Occurrence of plastic collapse under ratcheting due to gravity and seismic loading

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Abstract
The most dominant failure mode of piping components under seismic loading is fatigue failure with ratcheting. While it was confirmed via the experimental tests in the past, the Primary stress limit is applied to seismic loading to prevent plastic collapse. The plastic collapse due to seismic loading was first confirmed at Pipe-Fitting Dynamic Reliability Program (PFDRP) conducted by EPRI in 1980s. But, the mechanism and occurrence condition of this failure has not been clarified yet. In this research, a composite failure mode of the ratchet-induced collapse, which represents the behavior of the plastic collapse failure induced by ratchet deformation, is introduced. The transition of the failure modes along ratcheting is explained with the seismic failure mode map which identifies the occurrence condition of ratcheting and first-excursion failure, and the X-Y trajectory, which explains the excitation condition of structures under ratcheting, is introduced to project the transition. With the X-Y trajectory and the occurrence condition of the plastic collapse, this study conceptually proposes the prediction approach of the ratchet-induced collapse without the simulation analyses.

Keywords : Seismic response, Piping, Ratcheting, Collapse, Failure mode, Primary stress

1. Introduction
The possible failure modes of piping components under seismic loading are generally assumed as plastic collapse, ratcheting, and fatigue failure. The design codes for nuclear power plants, such as the ASME Section III specify the design limits against each failures mode. The Primary stress limit is one of the design limits to prevent plastic collapse. The failure modes of piping components under excessive seismic loading were investigated in the experimental tests (Touboul et al., 1999; Ravikiran et al., 2015; Nakamura and Kasahara, 2016). While the applied seismic input level was several times higher than the Primary stress limit, the failure mode of piping components was fatigue failure. Therefore, the plastic collapse of piping is considered unlikely under seismic loading. However, one instance of plastic collapse due to seismic loading exists (Tagart, 1990; EPRI, 1994). In this experiment, progressive ratcheting under the seismic excitation was followed by plastic collapse (this behavior is referred to as the ratchet-induced collapse in this study) under the seismic input around the design limit. Although this failure was expected as a combination of ratcheting and plastic collapse, the mechanism of this failure is not fully revealed yet. Recently, plastic collapse under seismic loading can be induced on the shaking table by using an alternative material (Nakamura and Kasahara, 2017). The occurrence condition of a plastic collapse induced by an impulsive acceleration, referred to as the first-excursion failure, was also investigated using the alternative material (Sasaki et al., 2020). However, the observed occurrence condition of plastic collapse is far beyond the design limit. Therefore, the mechanism of the ratchet-induced collapse needs to be investigated.

2. Seismic Failure Mode Map
Ratcheting is the phenomenon of the accumulation of progressive plastic deformation. For the thermal ratcheting, Bree diagram is one of the methods to describe the behavior of shakedown and ratcheting under the open-ended thin-wall cylindrical vessels under the combination of the membrane stress due to internal pressure and the bending stress due
to thermal expansion (Bree, 1967). Then, Yamashita’s diagram, which extends the applicability of the loading to the bending stress, was developed after the Bree diagram (Yamashita et al., 1989). In those diagrams, the occurrence condition of ratcheting is aligned by using two parameters: the Primary stress parameter $X$ defined by Equation (1) and the Secondary stress parameter $Y$ defined by Equation (2). With the $X$ parameter for the horizontal axis and the $Y$ parameter for the vertical axis, the X-Y plane can be divided into areas where ratcheting occurs.

$$X_{\text{Bree}} = \frac{\sigma_p}{\sigma_y} \quad (1)$$

$$Y_{\text{Bree}} = \frac{\sigma_t}{\sigma_y} \quad (2)$$

Where, $\sigma_p$ is the membrane stress due to the internal pressure, $\sigma_t$ is the cyclic bending stress due to the thermal expansion, and $\sigma_y$ is the yield stress.

The failure mode map for seismic loading is organized in the same manner with the Bree diagram but using the alternative $X$ and $Y$ parameters defined by Equations (3) and (4), and an additional parameter of the frequency ratio defined by Equation (5) (Bari et al., 2018). Here, $X$ is the normalized constant bending stress due to gravity, and $Y$ is the normalized alternating bending stress due to the peak acceleration of the seismic loading, assuming the seismic loading is static acceleration (Lyu et al., 2020; Sasaki et al., 2020). Also, the frequency ratio is defined as the ratio of the input frequency to the natural frequency of the structure.

$$X = \frac{\sigma_g}{\sigma_y} \quad (3)$$

$$Y = \frac{\sigma_{in}}{\sigma_y} \quad (4)$$

$$f_r = \frac{f_w}{f_n} \quad (5)$$

Here, $\sigma_g$ is the constant bending stress due to gravity, $\sigma_{in}$ is the bending stress when the peak amplitude of the seismic loading is assumed to be statically applied, and $\sigma_y$ is the yield stress. Also, $f_w$ is the excitation frequency, and $f_n$ is the natural frequency.

Fig. 1(a) is an example of the seismic failure mode map. The occurrence conditions of ratcheting and the first-excitation failure are summarized in Fig. 1(b) based on the research results (Lyu, 2020; Sasaki, 2020). The two boundary lines that represent the occurrence condition of the two failure modes divide the X-Y plane into two failure regions and one no-failure region, as shown in Fig. 1(b). The boundary lines trend that ratcheting and first-excitation failure occurrences are sensitive to the X and Y parameter. These failure modes are likely to occur when the X and Y parameters become large.
The failure mode of structures under seismic loading can be predicted by determining the X and Y parameters, called excitation conditions in this study. The first-excursion failure, one of plastic collapse, occurs when the excitation condition of structures represented as X and Y parameters are located above the first-excursion boundary line. Likewise, ratcheting is expected when the excitation condition of structures is within the ratchet region identified in Fig. 1(b). No ratcheting is expected when the X and Y parameters are below the ratchet boundary.

3. PFDRP and Test #37 Failure

EPRI performed a series of shaking table tests focusing on the dynamic behavior and failure mode of piping components, including elbows, tees, reducers, nozzles, and weld attachments, which is called PFDRP (Pipe-Fittings Dynamic Reliability Program). The vertical cantilever with a shifted mass installed at the top was excited by the artificial seismic motion. The dominant frequency was adjusted to 0.875 times the natural frequency of each test setup. The amplitude of the seismic motion was gradually scaled up to the maximum capacity of the shaking table and repeated until the specimen failed. Most piping components were confirmed to have failed in fatigue failure with ratcheting (EPRI, 1994). Test #37 is part of the test setup configurations in PFDRP which the different dynamic behavior was confirmed from other tests. The piping component of this test case had a thin wall-thickness of Sch.10, a high deadweight stress level of 10ksi [68.9 MPa], a low excitation frequency of 1.4Hz, and a long moment-arm of 111 inches [2.81 m]. The elbow began to ratchet buckle in the closing direction, and the test was terminated 72 seconds into the run because of the excessive displacement of the inertia arm (Tagart, 1990). Although the failure mode of Test #37 remains controversial if it was part of ratcheting or plastic collapse, the design evaluation for seismic loading was arranged based on Test #37 result because the seismic response was close to the design limit as well as the possibility of the plastic collapse.

![Fig. 2 The setup of Test #37 in PFDRP (EPRI, 1994). The piping was vertically aligned with the concentrated mass installed at the top of the specimen. The specimens were excited with the artificial seismic motion whose dominant frequency was set to 0.875 times of the natural frequency of the specimen.](image)

The dynamic behavior of Test #37 under the excitation can be interpreted as being comprised of three parts when being closely looked into. According to the measured rotation angle of the specimen as shown in Fig.3(a), the symmetric rotation deformation angle turned into ratcheting about 20 seconds into the run (① in Fig. 3-a). Then the amplitude of the alternating rotation gradually increased along with the progress of ratcheting (② in Fig. 3-a). The peak-to-peak rotation angle of 0.1 [rad] at the beginning of the ratcheting was deemed to reach 0.25 [rad] at maximum after 50 seconds into the run. The significant alternating deflection was recognized as plastic collapse. This Test #37 behavior can be summarized as the plastic collapse under dynamic acceleration induced by the accumulation of ratcheting. This behavior is identified as ratchet-induced collapse and is discussed in this study.
For Test #37 configuration, X=0.36 and Y=2.1 are the initial conditions. The predicted failure mode of Test #37 is ratcheting according to the seismic failure mode map as the initial condition is above the ratchet occurrence condition. The ratcheting in the elbow closing direction extends the arm length acting on the deadweight, as shown in Fig. 3(b). It increases the deadweight stress $\sigma_g$ and the X parameter accordingly. Likewise, the Y parameter decreases due to ratcheting under this test configuration. This transition of the X and Y parameter in the time domain is expressed as the translational movement of the excitation condition toward the first-excursion failure condition on the seismic failure mode map, as shown in Fig. 3(b). The transition of the X and Y parameters needs to be investigated to predict the plastic collapse due to ratcheting and clarify the failure mode of Test #37.

4. Occurrence of Ratchet-induced Collapse

4.1 Transition of X-Y Parameters

The transition of X and Y parameters is the key to the ratchet-induced collapse. The cantilever configurations are generalized to the four patterns shown in Fig. 4 based on the combination of gravity and seismic loading. While gravity increases the deformation due to the seismic loading in Shape 1, 3, and 4, Shape 2 can behave like a pendulum where gravity could help to suppress the seismic loading. The numerical analyses were conducted to compare the difference of behaviors from the viewpoint of X and Y parameters.

As shown in Fig. 5, Shape 1 and Shape 2 are examined as the representative patterns of cantilever beams. The material of the models was set to the Pb99%-Sb1% alloy considering experimental verification in the future. The Young’s Modulus is 19.1 GPa, and the yield stress is 8.5 MPa for this material. The elastic-perfect-plastic property was considered for simplicity. The material properties shown in Fig. 5 were applied to the analysis models. The cross-section of the beam is $b=13\text{mm}$ of depth and $t=6\text{mm}$ of width, which corresponds to the past studies (Lyu, 2020). The mass of 0.55kg was considered to induce the moderate X parameter of 0.6. The sinusoidal wave of 20 constant cycles, as shown in Fig. 6, was used as the input dynamic acceleration to induce ratcheting. The $fr$ was set to 1.0, which is the resonant condition. In the analysis, the gravity was applied to the models at the first step, and then the dynamic acceleration was applied orthogonal to the gravity. The ABAQUS 2018 Student Edition was employed to conduct the inelastic time-history analysis.

Fig. 3 The dynamic behavior of Test #37 in time domain and the projected failure on the seismic failure mode map. (a) The progressive accumulation of plastic deformation was assumed to result in promoting the amplitude of the seismic response. (b) The transition of the excitation condition along the accumulation of ratcheting.
The top deflection of the beams and the estimated X and Y parameters based on the deflections are shown in Fig. 7.

\[ X = \frac{\sigma_y}{\sigma_y} = L_2 \cdot \frac{m \cdot g}{Z \cdot \sigma_y} \]  
\[ Y = \frac{\sigma_m}{\sigma_y} = L_1 \cdot \frac{m \cdot i}{Z \cdot \sigma_y} \]  

For Shape 1, ratcheting due to the sinusoidal loading increases the X parameter while the Y parameter decreases. The gradual decrease of the response displacement shown as the top deflection in Fig. 7(a) is caused by the reduction of the Y parameter which is equivalent to the decrease of the input loading. However, the continuous ratcheting behavior is also observed because ratcheting can occur at a smaller Y parameter when the X parameter becomes high. For Shape 2,
ratcheting decreased the X parameter and slightly increased the Y parameter, as shown in Fig. 7(b). The significant decrease in the X parameter is expected to have brought the excitation condition below the ratchet occurrence condition. However, since the Y parameter increased, the amplitude of the top deflection at each cycle becomes slightly large in Fig. 7(b).

![Fig. 7](image)

(a) Shape 1  
(b) Shape 2

Fig. 7  The top deflection of the beam and the estimated X, Y parameters from analysis results. (a) The increase of X parameter and decrease of Y parameter are observed in Shape 1. (b) The opposite trend in Shape 2.

Fig. 8 shows the top deflection and the transition of the X and Y parameters for Shape 1 under the 100 constant cycles of sinusoidal waves, which were extended from the waveform in Fig. 6. The saturation of ratcheting corresponds to the dissatisfaction of the ratchet occurrence condition due to the transition of X and Y parameters when the X and Y parameters are plotted on the seismic failure mode map in Fig. 8. Accordingly, the transition of X and Y parameters can describe the change of the failure mode due to ratcheting. However, precise prediction of the ratcheting deformation by numerical analysis is difficult in general. The possibility of the transition of the X and Y parameters must be estimated other than typical analytical approaches such as a non-linear time-history response analysis.

![Fig. 8](image)

Fig. 8  Trend of Ratcheting projected to Seismic Failure Mode Map. Ratcheting increases the X parameter as expected but is saturated when the X-Y parameters reach the occurrence condition of ratcheting.
4.2 Introduction of Trajectory

The precise estimation of ratchet deformation is generally tricky, as mentioned, while it requires a lot of analysis costs due to the inelastic time-history response analysis. However, the possible transition path of X and Y parameters, called the trajectory, can be estimated if the deflection path of structures is obtained. Then, the conjunction points of the trajectory and the occurrence conditions explain the transition of failure modes. The theoretical deformation of a flexible beam is determined by an elliptic integral (Bisshopp et al., 1945). The theoretical deflections in the vertical and horizontal direction at the free end of the beam are expressed by Equations (8) and (9). These equations assume that the beam length is defined as \( L \), the horizontal deflection as \( \delta \), the vertical deflection as \( \Delta \), the rotation angle at the free end as \( \phi_0 \), and the loading applied on the beam is \( P \), as shown in Fig. 9. Also, the cross-sectional parameter of the beam is defined as \( EI \).

\[
\frac{L - \Delta}{L} = \left[ \frac{2EI(2p^2 - 1)}{PL^2} \right]^{1/2} \tag{8}
\]

\[
\frac{\delta}{L} = \left( \frac{EI}{PL^2} \right)^{1/2} \left[ F(p, \pi/2) - F(p, \phi_1) - 2E(p, \pi/2) + 2E(p, \phi_1) \right] \tag{9}
\]

Where,

\[
F(p, \phi) = \int_0^\phi \frac{d\phi}{(1 - p^2 \sin^2 \varphi)^{1/2}} \tag{10}
\]

\[
E(p, \phi) = \int_0^\phi \left(1 - p^2 \sin^2 \varphi \right)^{1/2} d\varphi \tag{11}
\]

\[
\phi_1 = \sin^{-1} \left( \frac{1}{\sqrt{2p}} \right) \tag{12}
\]

\[
p = \frac{1 + \sin \phi_0}{2} \quad (for \ free \ end) \tag{13}
\]

Equations (8) and (9) derive the normalized deflection of the beam with the beam length of \( L \). The coordinate of the free end, which is expressed as \((x, y) = (\delta, L - \Delta)\), is rewritten as Equation (14) by combining Equations (8) and (9). Since Equation (14) is independent of \( EI \) and \( P \), the free end path of the beam is uniquely determined by the length \( L \).

\[
L - \Delta = \frac{2(2p^2 - 1)^{1/2}}{[F(p, \pi/2) - F(p, \phi_1) - 2E(p, \pi/2) + 2E(p, \phi_1)] \delta} \tag{14}
\]

Fig. 10 shows the free end path, called the trajectory, calculated by Equations (8) and (9). As the trajectory lines have a good agreement with the fitted ellipse, the trajectory can also be approximated by an ellipse. In addition, the trajectory is also roughly approximated by a circle while the deflection is relatively small. Therefore, the trajectory of a beam can be represented by an ellipse or a circle instead of Equations (8) through (14).
The validity of the approximation of the trajectory by a circle equation is verified by the FEA approach. The static analyses of the beam model in Fig. 5 (a) applying a force at the free end were conducted without the gravity by changing the length $L_1$ and the thickness $t$ of the cross-section of the beam. The elastic perfect-plastic material property was used in the analysis model so that the plastic hinge effect is also included. Fig. 11 shows the trajectories of cantilever beams with various cross-sections and lengths. While the length $L_1$ was varied from 50 [mm] to 500 [mm] and the thickness $t$ was varied from 3 [mm] to 12 [mm], the trajectories are very close to the ellipse. While the fitting curve of the trajectory is close to an ellipse in Fig. 10, the FEA result shows the trajectory is closer to a circle. The difference in the trajectory between the theoretical calculation in Fig. 10 and the FEA in Fig. 11 can be caused by the assumption that the beam is inextensible in the theoretical equations. However, it is confirmed that the trajectory of a cantilever beam can be expressed as a circle regardless of the cross-sectional characteristic. This means that the trajectory of a cantilever beam is alternatively expressed as a rotation of a rigid beam along an imaginary hinge at the anchor point.

![Diagram](image)

**Fig. 10** The theoretical deflection of a flexible beam. The deflection of the free end of the beam can be approximated by an ellipse.

4.3 Characteristic of X-Y Trajectory

The transition of the X and Y parameters are investigated because it is essential to identify the failure mode. The X and Y parameters are dependent on the $\sigma_g$ and $\sigma_{in}$ according to Equations (3) and (4) because the yield stress is constant. Also, since the mass, gravity, and the peak acceleration are constant or uniquely determined when focused on a
single seismic event, $\sigma_g$ and $\sigma_{im}$ are mainly driven by the moment arms for the bending moments, which are dependent on the deflection of the beam. When a simplified cantilever beam with a concentrated mass as shown in Fig. 12(a) is assumed, the original moment arm of $L_1$ turns out to $L_1'$ after deformation. Likewise, the initial moment arm of $L_2$ becomes $L_2'$ as shown in Fig. 12(a). Since the trajectory of a beam can be approximated by a circle as earlier mentioned, the moment arms $L_1'$ and $L_2'$ can also be expressed as the rotation of rigid beams $L_1$ by the beam root angle $\theta$ and $L_2$ by the beam top angle $\phi_0$ as shown in Fig. 12(b). The $X$ and $Y$ parameters defined by Equations (5) and (6) can be written using $L_1$ and $L_2$ as Equations (15) and (16) for a cantilever under deformation.

\[
X = \frac{m(L_1\sin\theta + L_2\cos\phi_0)}{Z \cdot \sigma_y} g \\
Y = \frac{m(L_1\cos\theta - L_2\sin\phi_0)}{Z \cdot \sigma_y} l
\]

The transition of the $X$ and $Y$ parameters plotted on the seismic failure mode map is called as X-Y trajectory. The difference of the cantilever structures is compared between the four configurations, which are shown in Fig. 13(a). Cantilever structures subject to the deadweight and seismic loading are generalized and represented by those four configurations. The arrows in Fig. 13(a) show the expected deflection directions. The X-Y trajectories for the four configurations are shown in Fig. 13(b). In this figure, $X$ and $Y$ parameters are normalized by the initial values so that the trajectory is independent of the magnitude of the mass, gravity, or seismic loading.

![Fig. 12](image1)

(a) Theoretical Cantilever Deformation  
(b) Approximated Deformation Model

![Fig. 13](image2)

(a) Representative cantilever configurations  
(b) Transition of X-Y parameters

Fig. 12 Transition of the effective moment arms under large deformation. (a) The theoretical deformation. (b) The equivalent deformation model expressed as the root angle $\theta$ and the top angle $\phi_0$.

Fig. 13 The trajectory of various cantilever beams. (a) 4 cantilever beams are considered as representative layout. (b) The transition of X-Y parameters is dependent on the layout. In Shape 1 and 2, significant transition of the $X$ parameter occurs, while significant transition of $Y$ parameter was found in Shape 3 and 4.
At Shape 1, the mass is located at the top of the structure. It was revealed that the significant increase of the X parameter and relatively insignificant decrease of the Y parameter along with the deformation. The significant X parameter reduction in parallel with the negligible Y parameter increase is confirmed when the mass at the bottom of the structure that is Shape 2. According to the seismic failure mode map, a smaller Y parameter can cause a failure when the X parameter is high. Because the occurrence conditions are sensitive to the X parameter, failure due to ratcheting is more likely at Shape 1. A stable behavior is expected at Shape 2 because the X and Y parameters move away from the occurrence condition due to ratcheting. Likewise, stable behavior is expected at Shape 3 compared to Shape 4. The specimen of Test #37 corresponds to the Shape 1 configuration. According to the character of the trajectory, the failure mode of Test #37 could have turned to plastic collapse from ratcheting.

4.4 Occurrence of Ratchet-induced Collapse

The significant effect of ratcheting is expressed as the transition of the X and Y parameters. The failure of a structure is considered to occur when the X and Y parameters satisfy the occurrence condition of the failure modes during ratcheting. The occurrence condition of the first-excursion failure, one of the plastic collapses, was developed assuming a half-sine loading shown in Fig. 14(a) in the past study (Sasaki, 2020). On the other hand, the impulsive character of seismic motions is represented as a sine loading (G.P Mavroeidis, 2004). Thus, the occurrence condition of plastic collapse due to sine loadings is investigated by numerical analysis. The FEA model for Shape 1, shown in Fig. 5 (a), is used in the numerical analysis. The applied parameters are tabulated in Table 1. The acceleration function in Fig. 14(b) is adjusted in the time domain to achieve the specific frequency ratios of 0.5, 1.0, and 1.5. The 3% plastic strain at the root surface of the beam, the stress/strain calculation point in Fig. 5 (a), is used as the criterion of plastic collapse. The amplitude of the acceleration function was gradually increased until 3% of plastic strain was observed, and the peak acceleration was converted to the Y parameter to be plotted.

The occurrence conditions of the plastic collapse due to a full-sine loading for each frequency ratio are summarized in Fig. 15. The trend of the occurrence of the plastic collapse due to a sinusoidal wave is the same as those of other failure modes, as the less Y parameter is needed to induce the failure mode when the X parameter becomes large. On the other hand, since the occurrence condition of the plastic collapse stays below that of the first-excursion failure at any frequency ratio, the plastic collapse due to sinusoidal loading can easily occur. The difference of the occurrence conditions is considered to depict the difference of the characteristic of seismic loading against plastic collapse. The plastic collapse under ratcheting will occur at the first-excursion region when the seismic loading is simplified by a half-sine loading. However, if the characteristic of the seismic loading is close to the full-sine loading, the plastic collapse under ratcheting may occur below the occurrence condition of the first-excursion failure. In other words, the difference of the characteristic of seismic loading can be represented by the occurrence condition of the failure on the seismic failure mode map.

Therefore, the concept of predicting the occurrence of the ratchet-induced collapse can be summarized as Fig. 16. The initial X and Y parameters are determined by the static stress of the gravity and the peak acceleration of the seismic loading. Then the X-Y trajectory can also be determined using the ellipse approximation. The ratchet-induced collapse is expected when the occurrence condition and the X-Y trajectory have the conjunction points. Although the occurrence condition of the plastic collapse depends on the characteristic of the seismic loading, the bounding condition can be
developed using a simplified loading function shown in Fig. 14(b) because the plastic collapse is an instantaneous phenomenon within a cycle of seismic loading. This approach predicts the ratchet-induced collapse without a ratchet deformation from the simulation analyses such as an inelastic time-history response analysis since the X-Y trajectory is calculated from the kinematic path of beams.

Table 1 The parameters of the structure to be examined in the numerical analysis.

<table>
<thead>
<tr>
<th>X</th>
<th>Mass [kg]</th>
<th>L₁ [mm]</th>
<th>L₂ [mm]</th>
<th>fₚ [Hz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.61</td>
<td>0.55</td>
<td>130</td>
<td>75</td>
<td>10.62</td>
</tr>
<tr>
<td>0.85</td>
<td>0.77</td>
<td>130</td>
<td>75</td>
<td>9.17</td>
</tr>
<tr>
<td>1.1</td>
<td>0.99</td>
<td>130</td>
<td>75</td>
<td>8.33</td>
</tr>
</tbody>
</table>

Fig. 15 The occurrence conditions of the failure modes at various frequency ratio. (a) At fr=0.5, (b) At fr=1.0, and (c) At fr=1.5. At any frequency ratios, ratcheting is most likely, the plastic collapse easily occurs compared to the first-excursion failure. Also, the failure becomes hard to occur when the frequency ratio becomes high.

Fig. 16 The prediction concept of the ratchet-induced collapse. The trajectory describes the X and Y parameters of structures under ratcheting. The collapse is expected if the trajectory has a possibility to satisfy the collapse condition, which is expressed as the conjunction of the trajectory and the occurrence condition.

5. Conclusion

The failure at Test #37 of PFDRP is interpreted as the plastic collapse induced by ratcheting. This failure mode was defined as the ratchet-induced collapse, and the mechanism has been investigated based on the simplified cantilever beam. The results are summarized below.

1) The transition of the excitation condition along ratcheting is expressed as the transition of the deadweight stress and the seismic stress on the structure, which are expressed as X and Y parameters. The X-Y trajectory, which expresses...
the transition path of those parameters, can be obtained by the theoretical equations.

(2) The transition of the X and Y parameters contributes to changing the failure mode. The failure mode change due to ratcheting occurs at the conjunction points between the X-Y trajectory and the failure occurrence conditions. The ratcheting is saturated when the X-Y trajectory goes below the ratchet occurrence condition. The ratchet-induced collapse occurs when the X-Y trajectory goes above the plastic collapse occurrence condition.

(3) The occurrence condition of the plastic collapse depends on the characteristic of the seismic loading. The effect of the seismic loading on the occurrence condition needs to be investigated.

(4) The prediction approach of the ratchet-induced collapse is proposed. Since this approach does not rely on the calculation of the ratchet deformation, the precision of the simulation analysis is no longer the concern. The occurrence of the ratchet-induced collapse can be predicted by using the seismic failure mode map and the X-Y trajectory of structures.

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