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Development of thermal fatigue evaluation methods of piping systems

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ABSTRACT

Nuclear piping has various kinds of thermal fatigue failure modes. Main causes of thermal loads are structural responses to fluid temperature changes during plant operation. These phenomena have complex mechanisms and many patterns, so that their problems still occur in spite of well-known issues. The guideline of the JSME (Japan Society of Mechanical Engineering) for estimation of thermal fatigue failures in piping system is employed as Japanese regulation. To improve this guideline, generation mechanisms of thermal load and fatigue failure have been investigated and summarized into the knowledgebase. And numerical simulation methods to replace experimental based methods were studied.
Furthermore, probabilistic failure analysis approach with main influence parameters was investigated to be applied for the plant system safety. Thus, based on the knowledge, estimation methods revised from the JSME guideline were proposed.

KEYWORDS

Fatigue, Thermal Stress, Thermal Hydraulics, Numerical Simulation, Piping, Nuclear Reactor Plant

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1. Introduction

In spite of well-known issues from past time, thermal fatigue failures occur in nuclear power plants [1]. One of the most major reasons is that the issue is caused by complex interactive phenomena among thermal hydraulics, structural physics and material properties.

Kinds of thermal fatigue phenomena experienced in the world can be summarized as Fig. 1. From view point of thermal loads, they are categorized into high and low temperature fluid mixing, thermal stratification, system thermal transients and others[2]. Among them, “a. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid” and “b. Thermal fatigue by temperature stratified layer at stagnant branch pipe” (Fig.2) are recognized as important modes in viewpoint of their frequency and difficulties of counter measurements, and their evaluation procedures were developed as the JSME(Japan Society of Mechanical Engineering)'s Guideline for Evaluation of High-Cycle Thermal Fatigue of a Pipe [2].

Japanese regulation for thermal fatigue issues mainly based on the JSME guideline. Recently, this guideline is required to have reasonable safety margin and accountability. Clarification of influence of fatigue issues on plant system safety is expected to the guideline due to the Fukushima-daiichi nuclear plant accident.

From above background, the NRA (Nuclear Regulation Authority) project has launched. The objectives of this project are the clarification of thermal loads by fluid temperature change and failure mechanism, the proposals of rational evaluation methods for the JSME guideline, the development of numerical simulation methods of thermal fatigue phenomena and the study of failure probability evaluation methods for plant system safety.

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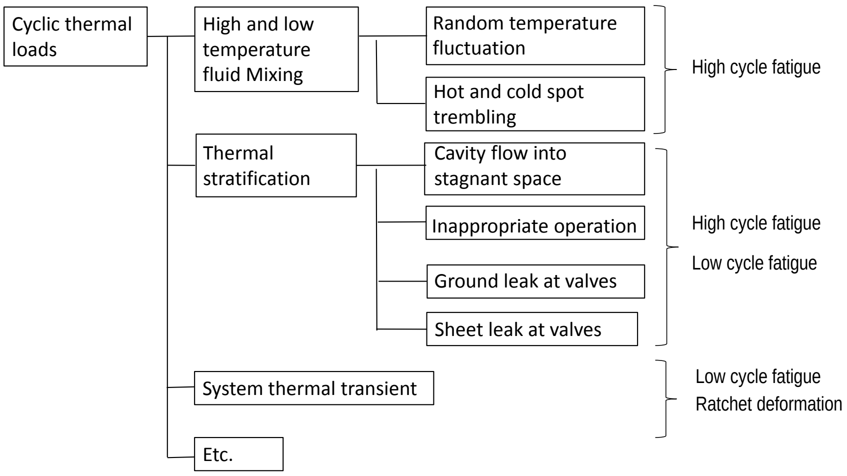
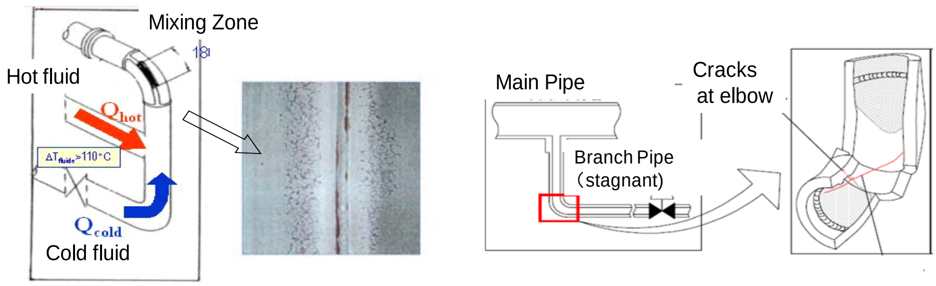


Fig.1 Classification of thermal loads and induced failure modes in nuclear pipes



A. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid

B. Thermal fatigue by temperature stratified layer at stagnant branch pipe

Fig. 2 Typical thermal fatigue failure modes dealt with JSME guideline

2. Clarification of mechanism on loadings and failure

2.1. Loading mechanism

"a. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid"

Thermal load and failure mechanism at mixing zone of hot and cold fluids can be decomposed into elemental processes as Fig.3. Dominant parameters during loading process from (A) to (D) are attenuation factors. Therefore clarification and consideration of their mechanism are main issues to rationalize evaluation methods. Authors have studied frequency dependent attenuation mechanism ([4] for example). At the stage (E), multi-axial loadings and valuable stress amplitudes become main factors especially for thermal fatigue strength. Conditions at weldment, surface roughness and deterioration due to aging have influence on fatigue strength. These are studied though international cooperation especially with France who experienced thermal fatigue failure[1].

"b. Thermal fatigue by temperature stratified layer at stagnant branch pipe"

Thermal load and failure mechanism at elbows of stagnant branch pipes due to temperature stratification layer have not been clarified compared with above mixing pipes. When main pipes connect to stagnant branch pipes, parts of main flow can invade into the branch pipe (so called cavity flow). In the case that main flow temperature is higher than branch pipes, temperature stratified layer appear and their oscillations induce thermal fatigue on the branch pipes. Especially, it was known that significant unstable oscillations and large fatigue damage can be induced when stratified layer exists around elbows. Above mechanism was roughly understood as Fig.4. Current study focusses on evaluation of stratified layer location [5].

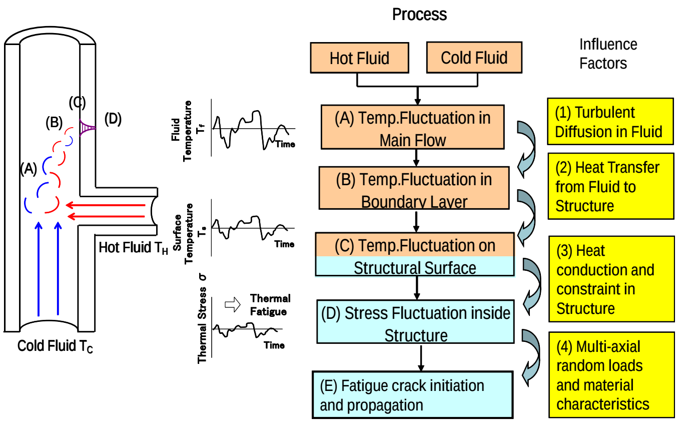


Fig.3 Thermal load and failure mechanism at mixing zone of hot and cold fluids

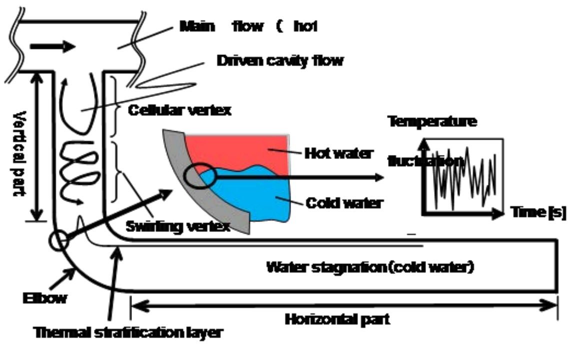


Fig.4 Thermal load and failure mechanism at elbows of stagnant branch pipes due to temperature stratification layer

2.2. Failure mechanism

Concerning failure mechanism, studies focus on particular issues of thermal fatigue induced by fluid temperature change. One is strength of multiplication of high cycle and low cycle fatigue from various kinds of thermal hydraulic phenomena during plant life. To clarify above mechanism, variable amplitude fatigue tests were conducted. Their results clarified sensitivities of lower load limit of crack propagation to loading histories. Details of fatigue strength study are introduced by the associated paper [6]. Another fatigue strength issue is multi-axial stress problems with proportional and non-proportional loadings. Fig.5 shows history of principal stress components on the piping inner surface at mixing zone of hot and cold fluids. There are somewhat non-proportional characteristics. Equi-bi-axial fatigue tests of circular plates under alternating air pressure were conducted as Fig.6 [7]. In the case of proportional loadings, bi-axial fatigue strength can adequately be evaluated by the equivalent stress [7]. On the other hand, non-proportional loadings reduce fatigue strength, the most significant case of fatigue life is less than 10% of uniaxial loading one [8]. Therefore quantification method of non-proportion degree and fatigue strength with this degree is under development for the realistic loadings as Fig.5.

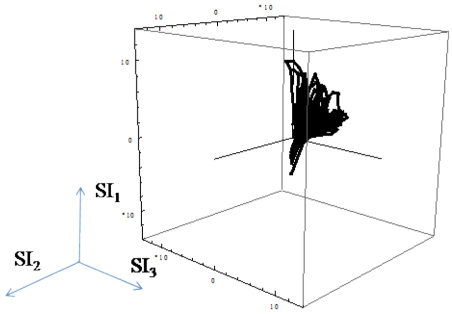


Fig.5 History of principal stress components at mixing zone of hot and cold fluids

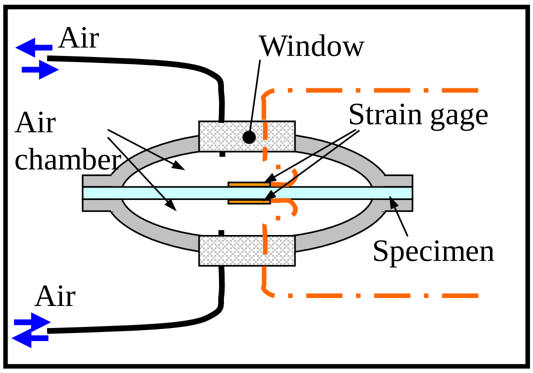


Fig.6 Equi-biaxial fatigue tests of circular plates under alternating air pressure

3. Proposals for the JSME guideline

A thermal stress prediction method of the JSME guideline for "a. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid" is basically the static equation which calculates stress from temperature amplitude and material parameters as Eq.(1).

$$\Delta\sigma = F\frac{E\alpha}{1-\nu}\Delta T \qquad \Delta T = T_H - T_L \tag{1}$$

Where E is Young's modulus, α is thermal expansion factor, ν is Poisson's ratio and ΔT is temperature range between T_H and T_L. For consideration of attenuation factors in Fig.3, a constant design factor F is employed.

Actual thermal stress strongly depends on frequency of fluid temperature fluctuation as in Fig.7[4]. In this figure, the horizontal axis is non-dimensional frequency and the vertical axis is the stress conversion ration from fluid temperature range. Thermal stress is attenuated due to temperature homogenization in low frequency range and heat transfer loss in high frequency area. These effects were experimentally validated [2]. For considering frequency effect on thermal stress, the Power Spectral Density (PSD) Method was developed [4,9 for example]. Furthermore, an equivalent stress amplitude method with constant frequency is proposed to simplify fatigue damage calculation process from the PSD of thermal stress. In Fig.9, an equivalent stress amplitude is the root mean square of the zero order moment of random signal $\sqrt{\mu_0}$ and frequency ν_0 can be derived from statistical theory [9]. Design margin was compared between the most precious evaluation method of the JSME guideline (Step4) and the proposed equivalent stress amplitude method. The result shows that the proposed method has almost homogeneous (around 10 times of fatigue damage factor) design margin than the JSME guideline (change from 10 to 20,000) as Fig.10[10], because the proposed method considers frequency dependency of thermal stress as Fig.7.

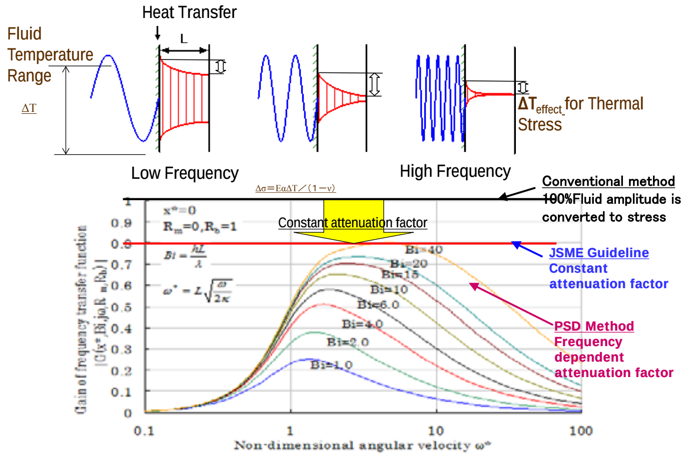


Fig.7 Frequency response of thermal stress

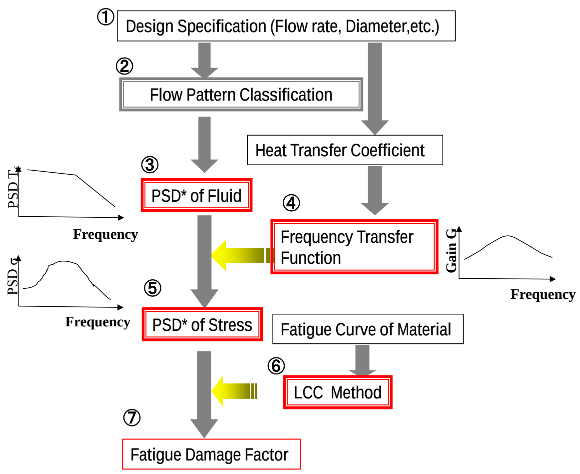


Fig.8 PSD Method for considering frequency effect

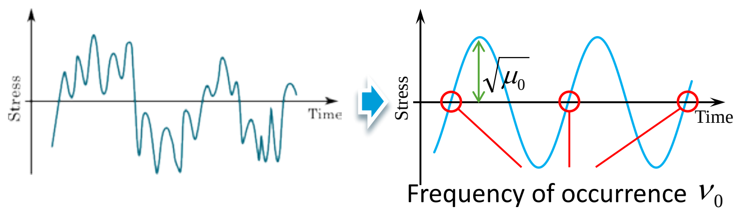


Fig.9 Proposal of Equivalent stress amplitude with constant frequency

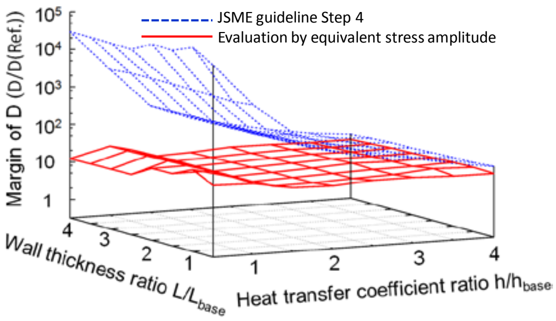


Fig. 10 Comparison of Fatigue strength margins between JSME guideline and the proposed method

(Impinging jet, ΔT=150deg)

Thermal stress mechanism of “b. Thermal fatigue by temperature stratified layer at stagnant branch pipe” is different from “a. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid”. Temperature oscillation with the fixed layer model (Fig.11) is similar to the later problem. Temperature oscillation with the moving layer model (Fig.12) can approximate the former problem. Fig.13 compares thermal stress response between the fixed and moving layer model. Thermal stress of the moving layer model is higher than the fixed model in both low and high frequency area. The frequency response function of thermal stress for the proposed PSD method can be applied for the fixed model, however underestimates for the moving model. To apply the PSD method to “b. Thermal fatigue by temperature stratified layer at stagnant branch pipe”, improved frequency response functions of thermal stress were studied.

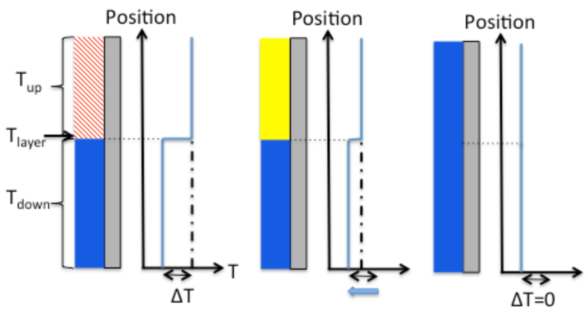


Fig.11 Temperature oscillation with the fixed layer model

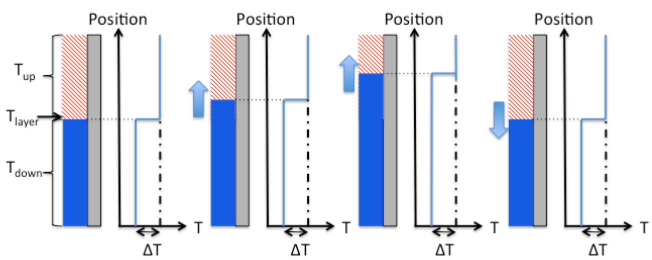


Fig.12 Temperature oscillation with the moving layer model

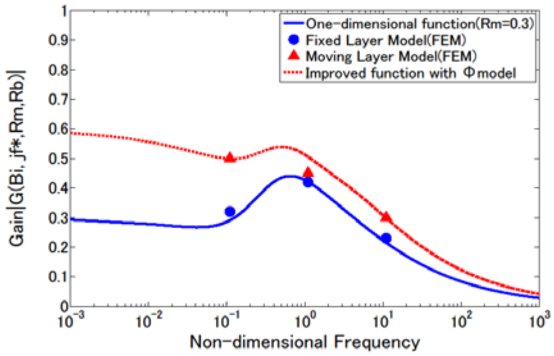


Fig.13 Comparison of thermal stress response between the fixed and moving layer mode

4. Development of Numerical simulation method

The JSME guideline was basically developed from experimental data and static equations. To replace experimental approach by simulation base one, fluid-structure numerical simulation methods with the background data and knowledge base are under developing.

Fluid-structure numerical simulation has different approaches (Fig.14). Structural temperature can be calculated by such two ways as thermal hydraulic (CFD) code and structural (FEM) code. Through previous investigations, authors selected the CFD approach to avoid hypothesis of heat transfer coefficient. Therefore, a single fluid-structure thermal interaction CFD code is recommended for considering local and temporal conjugate heat transfer between fluid and structure.

As for a turbulent model for the CFD analysis, the Dynamic LES (Large Eddy Simulation) model is recommended through comparison of the CFD results with various models and experimental results as shown in Table1[12, 13]. Heat transfer between fluid and structure is sensitive to mesh subdivisions of boundary layer. Since long simulation time is required to evaluate low frequency temperature fluctuation which is damageable on structures, computation time should be saved [13].

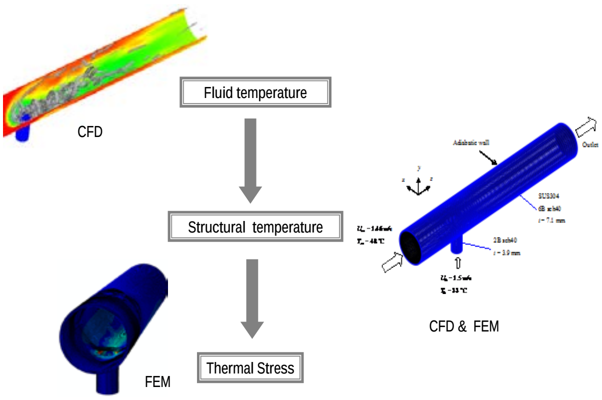


Fig.14 Fluid-structure numerical simulation for evaluation of thermal fatigue damage

Table 1 Comparison of CFD models

Turbulence model	Mesh	Accuracy	Computational time	Cost	Applicability
RANS	**Coarse**	**Low**	**Short**	**Low**	**Low for non stationary field**
DES (LES+RANS)	**Medium**	**Medium**	**Medium**	**Medium**	**To be confirmed for spatial distribution**
LES+Wall function	**Medium**	**Medium**	**Medium**	**Medium**	**To be confirmed for heat transfer on the surface**
LES	**Fine**	**High**	**Long**	**Large**	**To be confirmed for computational time and heat transfer on the surface**
DNS	**Very fine**	**High**	**Huge**	**Impractical**	**Impractical**

5. Probabilistic failure analysis approach for plant system safety

For considering fatigue failure in system safety and PSA approach, probabilistic failure analysis methods are under development to consider the fatigue failure in system safety and PSA approach.

From view point of system safety, through wall cracks are important than clack initiation. Therefore, probabilities of both crack initiation and propagation are required to evaluate possibilities of though wall cracks. Framework of probabilistic failure analysis approach for plant system safety can be described as in Fig.15. When fatigue damage factor become 1.0, cracks with 1mm depth are assumed to be initiated. Crack shapes are hypothesized as semi elliptical ones and Paris law is assumed for propagation rate.

There are many influential parameters on loadings and strength in thermal fatigue phenomena. Among them, dominant parameters are required to be extracted. By using the Monte Carlo method and the framework of Fig.15, sensitivities of fatigue damage factors to influence parameters were investigated. For example, lower threshold of crack propagation were successfully clarified as one of the dominant parameters (Fig.16). Details are explained in the associated paper [14].

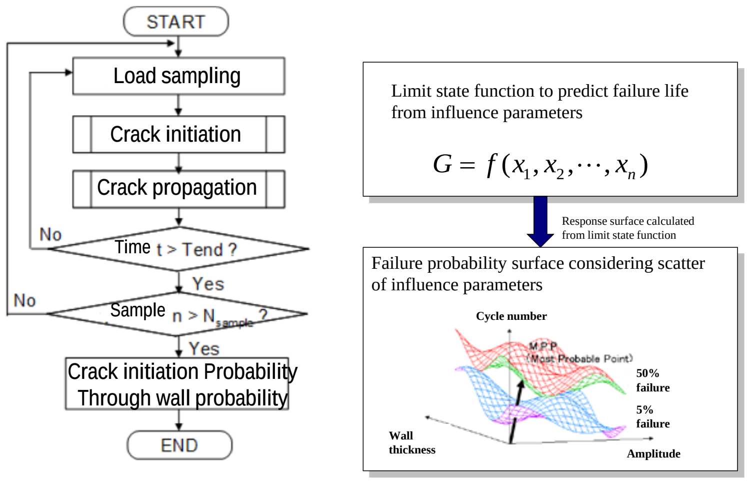


Fig.15 Probabilistic failure analysis approach for plant system safety

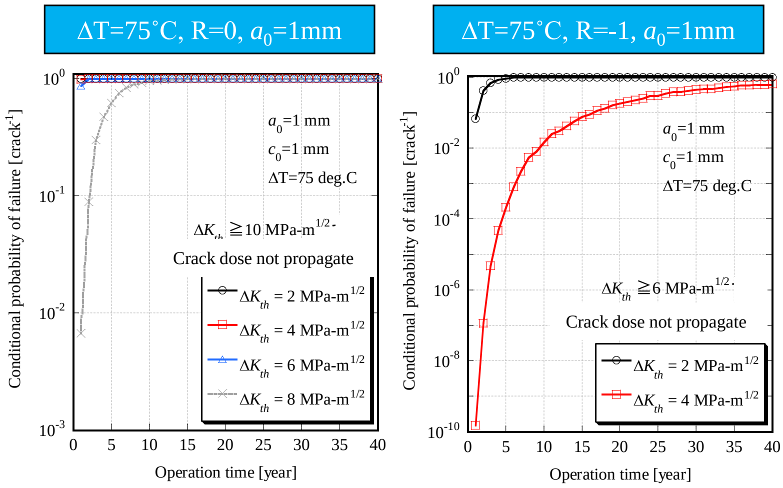


Fig.16 Examples of probabilistic crack initiation and propagation analysis results

Extracted dominant parameters will be utilized for developing the limit state function *G*. It can be calculated by the Monte Carlo method. However, this method requires huge computing and obtained results will be not easy for comprehensive understanding.

For simplification and engineering use, applicability of the Advance First Order Second Moment (AFOSM) method is studied by normal distribution assumption of influence parameters. As similar method to deterministic approach, there are the Load and Resistance Factor Design (LRFD) method, which utilizes partial safety factor for loads and strength corresponding to failure probability.

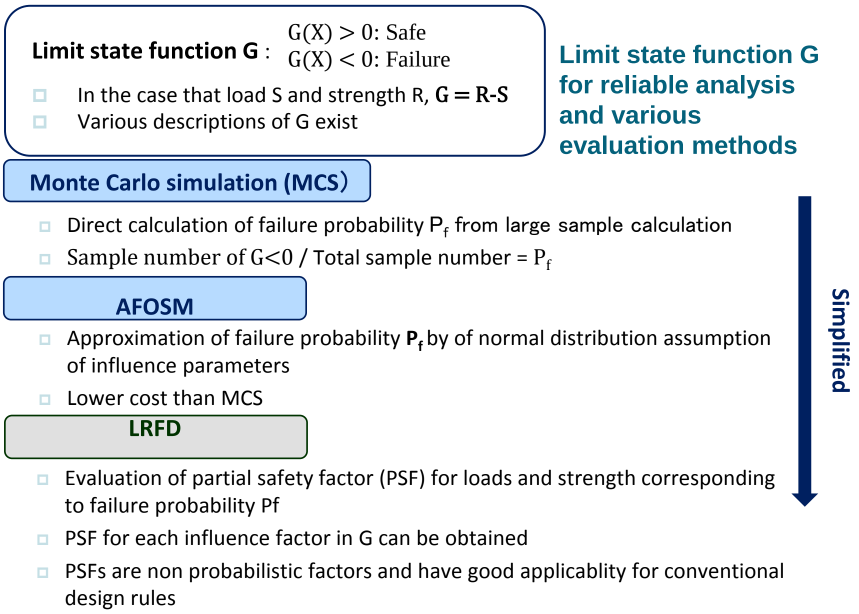


Fig.17 Reliability analysis methods for realistic evaluation of failure probabilities considering many influence parameters

6. Conclusions

(1) Clarification of mechanism on loadings and failure

Loading mechanisms were investigated on “a. High cycle thermal fatigue by temperature fluctuation at mixing zone between cold and hot fluid” and “b. Thermal fatigue by temperature stratified layer at stagnant branch pipe”. Concerning failure mechanism, studies focus on such particular issues as multiplication of high cycle and low cycle fatigue and multi-axial stress problems with proportional and non-proportional loadings.

(2) Proposals for the JSME guideline

By considering frequency dependency of thermal stress, rational evaluation methods were proposed, which has almost homogeneous design margin against various conditions than the JSME guideline.

(3) Development of Numerical simulation method

To replace experimental approach of the JSME guideline by simulation base one, fluid-structure numerical simulation methods were studied by using the two different codes for the thermal-hydraulics and the structure. For fluid-structure thermally coupled analysis, the Dynamic LES model is recommend for the numerical simulation of the thermal-hydraulics.

(4) Probabilistic failure analysis approach for plant system safety

For considering fatigue failure in system safety and PSA approach, probabilities of both crack initiation and propagation were studied. Framework of probabilistic failure analysis approach with the limit state function was proposed. As candidates of probabilistic parameters of the limit state function, some dominant parameters of fatigue failure were extracted.

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References

[1] Faidy,C., Thermal fatigue in mixing areas: Status and justification of French assessment method,3rd International conference on fatigue of reactor components, EPRI-US NRC-OECD NEA, Seville, Spain, （2004）

[2] Naoto KASAHARA, Thermal load and fatigue evaluation of nuclear piping, JSME-MMD, ATM'11, OS18-1-1, (2011)

[3] JSME, Guideline for Evaluation of High-Cycle Thermal Fatigue of a Pipe,S017-2003,(2003)

[4] Kasahara,N.,Takasho,H. and Yacumpai,A., Structural response function approach for evaluation of thermal striping phenomena, Nuc. Eng. Des., 212, pp281/292, (2002)

[5] Yoshihiro ISHIKAWA, Yukihiko OKUDA and Naoto KASAHARA, Thermal fatigue of pipes induced by fluid temperature change （CFD analysis of thermal stratification in a vertical branch pipe with a closed end） JSME, Annual Meeting(in Japanese), J032013,(2013)

[6] M. Okazaki, , M. Muzvidziwa, R. Iwasaki, and N. KASAHARA, Effect of Thermo-Mechanical Loading Histories on Fatigue Crack Growth, Behavior and The Threshold in SUS316 and SCM 440 Steels., -For prevention of high cycle thermal fatigue failures-, EJAM, JSM, The same vol., (2014)

[7] Takashi TSUJI and Masayuki KAMAYA, Thermal Fatigue of Pipes Induced by Fluid Temperature Change (Fatigue Strength of Stainless Steel under Bi-axial Load), JSME, Annual Meeting(in Japanese), J032024, (2013)

[8] Takamoto Itoh, Masao Sakane, Kazuki Ohsuga, Multiaxial Low Cycle Fatigue Life under Non-proportional Loading, International Journal of Pressure Vessels and Piping, No.7, (2013)

[9] Shinsuke SAKAI, Satoshi OKAJIMA, Naoto KASAHARA and Satoshi IZUMI, Design Method for Random Fatigue Based on Spectrum Characteristics, ASME, J. Pressure Vessel Technology, 134(3),031204.,(2012)

[10] Takafumi Suzuki and Naoto Kasahara, Thermal Fatigue Evaluation Method of Pipes by Equivalent Stress Amplitude, ASME, PVP2012-78347, (2012)

[11] Akira NAKAMURA, Yoichi UTANOHARA, Koji MIYOSHI and Naoto KASAHARA, Simulation of thermal striping at T-junction pipe using LES with parameters and temperature diffusion schemes, OECD/NEA and IAEA, CFD4NRS-4, (2012)

[12] Shaoxiang Qian, Shinichiro Kanamaru and Naoto Kasahara, High-Accuracy Analysis Methods of Fluid and Structure Temperature Fluctuations at T-Junction for Thermal Fatigue Evaluation, ASME, PVP2012-78159, (2012)

[13] Hitoshi NAKAMURA, Hitoshi Kawahara, Bo Li and Naoto KASAHARA, Thermal fatigue of pipes induced by fluid temperature change (Predictability of temperature fluctuations at T-junction pipes), JSME 2013 Annual meeting(in Japanese), J032012, (2013)

[14] Hideo MACHIDA and Naoto KASAHARA, Thermal Fatigue of Pipes Induced by Fluid Temperature Change(Study on Main Parameters for Failure Probability of Pipes) , JSME 2013 Annual meeting(in Japanese), J032032, (2013)