Integrity Evaluation of Ice Plugging of Short Pipes

Yeong-Don Bak

Korea Hydro & Nuclear Power Co. Ltd
991 Sinam-Li Seosaing-Myeon Ulju-Gun Ulsan 689-880, Korea

Doo-Ri Yun, Sang-Moon Hwang and Beom-Soo Kang

Busan National University
San 30 Janjeon-Dong Gumjeong-Gu Busan 609-735, Korea

Abstract

In many special industrial fields such as nuclear power plants and chemical plants, it is often necessary to repair internal leaking pipe with hazardous or expensive fluid. A ice plugging by blocking an internal flow is considered as a useful method in that case. According to the pipe freezing guideline of nuclear power plant, the length of a freezing jacket must be longer than twice of the pipe diameter. However, for applying the ice plugging to short pipes which do not have enough freezing length, it is inevitable to use shorter jacket less than twice of the pipe diameter. In this study, the integrity evaluation for short pipes in the nuclear power plant is conducted by the finite element analysis. From the results, the ice plugging process in the short pipes can be safely carried out without any plastic deformation and fracture.

1. Introduction

It often occurs to repair the piping system with valves that can not be isolated due to internal leakage of the system fluid from the valve components failure or absence of isolation valves. Especially in the field of energy systems and the chemical industry, where the piping systems with hazard fluid are operated under high pressure and high temperature, the fluid internal leakage can cause plant shutdown. Also if the plant is stopped to repair system with failed parts, a heavy economic loss may be induced. Thus the ice plugging method to freeze and to block the internal fluid of the pipe by cryogenic refrigerant is introduced in order to restore the affected system while the plant is still operating or even though the plant is shutdown the system need not to be drained.[1] This method has been used in the nuclear power plants due to low cost and ease of use since it was first applied at 1940 in U.S. navy.[2 3] But according to the pipe freezing guideline[4] of the nuclear power plant, the length of freezing jacket must be longer than twice of the pipe diameter. However, for applying the ice plugging to short pipes which do not have enough freezing length, it is inevitable to use shorter jacket less than twice of the pipe diameter.

In this study, shorter jacket ice plugging experiment is performed to identify plug formation and plug integrity. And the integrity evaluation of pipe material which directly contacted with refrigerant is performed by the finite element analysis. Because of the cryogenic liquid injection, pipes are subjected to severe thermal stress due to rapid cooling down, resulting in large tensile stresses, which may lead to propagation of pre-existent flaws. Thus, in addition to the thermal stress analysis, the fracture analysis has been performed to calculate the stress intensity factors for the postulated internal circumferential semi-elliptic cracks in the pipe. Fig.1 shows a flow chart of the research which includes a series of ice plugging experiment and their finite element analysis.

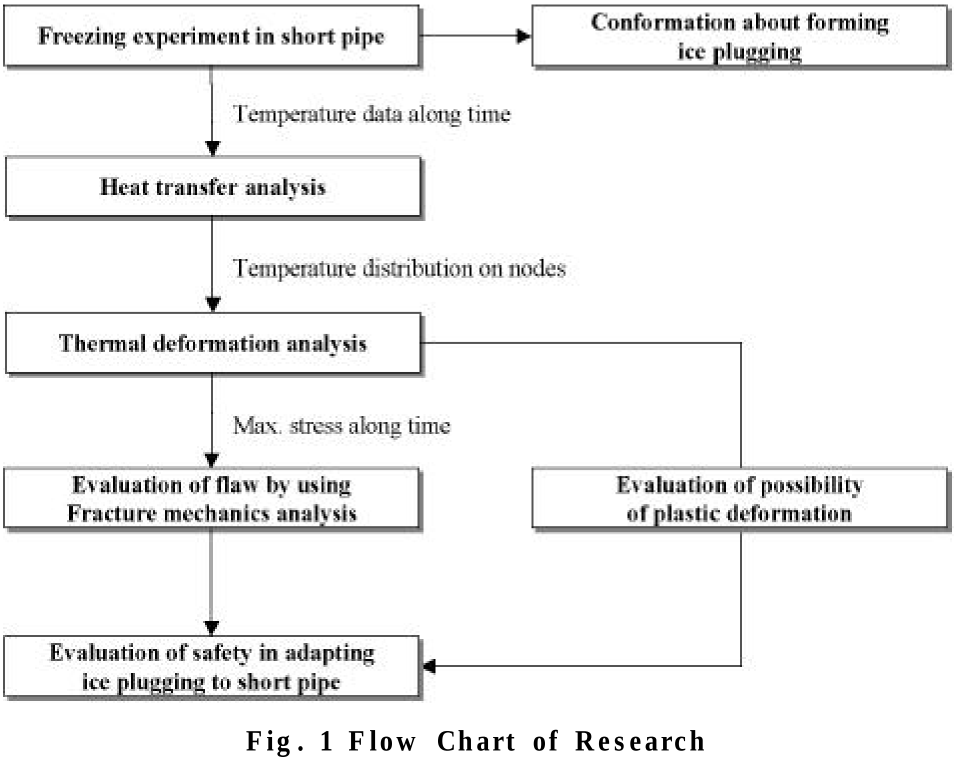
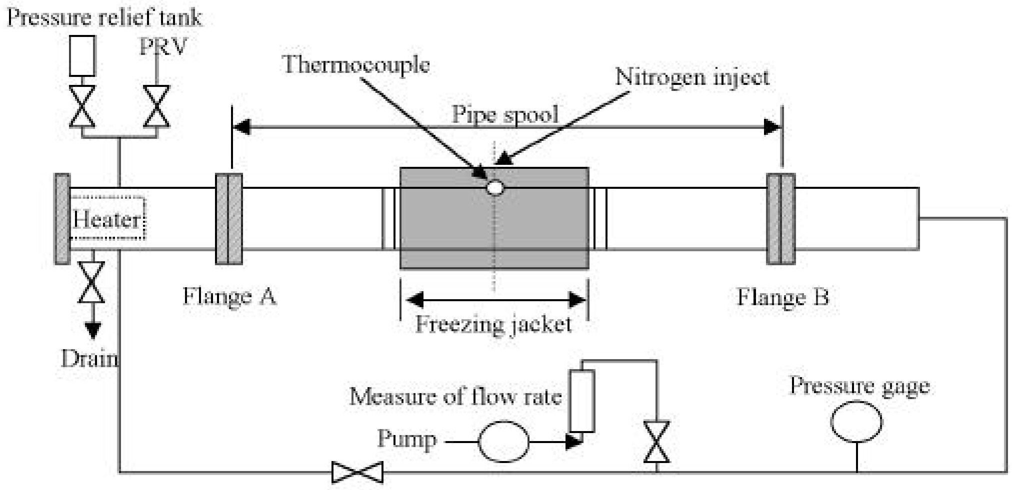


Fig. 1 Flow Chart of Research

2. Freezing Experiment

In this study, the experiment is performed to simulate feasibility of ice plugging task without system drain to repair some components. Only shorter jacket is suitable for the system piping configuration of actual work site in the A nuclear power plant as shown in Fig. 4. The system has atmospheric pressure, because the plant is under refueling outage. So the experiment is also implemented at atmospheric pressure. The temperature data for the stress analysis have been obtained from the experiment. A hydrostatic test is utilized to check the ice formation and the movement of ice plug in the shorter jacket pipes. The schematic of experimental set-up is shown in Fig.2, consisting of pipe, freezing jacket, heater, thermocouple, pressure gages and so on. Thermocouples are attached to the inside and outside of the center of pipe surface to measure temperature.



(a) Schematic of experimental set-up

(b) Side view (c) Front view

Fig.2 Experimental set-up

Tap water is employed as internal fluid, and liquid nitrogen is used as refrigerant. The jacket length around stainless steel pipe of 168mm outside diameter(schedule 80) is 150 mm and the room temperature is 14℃. The experiment is based on the following procedure. A sealing material is pasted around the jackets and two pieces of jackets are assembled around the pipe. A nitrogen container and jacket are connected with a hose for low temperature to provide enough refrigerant during experiment. The manifold valve attached to the nitrogen container is slowly released to prevent overflowing at the exhaust port of the jacket and to control flow rate to maintain the constant temperature inside the jacket, -196℃. After 40 minute, the ice plugging has been completed. The formation of the ice plugging in the shorter jacket pipe is evaluated using hydrostatic test. The pressure of 10 kg_f/cm^2 is applied for 10 minutes. Then the liquid nitrogen remaining in the freezing jacket is vaporized by closing the valve of the nitrogen container, and the jacket and the thermometer are removed from pipes. The temperature history is shown in Fig.3. From the hydrostatic pressure test, the ice plugging stands firmly without any collapse or movement. Therefore, it can be concluded that the ice plugging for the short pipe is successfully carried out. And melting time is observed to check how long exist the ice plug without any supply of refrigerant. This process is for the unexpected accident of interrupting refrigerant supply in the actual field. It took 13 hours and 15 minutes to melt the ice plug from stopping the refrigerant supply.

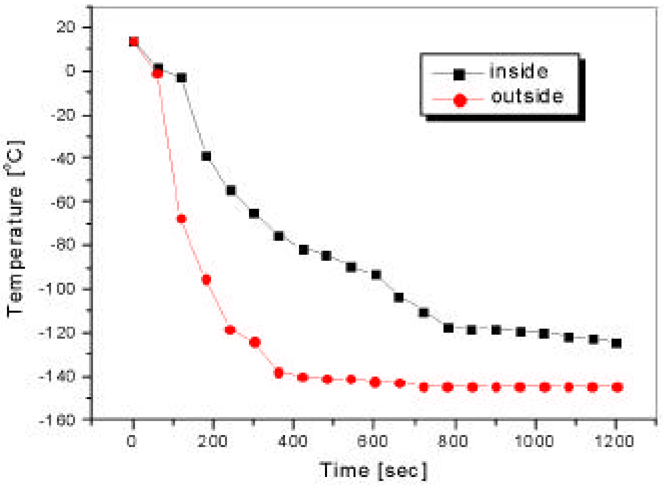
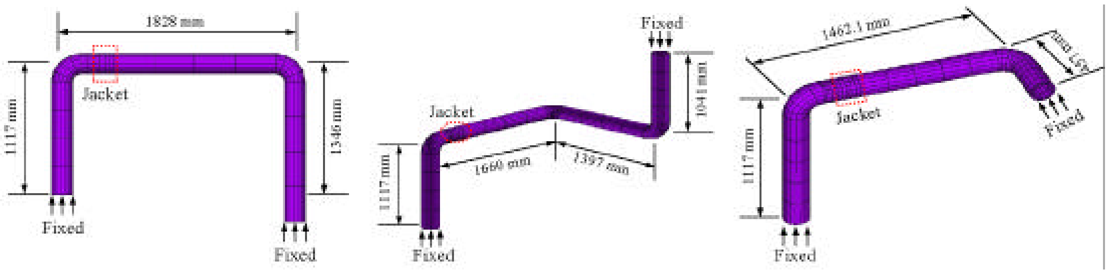


Fig.3 Temperature data of outside and inside surface

3. Thermal Analysis

3.1 Finite Element Model

The purpose of thermal analysis is to check whether the ice plugging in the shorter pipes can be safely performed without any plastic deformation, and to obtain input data for fracture analysis. The analysis is carried out for the pipes applied shorter jacket ice plugging used in nuclear power plant. These pipes can be classified into the three representative models as shown in Fig. 4. Eight-node isoparametric brick elements are used to build the finite element models. FE modeling of the pipes is constructed by using a commercial package of FE analysis, ANSYS 5.5.[5] The material properties and the geometries of pipe(schedule 80) are listed in Table 1.[6]



(a) Model A (b) Model B (c) Model C

Fig.4 Representative models for finite element analysis

Table 1. Material properties of stainless steel AISI 304 and AISI 1030 carbon steel

			AISI 304	AISI 1030
Material Properties	Yield Strength[4]	-196℃	433 MPa	≥1000 MPa
		-18℃	295 MPa	
		20℃	250 MPa	430 MPa
	Ultimate Strength[4]	-196℃	1,627 MPa	
		-18℃	862 MPa	
		20℃	590 MPa	620 MPa
	Young's Modulus		190 GPa	210 GPa
	Poisson's Ratio		0.3	0.27
	Mass Density		7,920 kg/m^3	7,870 kg/m^3
	Heat Conductivity	-173 ℃	9.2 W/m℃	53
		-73 ℃	12.6 W/m℃	52.5
		27 ℃	14.6 W/m℃	51.9
		127 ℃	16.6 W/m℃	50.7
	Thermal Expansion Coeff.	15℃~ -184℃	0.00167/℃	11.9e-6/℃ (R.T)
	Specific Heat	-173 ℃	272 J/kg℃	470
		-73 ℃	402 J/kg℃	474
		27 ℃	477 J/kg℃	477
		127 ℃	515 J/kg℃	486
Schedule 80	Outside Diameter	168 mm		
	Inside Diameter	157 mm		
	Wall Thickness	11 mm		

3.2 Initial and boundary conditions

- Initial temperature conditions:

In the thermal shock analysis, the initial temperature is 14℃ and the uniform temperature is applied to all nodes.

- Boundary conditions for heat transfer:

Due to heat transfer from refrigerant through the pipe material to internal fluid, selecting the heat transfer coefficient to apply at the pipe is very difficult. So the measurement of surface temperature from the experiment is the only useful method to consider the change of the fluid heat flux along with temperature and the latent heat effect by phase change. Temperature histories measured from the experiment are applied to the pipe of the jacket part as shown in Fig.5. The convection heat transfer coefficient of the atmosphere at room temperature is employed on the pipe area except jacket part as 15 $W/m^2 \cdot$ ℃.[7]

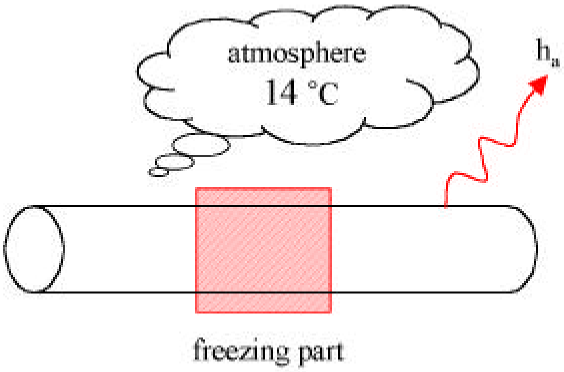


Fig.5 Boundary condition for thermal transfer

- Boundary conditions for thermal deformation:

The end sides of each pipe model are constrained by pipe supports as shown in Fig. 4.

3.3 Results and discussion

The equivalent stress distribution for model A is shown in Fig.6. Nodes (2 to 4) directly contacting with the liquid nitrogen and a node (1) located in the outside jacket are selected. The stress history of each node is shown in Fig.7. The maximum stress appears at the beginning stage due to extreme temperature variation, and then the stress converges to the steady state value. It can be seen that the maximum stress, 137 MPa, is below the yield strength of the pipe.

For models B and C, they show almost the same stress histories and the stress distributions. The stress analysis shows that the equivalent stress increases progressively to a maximum value due to large temperature difference in the beginning of the first freezing process. The maximum stress occurs around the freezing part directly contacting with the cryogenic nitrogen, and any plastic deformation or failure is not predicted, which indicates that ice plugging can be safely performed for the pipes applied shorter jacket ice plugging.

And the yield strength of the pipe material is increasing along with the temperature decrease as shown in the Table 1. The stress result occurred from the experiment is much less than the yield stress and increases conservatism.

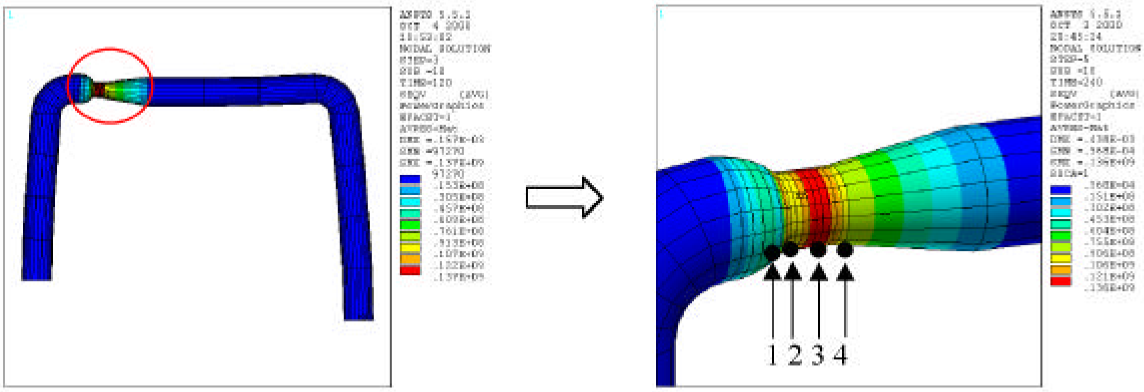


Fig.6 Equivalent stress distribution for model A

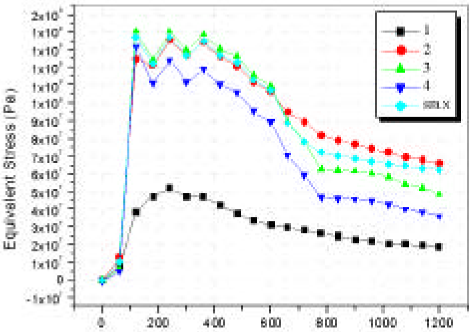


Fig.7 Stress distribution versus time

4. Fracture Analysis

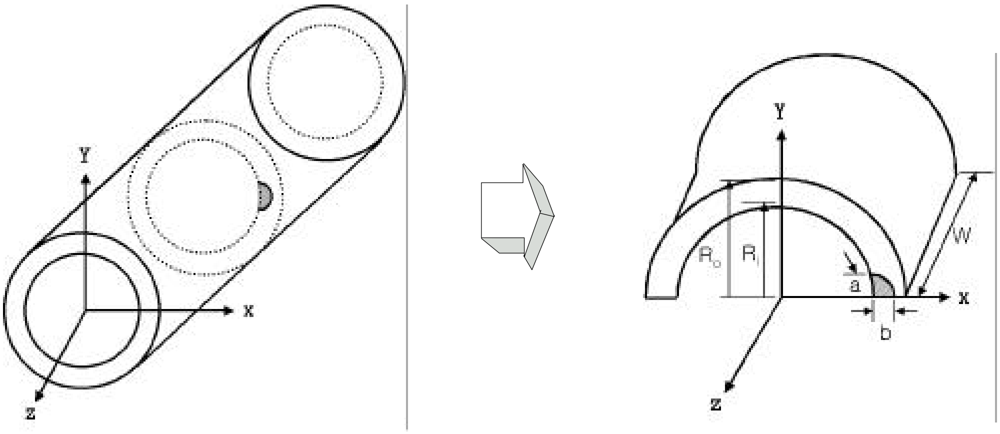
The existence of crack-like flaws can not be excluded in structural components. During the manufacturing and industrial applications of metallic pipes, there may exist some surface cracks which can not be detected by nondestructive testing and in-service inspection.[8 9] Noting that the fracture toughness of materials decreases at cryogenic temperature,[16] fracture analysis during ice plugging is necessary. In this paper, the possibility of crack initiation and propagation is evaluated using the finite element method. Since carbon steel pipe material is more susceptible to fracture than stainless steel at cryogenic temperature, this paper deals carbon steel pipe for fracture analysis instead of stainless steel. Material properties of the carbon steel pipe(AISI 1030) are shown in Table 1.

4.1 Finite Element Model

Due to the symmetry, only one-forth of the pipe with a circumferential crack at the center of the cylindrical portion is considered in the modeling as shown in Fig.8. The three-dimensional finite element models are prepared using the mixture of eight-nodes and twenty-nodes brick elements. The twenty-nodes elements are used near the crack to capture the steep stress gradient, while the eight-node elements are used at locations away from the crack zone. Sufficiently fine meshes are used near the crack tip. For elastic analysis, the singular elements are used to model around the crack front by shifting the mid-side nodes to the quarter position, which produce square root singularity along the crack. In most practical engineering accidents involving the metallic cylinders, the cracks are often found approximately to be semi-elliptical in shape.[10 11] The semi-elliptical crack and its coordinate system are shown in Fig.8 and the specification of the geometry is listed in Table 2. Fig.9 shows the detailed finite element modeling of the crack plane. The finite element analysis was carried out using the ANSYS program package.

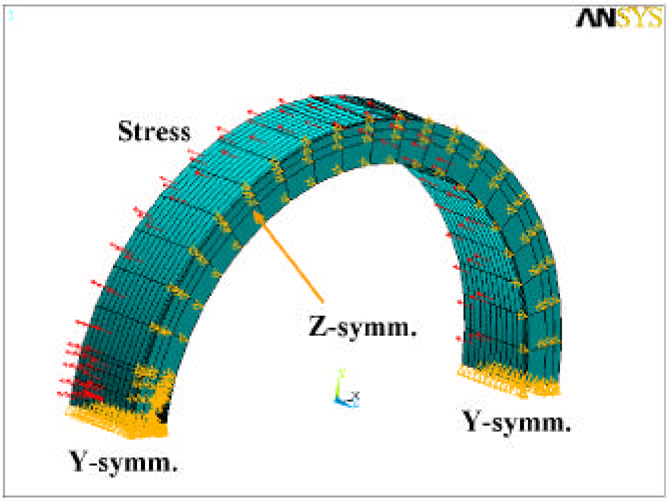
Table 2 Dimensions of semi-elliptic crack

R_o	84.14 mm
R_i	65.90 mm
W	30 mm
a (major)	8.25 mm
b (minor)	2.75 mm

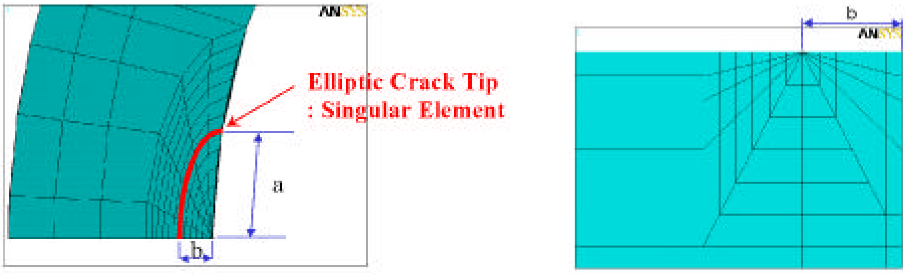


(a) Sub-model for fracture analysis (b) 1/4 FE model

Fig.8 Finite element model for fracture analysis



(a) Boundary condition for finite element model



(b) Front view (c) Bottom view

Fig.9 Finite Element modeling around crack plane

4.2 Stress Intensity Factor

The stress intensity factor has the three basic modes of fracture, an opening, a shearing and a tearing mode. Among them, the mode I (opening mode) is dominant under tension stress. In small scale yielding conditions, the plastic stress intensity factor is related to the elastic stress intensity factor. The stress intensity factor (K) of mode I is calculated from the J-integral value and given as

$$K = \sqrt{\frac{JE}{1 - \nu^2}} \qquad (1)$$

where υ and E denote Poisson's ratio and Young's modulus. The stress-strain state of the cylinder with a part-through defect has its peculiarities. The plane strain condition has been assumed for the crack front area close to the deepest point, whereas near the internal free surface of the cylinder it is generally believed that plane stress might prevail there. The J-integral is calculated in elliptic crack plane at deepest point using the following formulation by Shivakumar and Raju

$$J = \int_{\Gamma} \left(W \cdot dy - T_i \frac{\partial U_i}{\partial X_i} dS \right) \tag{2}$$

where Γ, W, T_i, U_i and S denote any path surrounding the crack tip, strain energy density, traction vector, displacement vector and distance along the path.[12 13] The J-integral is a path-independent line integral that measures the strength of the singular stress and stain near a crack tip. The J-integral calculated along the crack front will represent the average J over each domain. Therefore the effect of mesh sensitivity on the calculated J-integral values is significantly reduced at the crack front.[14 15]

4.3 Results and discussion

In this paper, the semi-elliptical internal surface flaw in a carbon steel pipe under tension loading is considered. The resulting stress distributions along the crack front are shown in Fig.10. It shows that the stress increases as approaching to the deepest point. Then the stress at the deepest point is only considered because it is proportional to the stress intensity factor. The transient stress intensity factor distribution along with temperature is computed as shown in Fig.11. It shows the comparison between the stress intensity factor (K_I) obtained from simulation and the fracture toughness (K_{IC}) for the material. It can be concluded that the stress intensity factor is below the fracture toughness.

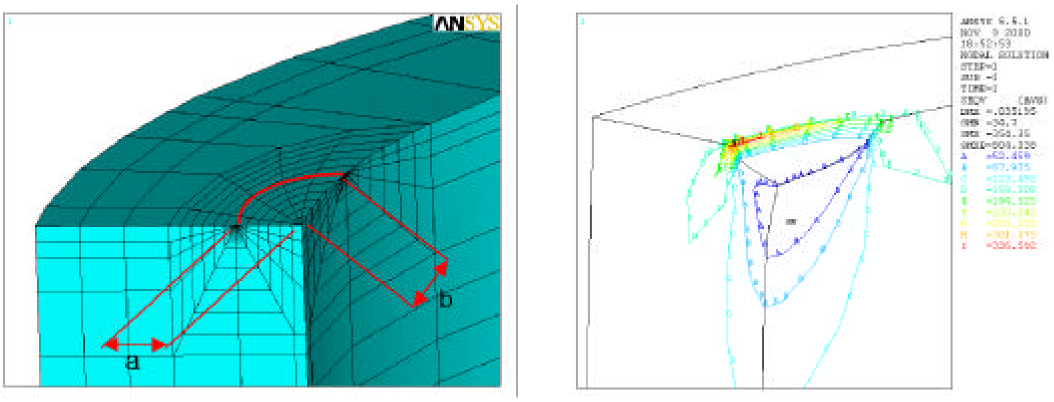


Fig.10 Stress distribution around crack tip

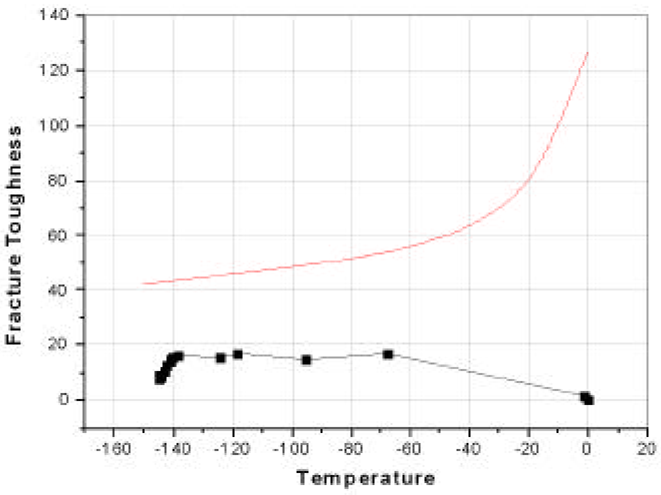


Fig.11 Comparison between stress intensity factors and fracture toughness

5. Concluding Remarks

Three-dimensional finite element analyses have been performed for integrity evaluation in ice plugging of short pipes. In this study, input codes for the thermal deformation analysis by APDL(Automatic Parameter Design Language) of ANSYS has been developed to evaluate the structural integrity and reliability of pipes with various crack size by nondestructive inspection. From the results, the ice plugging process in the short pipes can be safely carried out without any plastic deformation and fracture. In order to evaluate the ice plugging procedure more clearly, further study is needed to provide a quantitative analysis for the change of factors such as crack size, mechanical material properties and stress redistribution due to the plastic strain. The simulation results executed in this study is expected to make the maintenance of piping system in nuclear power plant using ice plugging method more efficiently.

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