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Decomposition of Pipe Stress Results from Time History Analysis under Seismic Loading Condition

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ABSTRACT

For safety evaluation under seismic loading condition, the pipe system requires to be evaluated for both the primary and the secondary stresses in compliance with ASME Boiler & Pressure Vessel Code (BPVC) Sec.III evaluation criteria. RS (Response Spectrum) analysis and SAM (Seismic Anchor Motion) have been generally used for the calculation of primary and the secondary stress analyses, respectively. However, the seismic loading case time history analysis may produce more precise results compared to RS and SAM because seismic loading changes very rapidly with time change. Nevertheless, there is no specific ASME code regarding stress decomposition method for time history results under seismic loading condition.

In this paper, stress decomposition methods are introduced. The results of the time history analysis can be decomposed to the primary and the secondary stresses. Therefore, the time history analysis become available to be used at the safety evaluation by ASME BPVC Sec.III for the piping structure under seismic loading. The introduced methods show similar results and they seem to be suitable for applying to the evaluation criterions at ASME BPVC.

INTRODUCTION

As the case of Japan and Haiti, so many severe earthquakes occurred frequently all over the world and they made great casualties and financial damage(estimated damage and loss of Haiti earthquake are about 7,800,000,000 $US. And 316,000 peoples died or were missing (Alon, 2014)). Therefore, there are many efforts have been proceeded to prevent severe damage by the earthquake. Especially, after the Fukushima accidents at Japan, there are so many concerns for the safety of the nuclear power plant under the earthquake. Failure or accident at the nuclear power plant can incur disasters on not only economic loss but also environment for centuries such as the cases of Fukushima and Chernobyl. So it becomes more important to secure the safety of the nuclear power plant from the potential severe earthquake.

For design and qualification of nuclear power plant structures, ASME Code has been widely used for decades. The ASME Code provides rules and standards on the design, fabrication and inspection for boilers, pressure vessels and piping. Especially, the piping is one of the most important part of the nuclear power plant. It delivers coolant and steam from reactor to the other components and maintains the pressure boundary. The ASME Boiler & Pressure Vessel Code provide the safety evaluation methods and criteria at Sec. III, NB-3600. At Sec. III, NB-3600, the code proposes that the integrity of the piping should be evaluated with primary and secondary stress, separately.

Generally, primary stress is defined as any normal stress or shear stress developed by an imposed loading that is necessary to satisfy the laws of equilibrium in terms of the external and internal forces and moments. Secondary stress is defined as a normal stress or a shear stress developed by the constraint of adjacent material or by self-constraint of the structure. However, in this study, stress due to weight and inertial loading for piping under seismic loading is called primary stress and stress due to the anchor motions by the seismic loading is called secondary stress. Commonly, the evaluation for primary stress is conducted by response spectrum analysis, and secondary stress is evaluated by static analysis with seismic anchor motion. But, these analyses are simplified methods to evaluate the safety of the structure approximately and the results of these would be too conservative. Kim (2014) verified that with simple beam model in his paper. Therefore, it is necessary to adopt analysis method that can take accurate pipe stress responses.

Since time history analysis provides every response under seismic loading which may vary according to the specified time domain, it is expected to be possible to get accurate pipe stress responses. But, it has a problem to apply time history analysis results to the equations at ASME code. As mentioned above, ASME code requires individual allowable stress limits for primary stress and secondary stress. But, general FE software do not have the feature to decompose primary stress and secondary stress for time history analysis. Therefore, it is necessary to develop the stress decomposing method for time history analysis under the seismic loading to adopt the equations at ASME Code.

In this study, the stress decomposing methods for time history analysis are suggested for applying ASME code on safety evaluation. In addition, the influences of suggested methods at the piping system ar e investigated by comparing the results of each methods.

FINITE ELEMENT ANALYSIS

Analysis Model

The piping model, depicted in Figure 1, consists of three types of pipe; straight pipe, elbow, branch pipe. And this model is fabricated from SA106 Gr.C. The Finite element analyses are performed using the general FE software ANSYS (ANSYS, 2014). The pipe elements within ANSYS (Pipe288 for a straight pipe, Elbow290 for an elbow pipe) are used. The mechanical properties including the elastic modulus, poisson's ratio and density are listed in Table 1 (ASME, 2007).

Loading Conditions

In this paper, seismic loading is only considered as loading conditions. Piping system is subjected to multiple support excitation and the displacement time history inputs are applied at each supports to investigate accurate response. The time step is 0.005 sec that is same with displacement time history input interval. The time history inputs are corresponding to a 0.5g target SSE (Safe-Shutdown Earthquake ground motion) for the APR 1400 NPP. And, for the security reason, it is difficult to show the detailed input information. The typical type of the time history input is depicted in Figure 2.

Boundary Conditions

Rigid supports are fixed corresponding to the restrained directions. And spring hangers are restrained only Y direction using a spring element of ANSYS (Combin14) with the corresponding elastic stiffness.

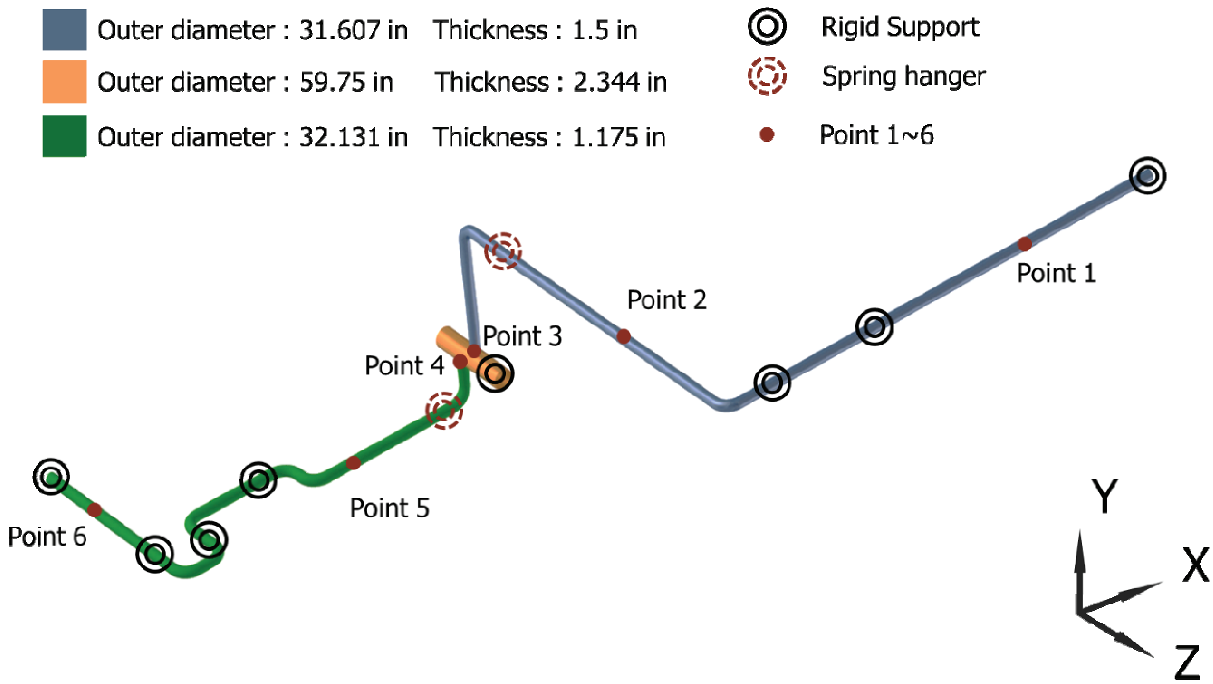

Figure 1. Finite element model

Table 1 : Material properties for the piping system

Material	Young's modulus (ksi)	Poisson's ratio	Density (lb/in^3)
SA106 Gr. C	29,500	0.28	0.304

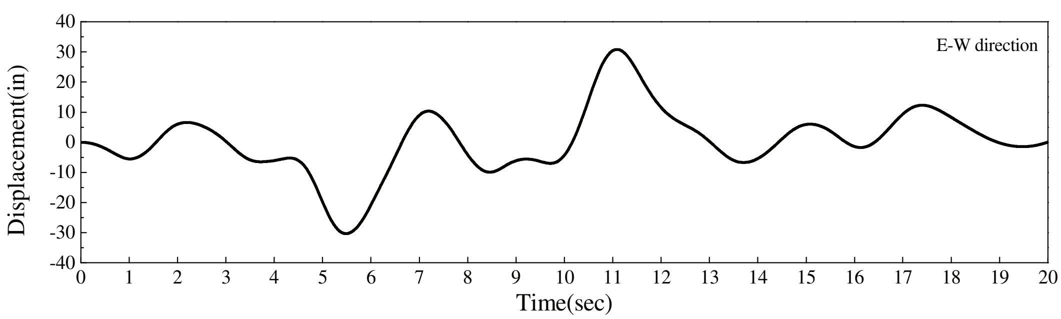

Figure 2. Typical time history inputs E-W direction (X axis)

STRESS DECOMPOSITION METHODS ON THE RESULTS OF TIME HISTORY ANALYSIS

As mentioned above, the stress evaluation, in level D service limits of ASME B&PV Code, requires decomposing the pipe analysis results into the primary stress and the secondary stress. But, the function of decomposing results into the primary and the secondary stress terms is not provided in ANSYS software. Therefore, additional analysis method is required to decompose the results. In this study, non-mass analysis and quasi-static analysis are suggested to decompose the pipe stress results from the time history analysis. In this section, the brief explanations on the time history analysis method and the stress decomposition methods are descripted.

Time History Analysis

To investigate the response of piping analysis is every points with time, time history analysis is performed. D. Costa (2003) defines time history analysis is a step-by-step procedure where the loading and the response history are evaluated at successive time increments. Thus time history analysis is effective to inspect response by seismic loading. Actually, time history analysis is convenient method to consider non-linear behaviours. But in this study, linear-time history analysis is considered because the properties are assumed constant during the entire loading. Usually, either of acceleration and displacement time history inputs can be considered for the seismic loading. In this paper, only the displacement time history inputs are used because displacement inputs are only accessible.

Many studies have handled the multiple support excitation seismic analysis for a piping system (Subudhi and Bezler, 1983; Kim et al., 2013). The NRC suggests to use 4% damping at the time history analyses at Reg Guide. 1.61. To consider the damping effect, Rayleigh damping model is adopted and the equation is followed.

$$\zeta = \frac{\alpha}{2\omega} + \frac{\beta\omega}{2} \tag{1}$$

Where, ζ is critical damping value; ω is natural frequency; and α and β are the Rayleigh damping coefficients. In this study, the critical damping value (ζ) is assumed to be 4% (NRC, 2007). For a given damping value, the Rayleigh damping coefficients can be calculated as follows:

$$\alpha = \frac{2\omega_i\omega_j(\omega_i\zeta - \omega_j\zeta)}{\omega_i^2 - \omega_j^2} \tag{2}$$

$$\beta = \frac{2(\omega_i\zeta - \omega_j\zeta)}{\omega_i^2 - \omega_j^2} \tag{3}$$

Where, ω_i and ω_j are minimum and maximum natural frequencies at the modal analysis, respectively. The cut-off frequency for the Rayleigh damping is determined as 33Hz. With these equations, the Rayleigh damping factors are calculated as $\alpha = 0.603$ and $\beta = 0.366\times10^{-3}$.

Non-mass analysis & Quasi-static analysis

Many FE analysis programs provide time history results that contain both the inertial effect and relative support movement effect (Kai, 2012). Therefore, to decompose the stress, the non-mass analysis and quasi-static analysis are conducted. Non-mass analysis and quasi-static analysis are based on the idea reducing the inertial effect. Non-mass analysis reduces the inertial effect extremely with performing analysis with decreased piping mass arbitrarily to 5%. If the pipe mass is decreased, the inertial term of the analysis result is also decreased and inertial effect becomes very small. Therefore, non-mass analysis could draw the secondary stress terms from time history analysis results by elimination of the inertial effect.

Generally, the inertial effect of time history analysis is affected by the time derivative terms, like as velocity or acceleration. However, quasi-static analysis does not involve time-integration. At quasi-static analysis the input loading data is time dependent but the analysis method is static analysis. This option can ignore the effect of the velocity and acceleration. So, it causes piping analysis neglects the inertial effect, and the pipe analysis results are only affected by the relative support movement. Therefore, quasi-static analysis can be used to draw the secondary stress terms from the pipe analysis results.

Generally, dynamic equations are expressed as follows:

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = F(t) \tag{4}$$

In non-mass analysis, mass is almost zero. Therefore, let assume $[M] = 0$. Then equation (4) is expressed as

$$[C]\{\dot{x}\} + [K]\{x\} = F(t) \tag{5}$$

Rayleigh damping matrix $[C]$ is expressed as

$$[C] = \alpha[M] + \beta[K] = \beta[K] \quad (\because [M] \approx 0) \tag{6}$$

Finally, dynamic equation for non-mass analysis is expressed as followed like

$$\beta[K]\{\dot{x}\} + [K]\{x\} = F(t) \tag{7}$$

In quasi-static analysis, acceleration and velocity are controlled as zero. Therefore, equation (4) is expressed as follows

$$[K]\{x\} = F(t) \quad (\because \{\ddot{x}\} = \{\dot{x}\} = 0) \tag{8}$$

Equation (7) and equation (8) are dynamic equations of each non-mass analysis and quasi-static analysis, respectively. Equation (7) includes β term, but β has very small value, 0.366×10^{-3}. And it can be assumed not to affect the results because it is almost zero. After β term removed, the equation (7) and (8) also have similar shape. For these reasons, non-mass analysis and quasi-static analysis are expected to draw the almost same results.

Decomposition method

To decompose the pipe stress results into the primary stress and secondary stress, as mentioned above, non-mass analysis and quasi-static analysis are used. Because these two methods provide secondary stress terms, it is necessary to conduct time history analysis for the complete resultant moment. For accurate results, these analyses must use the same inputs (displacement time history inputs) and apply same boundary conditions.

First of all, it is necessary to get the resultant moment ($M_{resultant}$) from the time history analysis. The maximum value of resultant moments for the entire time is used. And secondary moment ($M_{secondary}$) is get from decomposition methods; quasi-static and non-mass analysis. It is also the maximum values are adopted for evaluation. Finally, subtract the secondary moment from resultant moment to calculate primary moment ($M_{primary}$) . The superposition method is conducted because the material properties are considered as linear elastic behaviour. With these procedures, Resultant moments can be decomposed into primary and secondary moments. Following figure 3 shows the flow chart of the decomposition method.

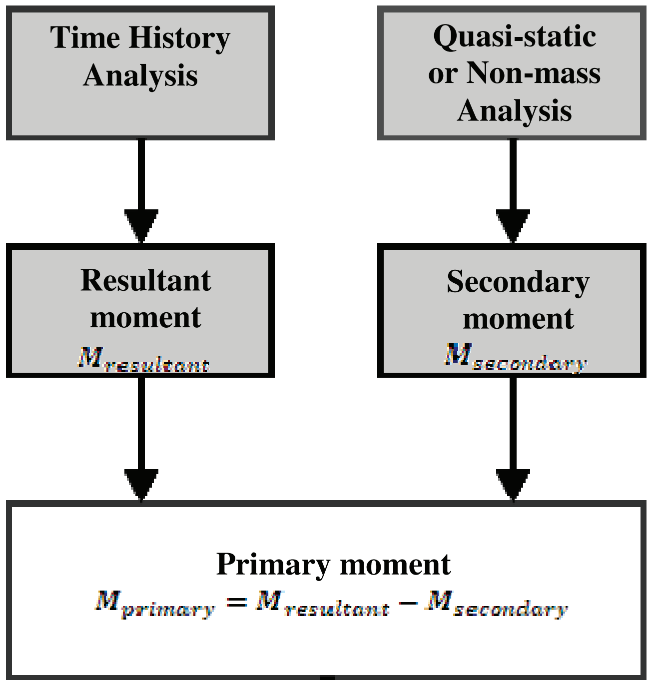

Figure 3. Flow chart of decomposition method

RESULT

Comparisons of analysis results : moment

To investigate each analysis result, time history analysis, quasi-static analysis and non-mass analysis are conducted and comparison of each analysis results is depicted at Figure 4. As shown in Figure 3, the results of the quasi-static analysis and non-mass analysis are smaller than that of time history analysis. And also the results of quasi-static analysis and non-mass analysis seem to be similar. Table 2 and 3 show the comparison of results for primary and secondary moments. As shown in the Table 2, 3, quasi-static and non-mass analysis have similar tendency and the errors are also very small, except for point 3 and 6. But please note that these points have much lower value then other points, so their differences are small, though they have large error. It implies that quasi-static and non-mass analysis, although they are different type of analysis, the same results will be calculated.

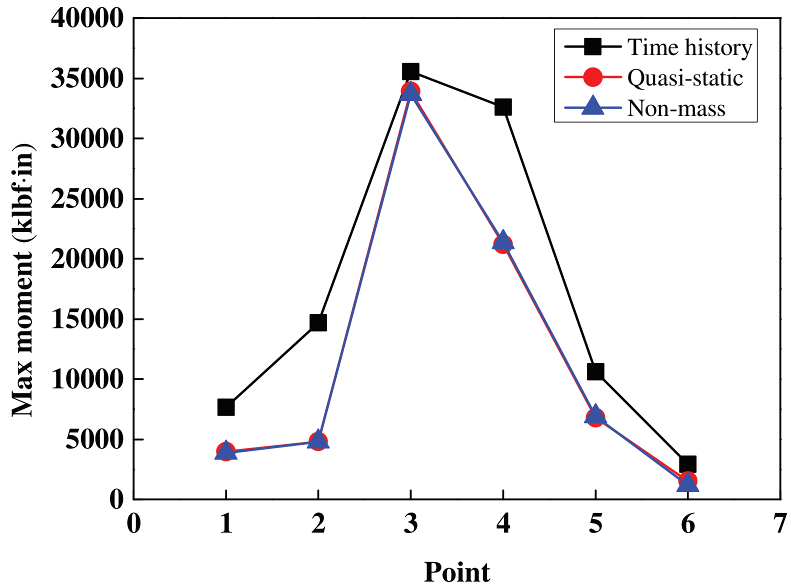

Figure 4. Comparison of analysis results on maximum moments

Table 2 : Comparison of results for primary moment

Point	Quasi-static(klbf·in)	Non-mass(klbf·in)	Errors (%)
1	3673.200	3789.720	-3.172
2	9860.550	9855.990	0.046
3	1641.800	1878.100	-14.393
4	11408.200	11234.400	1.523
5	3830.660	3722.160	2.832
6	1398.960	1716.260	-22.681

Table 3 : Comparison of results for secondary moment

Point	Quasi-static(klbf·in)	Non-mass(klbf·in)	Errors (%)
1	3985.35	3868.83	2.9237
2	4812.45	4817.01	-0.0948
3	33915.10	33678.80	0.6967
4	21199.00	21372.80	-0.8198
5	6785.84	6894.34	-1.5989
6	1518.49	1201.19	20.8958

Comparisons of analysis results : stress

Primary and secondary stresses are calculated with ASME code NB-3600 and the results of quasi-static and non-mass are compared. Equations provided in ASME code Sec.III NB-3600 are expressed at equation (4) and (5).

$$\sigma_{primary} = B_1 \frac{PD_0}{2t} + B_2 \frac{D_0}{2I} M_{primary} \tag{4}$$

$$\sigma_{secondary} = C_2 \frac{D_0}{2I} M_{secondary} \tag{5}$$

Where, $\sigma_{primary}$ and $\sigma_{secondary}$ are primary stress and secondary stress, respectively, and B_1, B_2 are primary stress indices, and C_2 is secondary stress index. P is design pressure and D_0 is outside diameter of pipe, t is thickness of pipe, I is geometrical moment of inertia, $M_{primary}$ is primary moment and $M_{secondary}$ is secondary moment. These moment components are drawn by the decomposition methods.

Table 4 and Table 5 express the comparisons of primary stresses computed by decomposition methods. As shown in Table 4 and 5 the quasi-static method and zero-mass method provide very similar results for the primary and the secondary stress. The point 6 is an exception, but it has very small value and the error may be neglected.

Table 2 : Comparisons of primary stress

Point	1	2	3	4	5	6
Quasi-static(ksi)	9.845	15.912	13.447	20.095	9.999	7.614
Non-mass(ksi)	9.959	15.908	13.763	19.932	9.893	7.925
Error(%)	-1.161	0.028	-2.349	0.809	1.064	-4.087

Table 3 : Comparisons of secondary stress

Point	1	2	3	4	5	6
Quasi-static(ksi)	3.908	4.719	68.797	37.702	6.655	1.489
Non-mass(ksi)	3.794	4.724	68.174	38.011	6.761	1.178
Error(%)	2.924	-0.095	0.905	-0.821	-1.599	20.896

CONCLUSITON

In this study, decomposition method for pipe stress results from time history analysis under seismic loading condition is proposed. For decomposing the pipe stress results, quasi-static analysis and non-mass analysis methods are suggested. Both analyses have something in common that can neglect inertial effect. However, they are essentially different analysis type, both analyses should present similar results to verify decomposition method.

As a result, decomposition method is regarded as valid for two reasons. Firstly, as shown in Table 2 and 3, quasi-static analysis and non-mass analysis provide similar results. It means that quasi-static analysis and non-mass analysis are effective to neglect inertia effect and also draw the primary state (neglected secondary effect). Secondly, secondary stress of points located at branch pipe is bigger than others. As shown in table 3 and 4, let group 1 is point 3 and 4 and let group 2 is 1, 2, 5 and 6. Group 1 is located at branch pipe and group 2 is located at straight pipe. In this study, since multiple excitation analysis is performed, group 1 is inevitably affected the most by relative seismic motions. Therefore, results of group 1 are predicted to present bigger values than group 2. Consequently, results of group 1 are bigger than results of group 2 (table 3 and 4). It means that decomposition method is effective for drawing secondary stress.

Quasi-static and non-mass analysis with the TH analysis can be regarded as valid for decomposing the primary and secondary stress under seismic loading. However, to verify it more accurately, additional research is necessary by comparing with response spectrum analysis and static analysis with seismic anchor motion.

Acknowledgement

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