Influence of dead weight and internal pressure to seismic buckling probability of fast reactor vessels

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Abstract
Seismic buckling of vessels is one of main concerns for the design of fast reactor plants in Japan. Rational design is important because of two conflicting requirements; thicker walls are preferable to prevent seismic buckling of vessels, while excessively thick walls introduce large thermal stress causing unacceptable creep–fatigue interaction damage. In previous studies, we discussed evaluation methods of seismic buckling probability of vessels by taking account of seismic hazards in order to rationalize seismic buckling evaluation, and proposed a rule for seismic buckling of vessels based on the load and resistant factor design method. The proposed rule is expected to widen design window regarding seismic buckling and contribute to more reasonable design of vessels of fast reactors. However, there is still a room for more rational design. The proposed method deals with only seismic load, but in actuality, dead weight and internal pressure also exist. The existence of these loads contributes to reducing the buckling probability because axial compressive load decreases. In this study, the rule was expanded so that dead weight and internal pressure can be taken into account. Furthermore, the influences of dead weight and internal pressure to seismic buckling evaluation were discussed. As result, it was shown that approximately 10 to 20% of further rationalization of allowable seismic load could be achieved by considering dead weight and internal pressure in the evaluation. In addition, it was found that the previously proposed design rule, not considering dead weight and internal pressure, includes approximately 2 to 10 times margins in terms of seismic buckling probability.

Keywords : Load and resistance factor design, Partial safety factor, Target buckling probability, Maximum allowable stress, Seismic hazard

1. Introduction
Seismic buckling of vessels is one of main concerns for the design of fast reactor plants in Japan. Implementation of rational design is very important because there are two conflicting requests to wall thickness; thicker walls are preferable in terms of prevention of seismic buckling, while excessively thick walls introduce large thermal stress causing unacceptable creep–fatigue interaction damage. In a previous study (Takaya et al., 2015a), we evaluated seismic buckling probabilities of fast reactor vessels by considering seismic hazards, and showed that seismic load gave a significant impact on buckling probability. In a subsequent study (Takaya et al., 2017), we proposed a new alternative design rule for seismic buckling of vessels to the conventional deterministic design rule in the Japan Society of Mechanical Engineers (JSME) fast reactor codes (The Japan Society of Mechanical Engineers, 2016), using the load and resistance factor design (LRFD) method. In addition, it was illustrated that the proposed rule would contribute to widening the design window of fast reactor vessels.

However, the proposed design rule still has a room for further rationalization. As mentioned, seismic load has a significant impact on buckling probability. Thus, the proposed design rule deals with only seismic load among loads acting on vessels. In actually, dead weight and internal pressure exist in addition to seismic load. The existence of dead
weight and internal pressure contributes to reducing buckling probability because axial compressive load decreases. These loads are random variables because variations in dead weight by manufacturing tolerances could be expected and internal pressure would fluctuate during operations. Further rationalization of seismic buckling evaluation would be possible by incorporating these loads into the previously proposed design rule. However, it does not work just to subtract axial tensile loads due to dead weight and internal pressure from an axial compressive load due to seismic load in the previously proposed design rule.

In this paper, a method to incorporate dead weight and internal pressure into the previously proposed design rule of seismic buckling of vessels is investigated. Then, the influence of these loads to seismic buckling probability is discussed.

2. Nomenclature

\begin{align*}
A & \quad \text{Cross-sectional area (mm}^2\text{) of a cylindrical shell} \\
B & \quad \text{Ratio of } d_1 \text{ to } d_2 \\
D_o & \quad \text{Outer diameter (mm) of a cylindrical shell} \\
E & \quad \text{Young's modulus (MPa)} \\
F_c & \quad \text{Axial compressive load (N)} \\
F_{cs} & \quad \text{Axial compressive load generated by a design basis earthquake (N)} \\
I & \quad \text{Moment of inertia of area (mm}^4) \\
M & \quad \text{Bending moment (N} \cdot \text{mm)} \\
M_{ss} & \quad \text{Bending moment generated by a design basis earthquake (N} \cdot \text{mm)} \\
S_y & \quad \text{Design yield strength (MPa)} \\
X & \quad \text{Annual maximum earthquake normalized by a design basis earthquake} \\
Y & \quad \text{Lognormal random variable of which median value is the same as that of } \sigma_{ac,ss}, \text{ incorporating logarithmic standard deviations (LSDs) of } X \text{ and stress due to a design basis earthquake} \\
c & \quad \text{Median value of } X \\
d_1 & \quad \text{Median value of } \sigma_{ac,ss} \\
d_2 & \quad \text{Median value of } \sigma_{bs} \\
f_s & \quad \text{Safety factor (} = 1.5 \text{ for the service condition D)} \\
t & \quad \text{Thickness (mm) of a cylindrical shell} \\
y & \quad \text{Ratio of bending buckling strength to axial compression one} \\
\sigma_{ac} & \quad \text{Axial compressive stress (MPa) due to an annual maximum earthquake} \\
\sigma_{ac,ss} & \quad \text{Axial compressive stress (MPa) due to a design basis earthquake} \\
\sigma_b & \quad \text{Bending stress (MPa) due to an annual maximum earthquake} \\
\sigma_{bs} & \quad \text{Bending stress (MPa) due to a design basis earthquake} \\
\sigma_v & \quad \text{Axial tensile stress (MPa) due to internal pressure} \\
\sigma_y & \quad \text{Actual yield strength (MPa)} \\
\mu_A & \quad \text{Mean value of } \sigma_y \\
\mu_B & \quad \text{Mean value of } \sigma_v \\
\mu_C & \quad \text{Mean value of } \sigma_p \\
\sigma_A & \quad \text{Standard deviation of } \sigma_y \\
\sigma_B & \quad \text{Standard deviation of } \sigma_v \\
\sigma_C & \quad \text{Standard deviation of } \sigma_p \\
\zeta & \quad \text{LSD of seismic load, including seismic hazard} \\
\zeta_X & \quad \text{LSD of } X \\
\zeta_{\sigma_{ac,ss}} & \quad \text{LSD of } \sigma_{ac,ss} \\
\zeta_{\sigma_{bs}} & \quad \text{LSD of } \sigma_{bs} \\
\gamma_{ss} & \quad \text{Partial safety factor for seismic load} \\
\phi & \quad \text{Partial safety factor for yield strength}
\end{align*}
3. Overview of the previously proposed rule

The previously proposed design rule for seismic buckling of vessels is briefly explained here. The design rule was developed using the LRFD method. In the LRFD method, a failure condition is defined using random variables, \( X_i, i = 1, \ldots, n \), and a limit state function, \( g(X_1, X_2, \ldots, X_n) \), as follows,

\[
 z = g(X_1, X_2, \ldots, X_n) < 0
\]  

In contrast to the conventional allowable stress design method which generally uses only one design factor, the LRFD method prepares multiple design factors corresponding to random variables in the limit state function. Their values are determined by considering probabilistic characteristics of random variables and a target failure probability. These design factors are called partial safety factors. Further details of the LRFD method are explained elsewhere (Avrithi and Ayyub, 2009; Haldar and Mahadevan, 2000).

In a previous study (Takaya et al., 2017), two limit state functions of seismic buckling, \( g_1 \) and \( g_2 \), were derived based on the JSME fast reactor codes.

The time-independent buckling limit for a cylindrical shell in the JSME fast reactor codes is as follows (The Japan Society of Mechanical Engineers, 2016):

\[
 F_c + D_c M \leq S_f
\]

Based on Eq. (2), the following limit state function, \( g_1 \), was defined at first:

\[
 g_1 = \sigma_y - \left( \sigma_{ac} + \sigma_{bs} \right)
\]

\( \sigma_{ac} \) and \( \sigma_{bs} \) are evaluated by the following equations, respectively:

\[
 \sigma_{ac} = \sigma_{ac}^{St} \cdot X
\]

\[
 \sigma_{bs} = \sigma_{bs}^{St} \cdot X
\]

The probability distributions of these variables were assumed as follows:

\[
 \sigma_y \sim N(\mu_a, \sigma_a^2)
\]

\[
 X \sim LN(\ln(c), \zeta_a^2)
\]

\[
 \sigma_{ac}^{St} \sim LN(\ln(d_1), \zeta_{ac1}^2)
\]

\[
 \sigma_{bs}^{St} \sim LN(\ln(d_2), \zeta_{bs2}^2)
\]

where \( N \) and \( LN \) mean the normal distribution and the log-normal distribution, respectively.

Subsequently, a perfect correlation was assumed between axial compressive stress and bending stress due to the annual maximum earthquake because variation of \( X \) is larger than those of \( \sigma_{ac}^{St} \) and \( \sigma_{bs}^{St} \) in general. Then, the following limit state function, \( g_2 \), was obtained:

\[
 g_2 = \sigma_y - c \left( 1 + \frac{1}{yB} \right) Y
\]

where \( B = d_1/d_2 \). \( Y \) was a newly introduced parameter that meets the following relations:
\[
\sigma_w = cY
\]  \hspace{1cm} (11)

\[
\sigma_b = c \frac{d_2}{d_1} Y
\]  \hspace{1cm} (12)

\[
Y \sim LN(\ln(d_1), \zeta_a^2 + \zeta_b^2)
\]  \hspace{1cm} (13)

where \( \zeta_a \) is appropriately determined from \( \zeta_1 \) and \( \zeta_2 \). For example, it can be determined as follows:

\[
\zeta_b = \text{MAX} \left[ \zeta_1, \zeta_2 \right]
\]  \hspace{1cm} (14)

Finally, based on the limit state function, \( g_2 \), the following design rule for the time-independent buckling of a reactor vessel in service condition D was proposed in the LRFD format (Takaya et al., 2017). The target buckling probability was assumed to be 10^{-6} yr.

\[
g_2 \left( \frac{F_{y,c}^{s} + D_{c, M}^{s}}{2Y} \right) \leq \phi \sigma_y
\]  \hspace{1cm} (15)

where \( \gamma^s \) and \( \phi \) are partial safety factors, and can be calculated as follows:

\[
\gamma^{s} = c \exp(4.75\zeta)
\]  \hspace{1cm} (16)

\[
\phi = a\zeta + b
\]  \hspace{1cm} (17)

\[
\zeta = \sqrt{\zeta_a^2 + \zeta_b^2}
\]  \hspace{1cm} (18)

where \( a \) and \( b \) are obtained from Table 1 corresponding to coefficient of variation (COV) of \( \sigma_y \).

| Table 1 | Coefficients in Eq. (17) |
|---------|-------------------------|
| COV of \( \sigma_y \) | \( a \) | \( b \) |
| 0.05    | 0.0121 | 0.9745 |
| 0.10    | 0.0522 | 0.8918 |
| 0.15    | 0.1380 | 0.7240 |

4. Incorporation of dead weight and internal pressure into the previously proposed design rule

The time-independent buckling limit for a cylindrical shell in the JSME fast reactor codes considers axial compressive load and bending moment as shown in Eq. (2). Both of dead weight and internal pressure contribute as negative axial compressive load. Therefore, the limit state function, \( g_3 \), is revised as follows;

\[
g_3 = \sigma_y - c \left( 1 + \frac{1}{YB} \right) Y + \sigma_w + \sigma_p
\]  \hspace{1cm} (19)

According to previous studies (Takaya et al., 2015a; Yokoi et al., 2016), the probability distributions of \( \sigma_w \) and \( \sigma_p \) are assumed as follows;

\[
\sigma_w \sim N(\mu_w, \sigma_w^2)
\]  \hspace{1cm} (20)

\[
\sigma_p \sim N(\mu_p, \sigma_p^2)
\]  \hspace{1cm} (21)
Because the probabilistic distribution of $\sigma_y$ is also assumed as normal distribution as shown in Eq. (6), $\sigma_y$, $\sigma_w$ and $\sigma_p$ are easily integrated into a new parameter, $\sigma_y'$ as follows;

$$\sigma_y' = \sigma_y + \sigma_w + \sigma_p$$  \hspace{1cm} (22)

$$\sigma_y' \sim N(\mu_A + \mu_B + \mu_C, \sigma_A^2 + \sigma_B^2 + \sigma_C^2)$$  \hspace{1cm} (23)

By substituting $\sigma_y'$ into Eq. (19), the following limit state function is obtained;

$$g_4 = \sigma_y' - c \left( 1 + \frac{1}{yB} \right) Y$$  \hspace{1cm} (24)

Based on analogy between Eq. (10) and Eq. (24), it is recognized that the previously proposed design rule for the time-independent buckling of a reactor vessel is applicable for cases considering dead weight and internal pressure just by replacing $\sigma_y$ with $\sigma_y'$ in Eq. (15) as well as Table 1.

5. Evaluation procedures

Influence of dead weight and internal pressure to seismic buckling probability was evaluated based on the newly derived limit state function, $g_4$.

Three combinations of probabilistic distributions shown in Table 2 were considered for $\sigma_w$ and $\sigma_p$, according to a previous study (Takaya et al., 2015a): “High”, “Low” and “N/A (Not Applied)”. Deference in influence of $\sigma_w$ and $\sigma_p$ by site was also investigated by considering three sites in Table 3: Sites A, B and C. The same seismic conditions were assumed for these sites as in a previous study (Takaya et al., 2017). At site A, the median value of $X$ was relatively small while the LSD of $X$ was relatively large. On In contrast, at site C, the median value of $X$ was relatively large while the LSD of $X$ was relatively small. At site B, the median value and the LSD of $X$ were in between those at site A and site C. In addition, $\phi$ was chosen as a parameter to see deference by the uncertainty of seismic response, and the value was assumed to be 0.2, 0.3 or 0.4, based on studies on seismic fragility of components in nuclear power plants (Pisharady and Basu, 2010; Takaya et al., 2017). As a result, 27 cases shown in Table 4 were prepared in total. The probabilistic distribution of actual yield stress was assumed to be $N(137.1, 13.71^2)$ based on statistical data of 316FR steel (Takaya et al., 2015b), and $yB$ in Eq. (19) was assumed to be equal to 1.

At first, the median values of $Y$ to meet the target buckling probability of $10^{-5}$/yr, $10^{-6}$/yr, and $10^{-7}$/yr, hereafter “Maximum allowable seismic stress”, were evaluated for the cases in Table 4. In addition, seismic buckling probabilities were calculated by substituting maximum allowable seismic stress evaluated without considering dead weight and internal pressure, for example, a results of A1, into cases considering these loads, for examples, A2 and A3. The evaluated buckling probability must have be smaller than the target values. If the influence of dead weight and internal pressure was small, the evaluated probabilities would be close to the target values.

The first order Gaussian approximation method (Haldar and Mahadevan, 2000) was used for calculation of seismic buckling probabilities.

### Table 2  Sets of conditions of $\sigma_w$ and $\sigma_p$

| Set   | $\sigma_w$ | COV | $\sigma_p$ | COV |
|-------|------------|-----|------------|-----|
| High  | 20         | 0.0194 | 10         | 0.1294 |
| Low   | 10         | 0.0194 | 5          | 0.1294 |
| N/A   | 0          | -    | 0          | -    |

### Table 3  Conditions for sites

| Site | $c$ | $\tilde{\omega}$ |
|------|-----|------------------|
| A    | 0.002 | 1.5             |
| B    | 0.01  | 1.0              |
| C    | 0.1   | 0.5              |
Table 4 Basic case sets

| Case ID | \(\varphi_b\) | \(\sigma_u\) and \(\sigma_p\) |
|---------|---------------|-------------------------------|
| A1      | 0.2           | N/A                           |
| A2      | 0.2           | Low                           |
| A3      | 0.2           | High                          |
| A4      | 0.3           | N/A                           |
| A5      | 0.3           | Low                           |
| A6      | 0.3           | High                          |
| A7      | 0.4           | N/A                           |
| A8      | 0.4           | Low                           |
| A9      | 0.4           | High                          |
| B1      | 0.2           | N/A                           |
| B2      | 0.2           | Low                           |
| B3      | 0.2           | High                          |
| B4      | 0.3           | N/A                           |
| B5      | 0.3           | Low                           |
| B6      | 0.3           | High                          |
| B7      | 0.4           | N/A                           |
| B8      | 0.4           | Low                           |
| B9      | 0.4           | High                          |
| C1      | 0.2           | N/A                           |
| C2      | 0.2           | Low                           |
| C3      | 0.2           | High                          |
| C4      | 0.3           | N/A                           |
| C5      | 0.3           | Low                           |
| C6      | 0.3           | High                          |
| C7      | 0.4           | N/A                           |
| C8      | 0.4           | Low                           |
| C9      | 0.4           | High                          |

6. Results and discussions

Figure 1 shows maximum allowable seismic stress in the case where \(\varphi_b\) was equal to 0.3. The maximum allowable seismic stress in “High” cases (A6, B6 and C6) was the highest at each site and for each target buckling probability, then that in “Low” cases (A5, B5 and C5) followed. As expected, the maximum allowable seismic stress in “N/A” cases where dead weight and internal pressure were not considered (A4, B4 and C4) was the lowest. The same tendency was observed for the other cases of \(\varphi_b\). The difference in the maximum allowable seismic stress by whether dead weight and internal pressure were considered or not was smaller than stress induced by dead weight and internal pressure. The total induced stress was 30 MPa in “High” cases, while the difference in the maximum allowable seismic stress was not more than approximately 20 MPa. The minimum difference was just about 3 MPa in the case of the target buckling probability of \(10^{-7}/\text{yr}\) at Site A. The difference in the maximum allowable seismic stress decreased with the target buckling probability. For example, at Site B, the differences were approximately 18 MPa, 11 MPa and 7 MPa in the cases of the target buckling probability of \(10^{-5}/\text{yr}\), \(10^{-6}/\text{yr}\) and \(10^{-7}/\text{yr}\), respectively.

Figure 2 shows the ratio of the maximum allowable seismic stress considering dead weight and internal pressure to that not considering these loads. For example, the result indicated as “A2” is the ratio of the maximum allowable seismic stress in the case of A2 to that in the case of A1.

The ratio was almost constant regardless of the target buckling probability: approximately 1.23 and 1.12 for “High” and “Low” cases, respectively. These values are very close to the ratios of \(\sigma_u^*\) to \(\sigma_u\): approximately 1.22 and 1.11 for “High” and “Low” cases, respectively. The difference between \(g_4\) and \(g_2\), the former is the limit state function incorporating dead weight and internal pressure and the latter is the previously proposed limit state function without considering these loads, is just that \(\sigma_u^*\) is used in \(g_4\) instead of \(\sigma_u\). If values of the parameters other than the mean value of \(\sigma_u^*\) were the same, the maximum allowable seismic stress based on \(g_4\) would be greater than that based on \(g_2\) exactly by the ratio of \(\sigma_u^*\) to \(\sigma_u\). However, in actual, COV of \(\sigma_u^*\) was also different from and slightly smaller than that of \(\sigma_u\), thus the ratios of the maximum allowable seismic stress were a little bit higher than the ratios of \(\sigma_u^*\) to \(\sigma_u\).
The site dependency was not significant, but the results at Site C were slightly higher than those at Sites A and B. As a reason, it can be given that the LSD of $X$ at Site C was smaller than those at the other sites. If the LSD is small, maximum allowable seismic stress will be more sensitively affected by the change from $\sigma_1$ to $\sigma_2$. In like manner, among the results at the same site, the ratio in the case where $\varphi$ was equals to 0.2, for example, “C3”, was higher than that in the case where $\varphi$ was equals to 0.4, for example, “C9”. As results, it was found that approximately 10 to 20% of further rationalization of the allowable seismic load would be possible by incorporating dead weight and internal pressure into the evaluation.

Figure 3 shows seismic buckling probabilities calculated by substituting maximum allowable seismic stresses evaluated in the cases without considering dead weight and internal pressure, for example, A1, into the cases considering these loads, for example, A2 and A3. As predicted, the evaluated buckling probabilities were smaller than the target buckling probabilities. The difference could be considered as implicit margin incorporated by intentionally neglecting dead weight and internal pressure.

The ratio of the evaluated buckling probability to the target buckling probability depends on target buckling probability, sites and $\varphi$, as well as $\sigma_1$ and $\sigma_2$. It is reasonable that the ratios in “High” cases of $\sigma_1$ and $\sigma_2$ were smaller than those in “Low” cases, because tensile stress not taken into account was larger in “High” cases than “Low” cases. In addition, the ratios in the cases of smaller target buckling probabilities were lower than those in the cases of higher target buckling probabilities. For example, in the “High” case shown in Fig. 3(e), the ratio was 0.41, 0.37 and 0.34 for the target buckling probability of $10^{-5}$, $10^{-6}$ and $10^{-7}$, respectively. The absolute values of neglected dead weight and internal pressure were the same, but the maximum allowable seismic stress in the cases of smaller target buckling probabilities were smaller than those in the cases of higher target buckling probabilities. Therefore, the effect of these loads could increase relatively in the cases of smaller target buckling probabilities. The site dependency seems to show the same tendency as in Fig.2. The evaluated buckling probabilities at Site C where $\varphi$ was 0.5 were the lowest, while those at Site A where $\varphi$ was 1.5 were the highest. The effect of $\varphi$ was very subtle, but the evaluated buckling probability increased with $\varphi$.

In “High” cases, the maximum ratio of the evaluated buckling probability to the reliability target was approximately 0.55 in the case where the target buckling probability was $10^{-5}$/yr and $\varphi$ was equals to 0.4 at Site A, while the minimum ratio was about 0.11 in the case where the target buckling probability was $10^{-7}$/yr and $\varphi$ was equals to 0.2 at Site C. As results, it was shown that approximately 2 to 10 times margins will be included in terms of buckling probability by evaluating maximum allowable seismic stress neglecting dead weight and internal pressure.
7. Conclusions

In the previous studies, a new design rule for the time-independent buckling of a reactor vessel in service condition D, in the LRFD format, was proposed. In this study, the rule was expanded so that dead weight and internal pressure can be taken into account by introducing the new random variable, $\sigma'_y$. Furthermore, the influence of dead weight and internal pressure to seismic buckling evaluation was discussed. Degree of increase in the maximum allowable seismic stress by considering dead weight and internal pressure was determined mainly by the ratio of $\sigma'_y$ to $\sigma_y$. Approximately 10 to 20% of further rationalization of the allowable seismic load could be achieved by taking into account of dead weight and internal pressure in the evaluation. In addition, it was found that the previously proposed design rule, not considering dead weight and internal pressure, includes approximately 2 to 10 times margins in terms of seismic buckling probability.

In this study, linear relations between earthquake intensity and loads generated by earthquake were assumed as shown by Eqs. (4) and (5). In contrast, for instance, in a case of a plant where a seismic isolator is installed, nonlinear...
The effect will appear if earthquake intensity exceeds the limit of the seismic isolator. Further studies are expected to reveal such nonlinear effects on seismic buckling probability.

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