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Finite Element Analysis of Pipe Whip Restraint Behavior Under Jet Thrust Forces

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유체 분사 추진력을 받는 배관 휩 구속장치 거동에 관한 유한요소해석

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Abstract

Many types of pipe whip restraints are installed to protect the structural components from the anticipated pipe whip phenomena of high energy lines in nuclear power plants. It is necessary to investigate these phenomena accurately in order to design the pipe whip restraints properly and/or to evaluate the acceptability of the pipe whip restraint design. Various research programs have been conducted in many countries to develop analytical methods and to verify the validity of the methods.

In this study, various types of finite elements in ANSYS [1], the general purpose finite element computer program, was used to simulate the postulated pipe whips to obtain impact loads and the calculated results were compared with the specific experimental results from the sample pipe whip test for the U-shaped pipe whip restraints. Some calculational models, having the gap element or the spring element between the pipe whip restraint and the pipe line, give reasonably good transient responses of the restraint forces compared with the experimental results, and could be useful in evaluating the acceptability of the pipe whip restraint design.

요 약

원자력 발전소에서는 고에너지배관이 파단되는 가상 배관 휩 현상으로부터 구조물을 보호하기 위하여 많은 종류의 배관 휩 구속장치(Pipe Whip Restraint, PWR)가 설치되어 있다. 이 배관 휩

구속장치를 보다 합당하게 설계하거나 배관 휩 구속장치의 설계타당성을 평가하기 위하여 배관 휩 현상을 자세히 관찰하는 것이 필요하다. 이와 같은 이유로 배관 휩 현상을 해석하는 방법 개발과 개발된 방법의 타당성을 입증하기 위한 다양한 연구 프로그램이 여러나라에서 수행되어 왔다.

본 연구에서는 배관 휩 구속장치에 가해지는 충격하중을 계산하기 위해 범용 유한요소 전산 프로그램인 ANSYS내의 여러 형태의 유한요소들을 이용하여 가상 배관 휩 현상을 모의했으며 계산 결과는 U 자형 배관 휩 구속장치를 갖는 배관계통의 배관 휩 모의시험으로부터 구해진 대상 실험 결과와 비교, 검토되었다. 배관 휩 구속장치와 배관 사이의 갭요소나 스프링요소를 갖는 계산모델의 일부는 해당 실험결과와 비교해 볼 때 배관 휩 구속장치에 걸리는 인장력을 사고기간 동안에 잘 모의함을 보여서 배관 휩 구속장치의 설계타당성을 평가하는데 유용 할 것으로 판단된다.

1. Introduction

Pressurized water reactor power plants have many types of pipe supports. Pipe whip restraints, a kind of them, are installed in order to protect the structural components from the dynamic effects of postulated pipe ruptures occuring at any location in high energy lines to which "Leak Before Break(LBB)" concept cannot be applied.

Experimental and analytical studies of the pipe whip phenomena have been conducted in many countries to investigate the pipe whip phenomena accurately.[2]-[5] The purpose of those research programs was to develop analytical methods of pipe whip phenomena and to verify the validity of the developed methods. To investigate pipe whip phenomena, designers and reviewers should perform three main evaluations as follows ; (1) Evaluation of fluid dynamic (blowdown) forces acting on the ruptured pipe which are induced from a double ended guillotine break. (2) Evaluation of system response to determine whether the pipe rupture will result in pipe whip or not. (3) Evaluation of pipe whip behavior(pipe movement, impact loads, restraint strains, etc.) when pipe whip is anticipated to occur.

T. Yano et al.[6] had performed the fluid jet test whose pipe specimen had the same size as that in this pipe whip analysis in order to obtain the jet thrust force induced through the pipe break point regarding item (1) in the above evaluation categories.

Recently, several kinds of the general purpose finite element computer programs have been developed to solve the elastic–plastic stress analysis problems, and those program are used in designing the components of a nuclear power plant and in reviewing the design materials for those components.

The objective of this study is to develop the evaluation method for the mechanical integrity of the pipe whip restraint regarding item (3) in the above evaluation categories. Specifically, various types of finite elements in the code were used to simulate the postulated pipe whips. Calculated values such as restraint strains, restraint forces and impact times were compared with the corresponding experimental results which were obtained by S. Ueda et al[7].

2. Numerical Illustration

The purpose of this dynamic analysis was to simulate the cantilever type pipe whip experiment performed by S. Ueda et al.[7] in 1983. That experiment was performed on the dynamic behavior of pipe and restraints under loss of coolant accident contained in a boiling water reactor. Fig.1 shows a 4–inch pipe whip test facility of the cantilever type pipe whip tests. The test pipe was connected to the pressure vessel which contained pressurized water and was fixed on a location of 3,000 mm from the free end of the test pipe by the pipe support. A rupture disk as shown in Fig.1 was welded at the free end of the test pipe in order to simulate the instantaneous pipe rupture by breaking it using an arc electrode. The saturated water was circulated through a warming–up line to keep the system temperature uniform. In order to minimize the constraint of the warming–up line against pipe whip motions, a flexible tube was used as a part of the warming–up line.

Table 1. Experimental Condition of Pipe Whip Test

Test Case Number	1	2	3	4	5
Pressure, Temp	6.57 MPa, 285 ℃				
Restraint Type	U–type, 8mm diameter				
Overhang Length, mm	400	400	250	400	400
Clearance, mm	30	100	100	50	100

The pipe whip tests were performed under boiling water reactor operational condition as summarized in Table 1. The test pressure is 6.57 MPa and the test temperature is 285 ℃. The overhang length of 250 and 400 mm and the clearance of 30, 50 and 100 mm were chosen as the experimental parameters, respectively. The overhang length(OH) is the distance between the center of four restraints and the pipe end. The clearance(CL) is the distance between the outer surface of the pipe specimen and the inner surface of the restraints. The effective clearance C_E is the distance between the outer surface of the pipe specimen and the inner side of the restraint when the restraints work as load carrying devices. Four pipe whip restraints were set on a restraint support as shown in Fig.2. The bearing plates were attached on the inside surface of the restraint bars so that the pipe specimen should contact directly to the restraints after the jet thrust force was initiated. In this test, the clearance equals to the effective clearance because the bearing plates keep the inside diameter of the restraint uniform during pipe whip event.

The pipe specimen and the restraints were fabricated from type 304 stainless steel. The pipe specimen used in this test were 4,500 mm in length and 114.3 mm in diameter and 8.6 mm in thickness.

The jet thrust forces obtained from the fluid jet

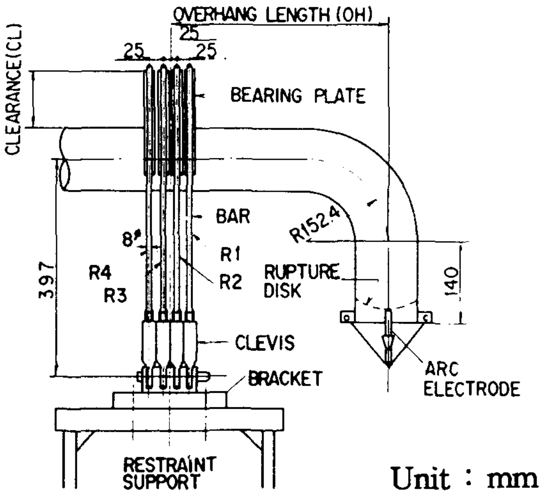

Fig. 1. Schematic of Test Equipment Analyzed in This Study.

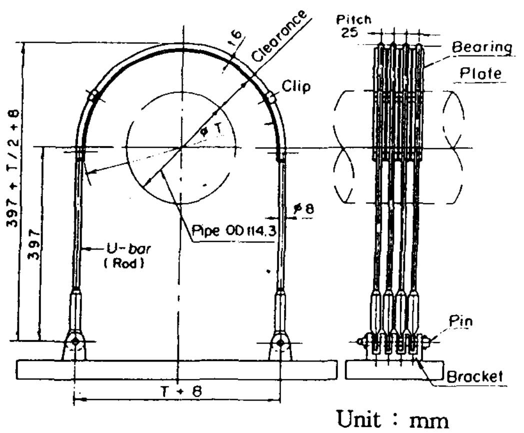

Fig. 2. Pipe Whip Restraint for the 4–Inch Diameter Test.

test[6] were simplified as Fig.3 and inputted as a table form in the calculation.

Stress–strain relations of the pipe specimen and the restraints were inputted as the table taken from the IPIRG program[8] upon which the dynamic loading effect was considered, which is shown in Fig.4. The yield strengths of the pipe specimens and the restraint materials are shown in Table 2. The ultimate strength was selected as 91 percents of the value tested at quasi–static loading rate.

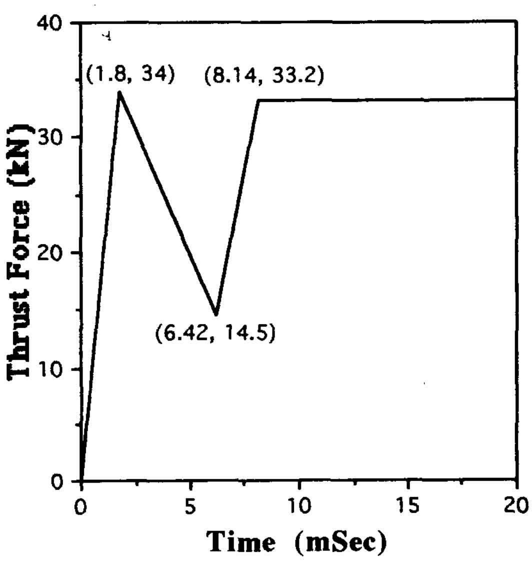

Fig. 3. The Blowdown Thrust Force–Time History Obtained From the Jet Discharge Test.

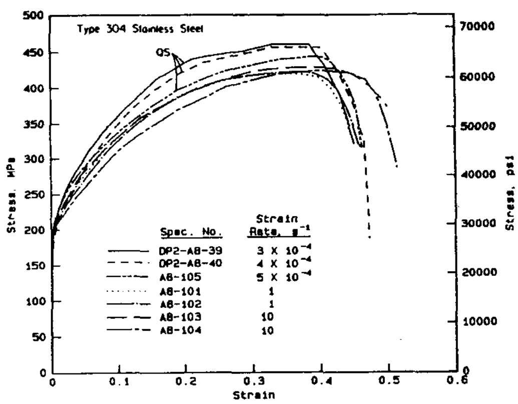

Fig. 4. Engineering Stress–Strain Curves for Type 304 Stainless Steel Pipe.

Table 2. Mechanical Properties of Pipe Specimen and Restraints

	Temp.	Y. S.	UTS
Pipe	R. T	287 MPa	560 MPa
	285 ℃	192 MPa	418 MPa
Restraint	R. T.	362 MPa	541 MPa

Y. S.–Yield Strength
UTS–Ultimate Strength
R. T.–Room Temperature

Fig.5 shows the finite element model of the 4–inch diameter pipe whip test. All the pipe specimen portion from the free end to the fixed pipe support was modelled as a pipe element which was filled with pressurized water in the calculation. Four pipe restraints were modelled as a spar element in the calculation. The restraint stiffnesses were set to very small values in the axis directions of the pipe specimen in order that the bending phenomena of the restraints were simulated along the axis of the pipe specimen after the impact. The clearance portion was modelled as an interface(gap) element or a spring element. The gap stiffness or the spring constant of the element was selected so that the actual behavior of the clearance could be simulated in more proper way. In the clearance portion, the pipe specimen would move without any restriction for a few milliseconds and then would show very complicated motion after the pipe specimen contacts to the restraints. The motion is that the pipe specimen would contact to the restraint and then be separated from the restraints, repeatedly.

To simulate the effect of damping factor of the pipe specimen on the velocity of the pipe specimen, one percent of critical damping was selected from the tablc in Refernce[9].

3. Numerical Results and Discussion

In this section, the analytical results of pipe whip behavior are described and compared with

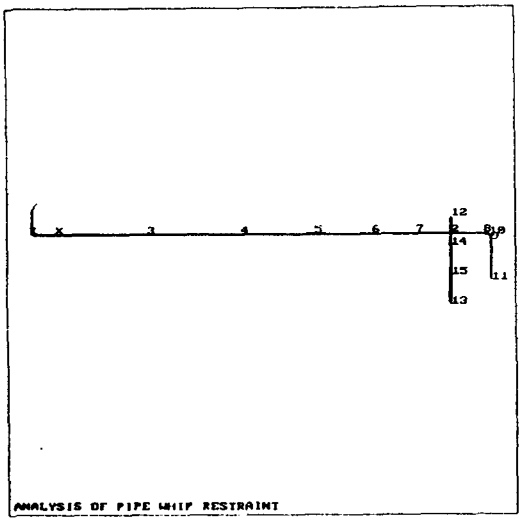

Fig. 5. The ANSYS Finite Element Model of the Pipe Whip Test.

the experimental results of 4-inch diameter pipe whip test[7]. An example of the analytical model of pipe whip behavior is shown in Fig.5. The pipe specimen is modelled with the pipe element whose material behavior is assumed to be bilinear elastic-plastic. In order to analyze the restraint force accurately, it is necessary to make a model of the restraint which simulate an U-shape geometry and has a gap between the modeled restraint and the pipe specimen, but such a complicated modelling needs lots of computing time, and so the restraints are modelled as a single spar element.

The calculated pipe deflection at the restraint and the restraint deflection versus time and the pipe impact force at the restraint versus time are shown in Fig.6 and Fig.7 respectively for the case of 400 mm in overhang length and 30 mm in clearance. After the pipe collides with the restraint, the pipe moves together with the restraint. The analytical results are valid until the restraint deflection reaches the first peak value after the pipe collides with the restraint. These are invalid afterward because the interface(gap) element or spring element cannot represent the real unloading hysteresis. But these analytical results are useful because the important quantities such as the maximum restraint deflection, the maximum restraint force appear until the first impact.

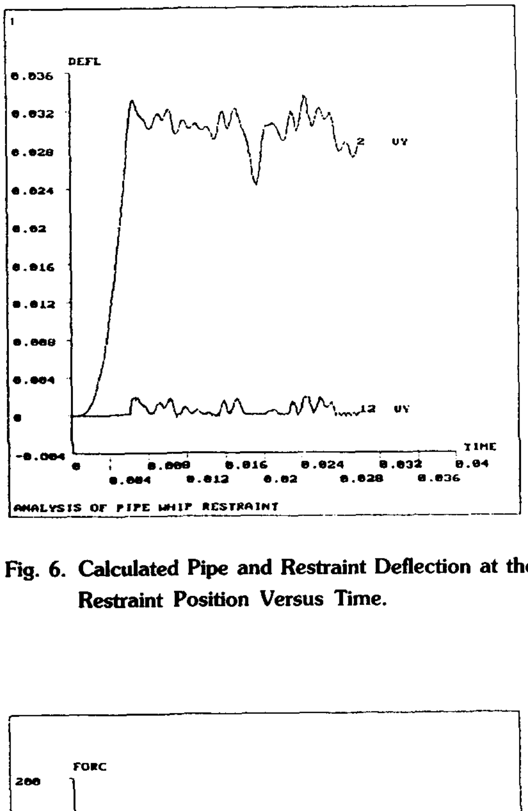

Fig. 6. Calculated Pipe and Restraint Deflection at the Restraint Position Versus Time.

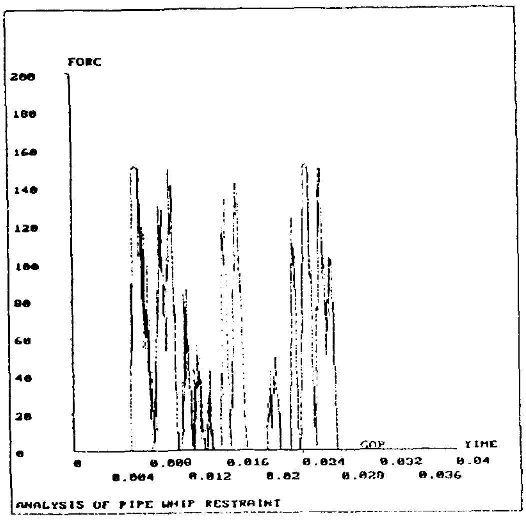

Fig. 7. Calculated Restraint Force Versus Time.

In Fig.8, the analytical results are compared with the experimental ones of Reference [7] for the various clearences at the overhang length of 400 mm. The calculated value is the maximum strain of the single spar element representing four restraints. The experimental value is the average of the first peak strains which were measured at the straight portion of four U-shape restraints in the corresponding experiment. The calculated values are larger than the experimental values, and the difference is the largest for the clearance of 50 mm. The calculated values and the experimental values of the maximum restraint strain are very close each other for the clearance of 30 and 100 mm. The experimental value of the maximum restraint force was measured only at the clearance of 50 mm, which was lower than the calculated value. The calculated results show that the maximum restraint strain increases with increase of the clearance, while the maximum restraint force does not depend on the clearance. This means that the kinetic energy of the pipe specimen is absorbed by the plastic deformation of the restraints and the pipe specimen, and the restraint force is mitigated. Therefore, it is understood that the plastic design method of the restraint is useful.

The calculated impact time corresponds to the time when the pipe deflection at the restraint reaches the initial clearance as shown in Fig.6 while the experimental impact time was the duration from the rising time of the accelerometer at the pipe end to the rising time of the strain gauge mounted on the apex of the restraint. The calculated impact time is shorter than the experimental results, and the difference increase with increase of the clearance.

In Fig.9, the analytical results are compared with the experimental results of the restraint strains, the restraint forces, the impact times for the various overhang length at the clearance of 100 mm. The calculated maximum restraint strain is larger than the experimental result, and the calculated value and the experimental value is the largest for the overhang length of 400 mm. This means that the kinetic energy of the pipe speci-

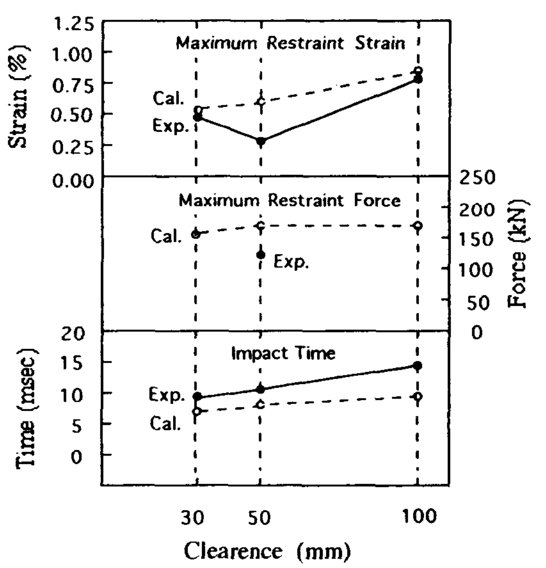

Fig. 8. Comparison Between Experimental Results and Analytical Results Against Clearance.

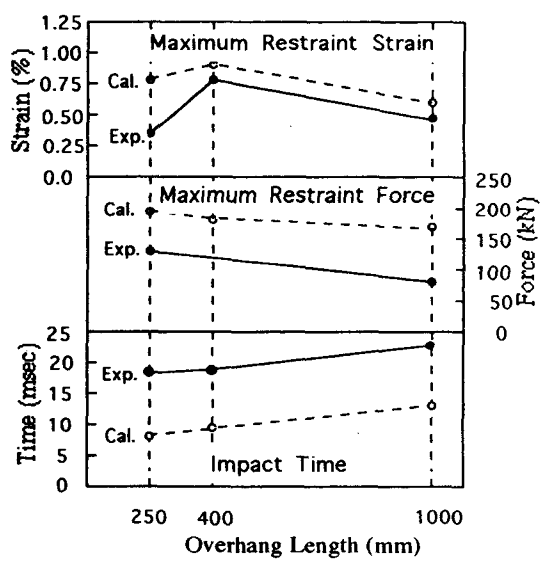

Fig. 9. Comparison Between Experimental Results and Analytical Results Against Overhang Length.

men is effectively absorbed by the restraints which are installed at the overhang length of 400 mm. The calculated maximum restraint force is larger than the experimental result, and both of them decrease with increase of the overhang length. The calculated impact times are shorter than the experimental result, and they increase with increase of the overhang length. This means that the impact velocity of the pipe at the restraints decrease with increase of the overhang length.

The calculated results give slightly conservative values, so that the calculational method could be useful in evaluating the mechanical integrity of pipe whip restraints during the pipe rupture event. The calculated results give very good agreement with the experimental values due to the following reasons compared with the calculated results of the former research[1].

(1) Effect of damping factor of the pipe specimen is considered on the velocity of the pipe specimen.
(2) Effect of dynamic loading of pipe specimen and restraints is considered.
(3) Bending of the restraints is simulated at the direction of the axis of the pipe specimen after the impact.
(4) Pipe specimen, restraints and gap are modelled properly. Gap is modelled as interface element or spring element which have the proper stiffness or the proper spring constant, while the nonlinear elastic behavior had been assumed for the restraint material in order to incorporate the effect of the clearance in the former research[7]. Pipe specimen is modelled as pipe beam element which is filled with water in the calculation.

The small difference between the analytical results and the experimental ones seems to be due to constraint of the warming–up line against the pipe motion at the end of the pipe specimen, absorption of kinetic energy of the pipe specimen by the bearing plates in the corresponding experimental and calculation errors and instrumentational errors.

4. Conclusions

In this study, various finite element models were selected to simulate the postulated pipe whips in proper way and the calculated results were compared with the specific experimental ones from the corresponding pipe whip test. The following conclusions are obtained from this analysis.

(1) The calculated results give good transient response of the corresponding experimental results.
(2) The calculated results of maximum restraint force and maximum restraint strain are slightly larger than the experimental results. This means that the calculated results give slightly conservative prediction of pipe whip phenomena, so that the calculational method used in this study can be useful in designing pipe whip restraint and in evaluating the validity of the pipe whip restraint design.
(3) The calculated maximum restraint force does not depend on the clearance and the overhang length. It means that the plastic design method of the restraints will be useful.
(4) The calculated maximum restraint force and restraint strain are the first peak values of the restraint force and the restrain strain just after the impact. Since the corresponding experimental results show the same trends as the calculated ones, the first peak value of the calculated restraint force and strain are very important values in pipe whip event analysis.

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