are assumed at the pipe connections in the FTL and these locations are chosen since static analysis shows that all the sections satisfy NUREG-0800 condition. A structural integrity evaluation of the ruptured FTL was performed. Through computer analysis and approximate engineering calculations, the following results are found:

- 1) The results obtained by the static model are compared with the results obtained by the Battelle Research Institution. The results are compatible with Battelle's results. Therefore, static analysis can be justified.
- 2) Through the final dynamic model it is found that all the fixed points can be plastic hinged, while double ended guillotine can not be expected.

7. References

- [1] Postulated pipe rupture ; Evaluation of thrust forces and jet impingement, including validity of utilization the leak before break, Battelle Northwest Research Institution, June, 1995 (classified document).
- [2] Design basis for protection of light water nuclear power plants against the effects of postulated pipe rupture, ANSI/ANS-58.2-1988.