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APPLICABILITY OF EQUIVALENT LINEAR THREE-DIMENSIONAL FEM ANALYSIS FOR REINFORCED CONCRETE SHEAR WALLS

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ABSTRACT

This paper proposes a novel equivalent linear three-dimensional finite element method (3D FEM) analysis method for the shear capacity of reinforced concrete (RC) shear walls, focusing on the analysis accuracy of the maximum shear strain γ_{max}, independent of coefficient α. To this end, we approximated the response of elastoplastic systems with nonlinear 3D FEM using 3D FEM of equivalent linear systems based on the strain-dependent characteristics of RC. We proposed a novel equivalent linear 3D FEM analysis method to evaluate the damping (h)–shear strain (γ) relationship based on a single-degree-of-freedom nonlinear analysis using the threefold skeleton curve and maximum point-oriented hysteresis curve provided by the Japan Electric Association (2023). To evaluate the proposed method, we determined the analysis accuracy for nonlinear 3D FEM for RC shear walls of a nuclear reactor building. The results indicated that the maximum shear forces Q_{max} and maximum shear strain γ_{max} obtained by equivalent linear 3D FEM tended to be slightly larger than those obtained by nonlinear 3D FEM. Therefore, by applying the proposed method and the h–γ relationship presented in this paper to equivalent linear 3D FEM analysis, Q_{max} and γ_{max} may be conservatively evaluated as larger than those in nonlinear 3D FEM analysis.

INTRODUCTION

In Japan, the seismic design of nuclear reactor facilities allows for plastic deformation in response to design-basis earthquakes (DBEs). Therefore, incorporating the nonlinear response of buildings into the design is of critical importance. However, reproducing the elastoplastic response to DBEs using nonlinear three-dimensional finite element method (3D FEM) analysis requires a large amount of computation time and cannot meet the speed requirements of the actual design.

To address this problem, equivalent linear analysis can be employed to considerably reduce the computation time. This method approximates the elastoplastic response to DBEs by a linear analysis that considers stiffness reduction and damping increase. Numerous studies have investigated this method, such as those by Schnabel et al. (1972), Yoshida et al. (2002), Ghiocel (2015), and Ichihara et al. (2022). Particularly in the field of geotechnical engineering, equivalent linear analysis conducted by SHAKE (Schnabel et al., 1972) is the most well-known and has been extensively applied in the seismic analysis of nuclear reactor facilities. The analysis employs the strain-dependent characteristics of the soil, specifically, the G/G_0–γ and h–γ relationships, where G/G_0 is the stiffness reduction ratio, γ is the shear strain, and h is the damping constant. These characteristics are derived from steady-state excitation tests. The analysis obtains the equivalent stiffness G_e and equivalent damping h_e in the subsequent step using the effective shear strain γ_{eff} during an earthquake. Then, convergence analysis is performed until the changes, including the difference between the k − 1st and kth analysis results, are within an acceptable range. Typically, γ_{eff} is obtained by multiplying the maximum shear strain γ_{max} by a coefficient α. It should be noted that α varies depending on the seismic motion and soil conditions, ranging from 0.55 to 0.65, as reported by Schnabel et al. (1972). A value of 0.65 is typically set empirically.

Ghiocel (2015) extended the SHAKE method to 3D FEM for buildings. This involved establishing a group of meshes, such as seismic walls, as a panel, obtaining the response as a member from the response of the four corners of the panel, and then subjecting it to equivalent linear analysis as in

SHAKE. Ichihara et al. (2022) confirmed the effectiveness of the equivalent linear analysis method for buildings proposed by Ghiocel (2015) by comparing its results with those of previous shaking table tests and nonlinear 3D FEM analyses of buildings. Their study proposed the optimal setting of α within the scope of consideration; however, their results were valid under limited conditions, and it was demonstrated that the optimal α can change depending on seismic motion and soil conditions.

In the aforementioned studies, the difference between the strain-dependent properties of the soil or reinforced concrete (RC) and the unsteady seismic response is represented as $\gamma_{eff} = \gamma_{max} \times \alpha$. Although the effectiveness of using γ_{eff} has been confirmed, the setting of α can change under different conditions (Yoshida et al., 2002). Furthermore, the range that can be adjusted with α is limited; as a result, the meaning of equivalence in equivalent linear analysis is unclear. In the design of RC seismic walls for nuclear reactor facilities in Japan, the maximum point-oriented model (Japan Electric Association (JEA), 2023) is employed as the hysteresis law for shear strength. However, this model has almost no hysteresis area and appears to be inconsistent with the h–γ relationship based on steady-state excitation and the concept of correction by α.

Therefore, this study proposes a novel equivalent linear 3D FEM analysis method for the shear capacity of RC seismic walls that is independent of α, focusing on the analysis accuracy of γ_{max}. We aim to approximate the response of elastoplastic systems obtained by nonlinear 3D FEM by employing 3D FEM of equivalent linear systems based on the strain-dependent characteristics of RC. Specifically, by determining h_e, which is equivalent to γ_{max} of an elastoplastic system based on the conventional lumped-mass stick (LMS) design model, by using a linear system model, we derive a new formula for calculating h that does not require the reduction of γ_{max} by α. Then, we perform a convergence analysis based on the strain-dependent characteristics of RC using the average shear strain γ_{ave} obtained from the relative displacements of the four corner nodes of the RC shear wall modeled by 3D FEM.

The target RC structure is the RC seismic wall of a nuclear reactor building (RB) provided by the Nuclear Power Engineering Corporation of Japan (NUPEC) in the 1996 Seismic Shear Wall International Standard Problem (OECD/NEA, 1996). The validity of the proposed method is confirmed through comparison with a nonlinear 3D FEM model of the same wall. To accurately evaluate γ_{max}, it is necessary to verify that the analytical model reproduces the actual response through simulation analysis and other verification methods. Herein, we propose an equivalent linear 3D FEM analysis method using the model verified by Ueda et al. (1996).

PROPOSED EQUIVALENT LINEAR 3D FEM ANALYSIS METHOD

Proposed Approach

This subsection presents the proposed approach to make the equivalent linear analysis method compatible with 3D FEM. The equivalent linear analysis method employed by Schnabel et al. (1972) and Ghiocel (2015) obtains the equivalent stiffness G_e and equivalent damping h_e based on γ_{eff}, which is calculated as follows:

$$\gamma_{eff} = \alpha \cdot \gamma_{max} \tag{1}$$

In the original paper (Schnabel et al., 1972), the maximum acceleration is considered approximately equivalent to that obtained by nonlinear analysis; however, the physical meaning is not specified. In this study, the strain-dependent properties of RC are determined such that γ_{max} is equivalent between nonlinear and equivalent linear analyses. That is, based on the hysteresis loop obtained by nonlinear analysis, G_e is evaluated by the secant stiffness connecting γ_{max} and the origin. Then, h_e, which is equivalent to γ_{max}, is identified.

The LMS model, a conventional design model, is employed as the reference nonlinear analysis, and an inverse analysis of h_e is performed for γ_{max} obtained from the LMS model. The reasons for selecting the LMS model for inverse analysis are as follows:

- The LMS model is the simplest method for predicting the elastoplastic response of superstructures due to its reduced degrees of freedom.
- This model corresponds to the threefold skeleton curve and maximum point-oriented hysteresis curve provided by JEA (2023). Moreover, it aligns with seismic design based on the current standard.
- This model has a small computational load and can easily consider several input seismic motions.

We believe that G_e and h_e, obtained as described above, can be extended to 3D FEM for building using the panel concept described by Ghiocel (2015). This can enable equivalent 3D FEM analysis with a certain degree of conservatism compared to γ_{max} obtained by nonlinear 3D FEM. In this study, the proposed method is validated on the assumption that the target RC structure is reduced to a single-degree-of-freedom (SDOF) system.

Calculation Procedure of Proposed Method

This subsection describes the calculation procedure of the equivalent linear 3D FEM analysis method, as illustrated in Fig. 1.

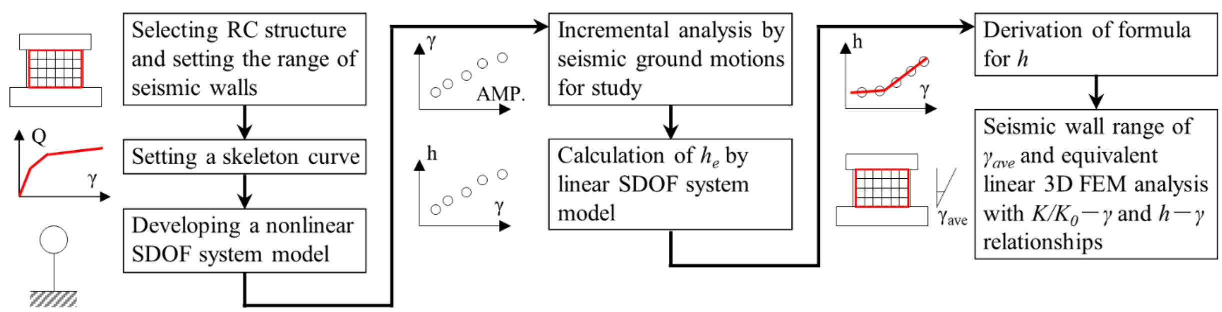


Fig. 1 Calculation procedure of equivalent linear 3D FEM analysis method

[1] The target RC structure is selected, and the extent of its main structural element, the seismic wall, is determined.
[2] The skeleton curves assumed in the design are assigned to each of the defined seismic walls.
[3] The structure extracted in Step 1 is reduced to a single LMS model, and the skeleton curve set in Step 2 is reflected in the model to create a nonlinear SDOF model.
[4] Incremental analysis is performed for several seismic motions with different input levels to investigate the structural response.
[5] The damping constant h_e, which is equivalent to γ_{max} obtained by the incremental analysis in Step 4, is determined from the linear SDOF model. Here, G_e is set using the secant stiffness connecting γ_{max} and the origin based on the relationship between the shear force Q and γ obtained from the nonlinear analysis.
[6] Based on the results obtained in Step 5, h is derived as a function of the ductility factor μ using equation (2). In this equation, A and B are unknown coefficients, as described in the following subsection, and h_0 is the initial damping constant:

$$h = A\left(1 - \frac{1}{\mu^B}\right) + h_0 \quad (2)$$

[7] Equivalent linear 3D FEM analysis is performed on the $G/G0$–γ curve determined by Step 2 and the h–γ curve determined by Step 6 based on γ_{ave} obtained from the relative displacements of the four corner nodes of the seismic wall range set in Step 1. G_e and h_e, obtained by equivalent linear 3D FEM analysis, are set to uniform values within the range defined for the seismic wall.

Identification Method for Unknown Coefficients A and B

In this study, h is derived as a function of the ductility factor μ presented in equation (2) based on the damping that is equivalent to the analysis results of the nonlinear SDOF model. The unknown coefficients A and B are determined using the following equation based on h_e, which is obtained by inverse analysis using the linear SDOF model:

$$E_{rr} = \sum(h_e - h)^2, \tag{3}$$

where E_{rr} represents the error between h_e and h. A and B, which minimize the sum of squares of the difference between the h_e and h in equation (3), are obtained by the least-squares method.

PROPOSED CONDITIONS AND MODEL

Damping Constant h

This subsection presents the proposed approach for integrating equivalent linear analysis methods with 3D FEM. Fig. 2 illustrates the RC seismic wall employed to calculate h and the calculation model (OECD/NEA, 1996). In this study, h was calculated using a model that reduces the seismic wall to an SDOF. Two types of SDOF models, nonlinear and linear SDOF models, were employed. The threefold skeleton curve and maximum point-oriented hysteresis curve provided by JEA (2023) were set as the nonlinear characteristics of the nonlinear model.

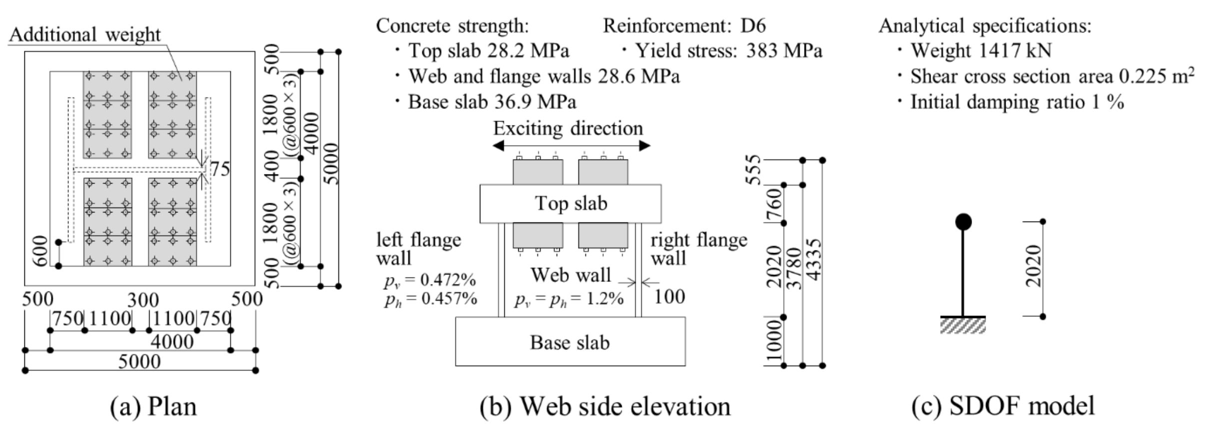


Fig. 2 RC seismic wall and model for the calculation of h (OECD/NEA, 1996): (a) Plan, (b) Web side elevation, (c) SDOF model

3D FEM Model

This subsection describes the validation conditions and model for evaluating the analysis accuracy of equivalent linear 3D FEM, which is described later. Fig. 3 illustrates the 3D FEM model employed for validation. This study utilized a nonlinear 3D FEM model, whose consistency with experimental results was demonstrated by Ueda et al. (1996) for the RC seismic wall displayed in Fig. 2 (OECD/NEA, 1996). The model uses layered shell elements with a smeared crack representation to model RC seismic walls. In addition, plastic deformation up to wall failure was considered based on the stress–strain relationship of the RC materials.

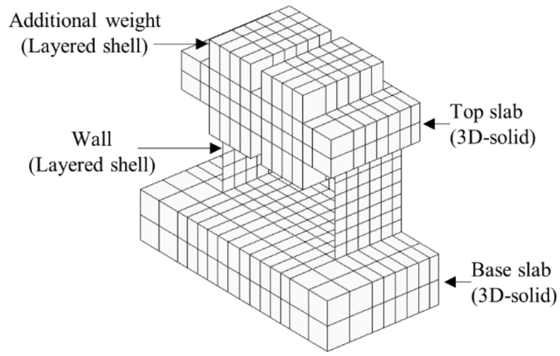


Fig. 3 3D FEM model used in validation (Ueda et al., 1996)

To convert the model into an equivalent linear 3D FEM model, the stress–strain relationship of the RC material due to plastic deformation of the wall was modeled as a 3D FEM model of an equivalent linear system by expressing it in terms of G_e and h_e, which were obtained from the strain-dependent characteristics of RC. The damping was implemented as stiffness-proportional damping with h_0 = 1.0%, and damping equivalent to h_0 = 1.0% was consistently maintained by increasing the damping as the stiffness was reduced. For the iterative equivalent linear analysis, the convergence condition for both stiffness and damping was that the error between the kth and $k-1$th iterations was less than 5%, or the upper limit of the number of iterations reached 10. If the number of iterations did not converge after reaching the upper limit, the result obtained from the 10th calculation was adopted. The 3D nonlinear response analysis program NAPISOS, developed by Takenaka Corporation, was employed to calculate h by the SDOF model and validate the accuracy by 3D FEM.

Seismic Motion for Analysis

This subsection describes the seismic motions employed in the above-mentioned SDOF model analysis and 3D FEM analysis. Fig. 4 presents the acceleration response spectrum and representative acceleration time history waveforms of the seismic motions used in this study. In the figure, RP represents the random phase.

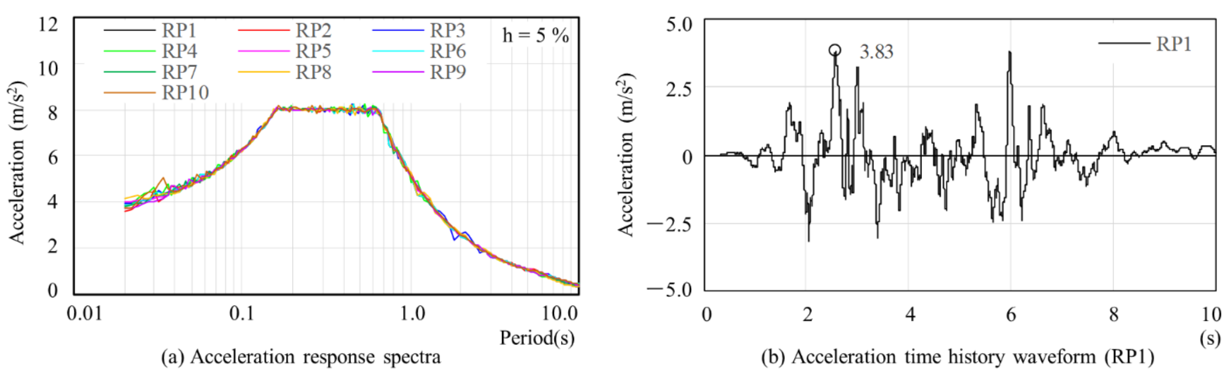


Fig. 4 Representative seismic motion: (a) Acceleration response spectra, (b) Acceleration time history waveform (RP1)

In this study, the seismic motion was based on the acceleration response spectrum (very rare seismic motion, L2) in accordance with Notification No. 1,461 of the Building Standard Law of Japan (2016) specified by the Ministry of Japan. By applying 10 different random phases to the spectrum, waves RP1 to RP10 with a maximum acceleration of 3.8 m/s^2 were generated. Furthermore, a total of 100 acceleration time history waveforms with maximum accelerations ranging from 2.85 m/s^2 (Case 1) to 4.56

m/s^2 (Case 10) were generated by multiplying each seismic motion by an adjustment factor incremented by 0.05 from 0.75 to 1.2.

The envelope curve of the acceleration time history waveform of the seismic motion was a Jennings-type envelope function (Jennings, 1969), with coefficients t_b, t_c, and t_d set to 2, 6, and 10 s, respectively. The duration of the seismic motion was set to 10 s, and the time increment Δt was set to Δt = 0.001 s. The seismic motion was created with Δt = 0.01 s. After creating the seismic motion, a wave with Δt = 0.001 s was created by dividing the original wave into 10 parts by linear interpolation between Δt. The seismic motion was subjected to a high-cut filter above 40 Hz to eliminate the effect of noise due to high-frequency components.

Validation of Proposed Method

Calculation Results of Damping Constant h

In this subsection, we present the calculation results of h, derived based on the conditions provided in the previous section. Fig. 5 presents the relationship between the maximum shear force Q_{max} and maximum shear strain γ_{max} for the nonlinear and linear SDOF models obtained from the seismic motions presented in Fig. 4. In Fig. 5, the black dotted line represents the threefold skeleton curve according to JEA (2023), while the blue circles represent the analysis results based on the nonlinear SDOF model (SDOF-NL). The green circles represent the analysis results based on the linear SDOF model (SDOF-L).

In this study, the plasticity levels for all seismic motions were set to fit between the first and second breakpoints. Therefore, as the scope of application of calculation formula (2), we first confirmed the distribution trend of h in the weakly nonlinear region from the first breakpoint to the second breakpoint. The Q_{max}–γ_{max} relationship between SDOF-L and SDOF-NL is almost identical because the SDOF-L results are obtained by inverse analysis of h_e, which is equivalent to γ_{max} obtained by SDOF-NL.

Fig. 6 presents the relationship between h_e and h, which is obtained using equation (2). The black dotted line represents the h–γ relationship based on the unknown coefficients A (0.059) and B (2.342) determined from h_e by SDOF-L, represented by green circles, and the initial damping constant h_0 (1.0%).

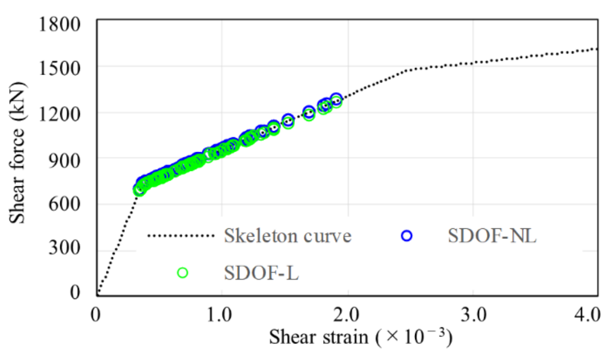


Fig. 5 Q_{max}–γ_{max} relationship for SDOF-NL and SDOF-L

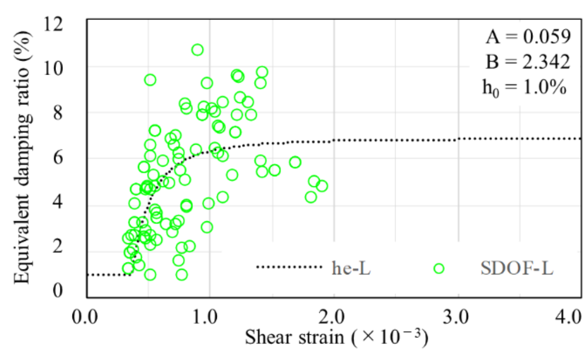


Fig. 6 Relationship between h_e and h

From Fig. 6, it can be seen that h increases rapidly after the first breakpoint, and the damping gradient is moderate after $\gamma = 1.0 \times 10^{-3}$. Moreover, h_e exhibits large overall variation and greatly exceeds h of the h–γ relation in some cases. This may be because the validation was performed on RC seismic walls of an RB, which tend to be more variable for structures with high stiffness, such as the same wall. However, due to this variability, the result of the equivalent linear 3D FEM analysis based on the equation for h may underestimate Q_{max} and γ_{max} by a certain percentage. Therefore, in the following subsection, the effect of equation h derived by equation (2) on the result of the equivalent 3D FEM analysis is assessed in terms of analytical accuracy.

Accuracy of Nonlinear 3D FEM Analysis

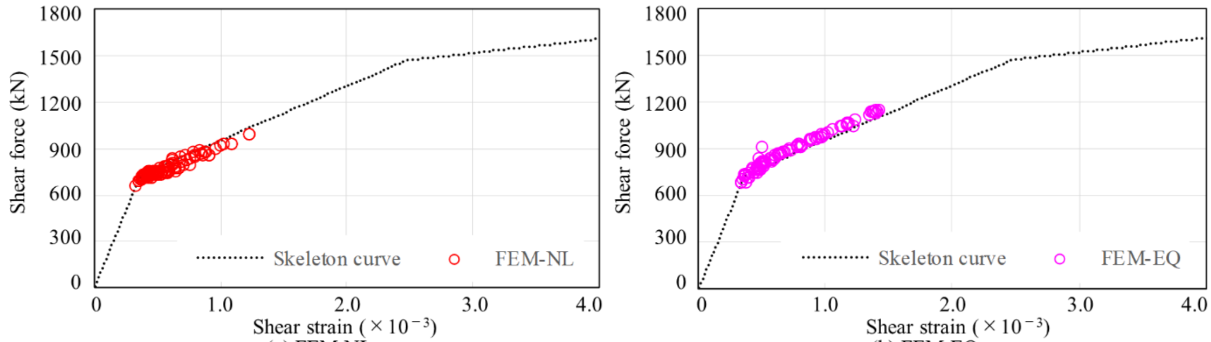
In this subsection, we use the results obtained from the nonlinear 3D FEM model analysis provided in the previous subsection as ground truth data to evaluate the analytical accuracy of the equivalent linear 3D FEM model based on the h–γ relationship illustrated in Fig. 6. Fig. 7 presents the Q_{max}–γ_{max} relationship for both the nonlinear and equivalent linear 3D FEM models. In this figure, red circles represent the analysis results of the nonlinear 3D FEM model (FEM-NL), while pink circles represent the analysis results of the equivalent linear 3D FEM model (FEM-EQ). It should be noted that γ_{max} in the figure was evaluated by replacing the maximum story drift angle with γ_{max} for simplicity since shear deformation is the dominant deformation component in the RC seismic wall presented in Fig. 2. Similarly, Q_{max} was assumed to be the maximum inertia force obtained by multiplying the maximum acceleration determined by each model by the mass. The skeleton curve provided by JEA (2023) is represented as a black dotted line for reference; however, the FEM-NL results are not necessarily plotted on this curve because there is no direct relationship between the stress–strain relationship set in the nonlinear 3D FEM model and the skeleton curve.

Fig. 7 indicates that FEM-EQ tends to overestimate Q_{max} and γ_{max} compared to the Q_{max}–γ_{max} relationship of FEM-NL, with plasticization progressing to approximately the intermediate position between the first and second breakpoints. The size of the Q_{max} and γ_{max} increases as follows: FEM-NL < FEM-EQ < SDOF-NL and SDOF-L. This indicates that the FEM-EQ results are closer than the SDOF results to the FEM-NL results.

Fig. 8 presents the analytical accuracy of Q_{max} and γ_{max} obtained by FEM-EQ and SDOF-NL relative to FEM-NL. In the figure, Q_{max} and γ_{max} obtained by FEM-EQ and SDOF-NL are represented on the horizontal axis, while Q_{max} and γ_{max} obtained by FEM-NL are represented on the vertical axis as ground truth data. The black dotted line with a slope of 1 corresponds to the case where the maximum value matches that of FEM-NL. The pink dotted line corresponds to the average value of FEM-EQ, while the blue dotted line corresponds to the average value of SDOF-NL.

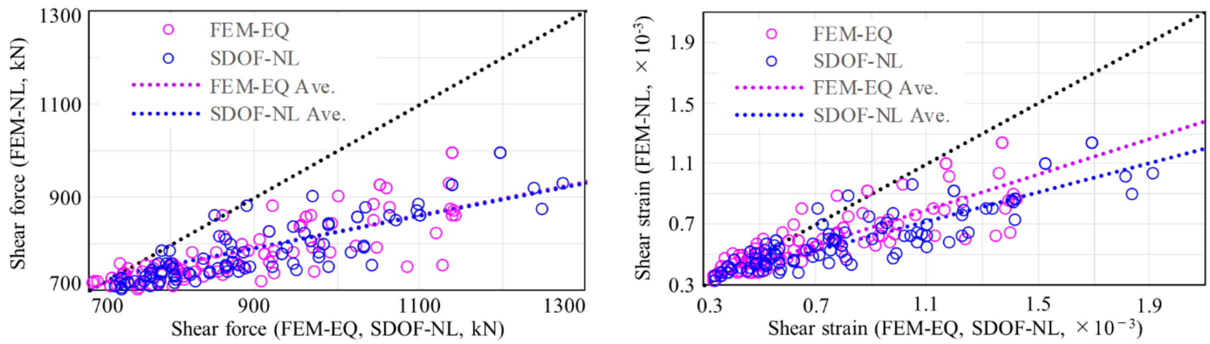
From Fig. 8, it can be seen that both FEM-EQ and SDOF-NL exhibit the same level of accuracy in reproducing Q_{max}. In addition, Q_{max} obtained by FEM-EQ and SDOF-NL tends to be slightly larger than that obtained by FEM-NL, including individual variations. This difference appears to be due to the respective damping of the models and the fact that the damping effect associated with an increase in hysteresis area is expected more for FEM-NL, which has a hysteresis loop, than for FEM-EQ and SDOF-NL. In contrast, γ_{max} obtained by FEM-EQ exhibits a closer correspondence to γ_{max} obtained by FEM-NL than γ_{max} obtained by SDOF-NL. Moreover, γ_{max} obtained by FEM-EQ, including individual variations, is more accurate than γ_{max} obtained by SDOF-NL. As mentioned earlier, this may be due to the fact that the damping in FEM-EQ is obtained from the h–γ relationship presented in Fig. 6, and damping associated with an increase in γ is evaluated as larger than that in SDOF-NL. It should be noted that these trends in Q_{max} and γ_{max} are consistent with the results presented in Figs. 5 and 7.

Fig. 9 presents the relationship between the Q–γ waveforms of FEM-NL, FEM-EQ, and SDOF-NL for 10 waves of maximum acceleration 2.85 (Case 1) to 4.6 (Case 10) of RP1 as representative random phase waves. The red solid line represents the Q–γ waveform of FEM-NL, while the blue solid line represents the Q–γ waveform of FEM-EQ or SDOF-NL.



(a) FEM-NL (b) FEM-EQ

Fig. 7 Q_{max}–γ_{max} relationship: (a) FEM-NL, (b) FEM-EQ



(a) Q_{max} (b) γ_{max}

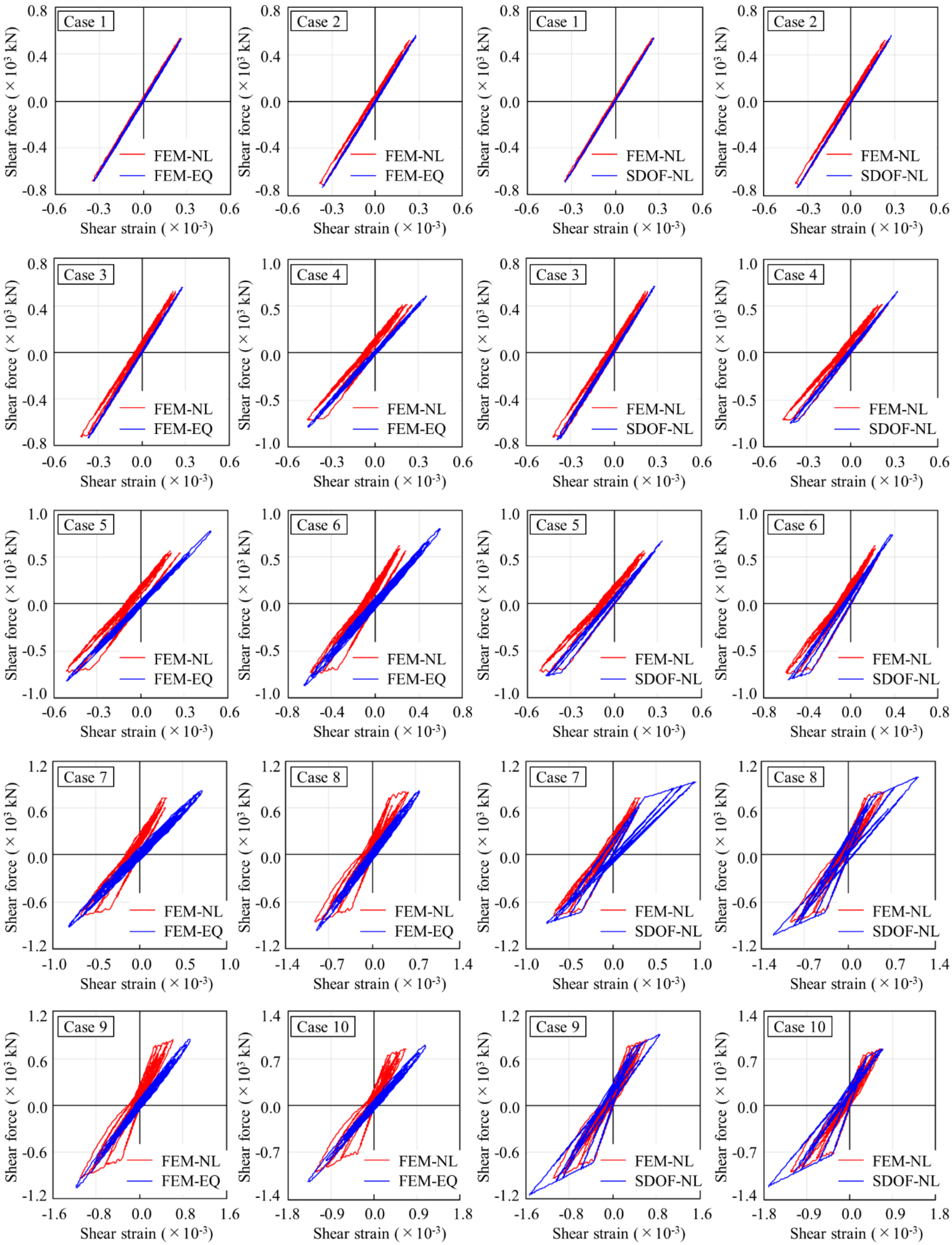
Fig. 8 Analytical accuracy of FEM-EQ and SDOF-NL relative to FEM-NL: (a) Q_{max}, (b) γ_{max}

As observed in Fig. 9, the hysteresis loop of FEM-EQ demonstrates that the gradient of Q–γ tends to decrease with the input seismic motion from Cases 1 to 10. This gradient is approximately represented by the secant stiffness connecting the maximum response displacement of FEM-NL and the origin, indicating that the hysteresis loop of the linear system reproduces Q_{max} and γ_{max} of FEM-NL relatively well. Similarly, for the SDOF-NL hysteresis loop, plasticization development proportional to the input seismic motion is observed, confirming the unique maximum point-oriented hysteresis shape. However, the difference between Q_{max} and γ_{max} of SDOF-NL and FEM-NL gradually expands with increasing case numbers, indicating the tendency to slightly overestimate Q_{max} and γ_{max} compared to FEM-EQ.

As described above, by applying the proposed method and the formula for calculating h presented in this study to equivalent linear 3D FEM analysis using FEM-EQ, Q_{max} and γ_{max} tend to be evaluated conservatively compared to the values obtained by nonlinear 3D FEM analysis using FEM-NL. Moreover, compared to γ_{max} obtained by the nonlinear analysis of the SDOF system by SDOF-NL, which is similar to the conventional design model, γ_{max} obtained by FEM-EQ of FEM-EQ, is similar to the value obtained by FEM-NL. Furthermore, the accuracy of γ_{max} improves slightly using the proposed method.

CONCLUSIONS

The aim of this study was to propose a new equivalent linear 3D FEM analysis method for the shear strength of RC seismic walls, focusing on the analysis accuracy of γ_{max}, independent of α. To this end, the analysis accuracy of FEM-EQ using the proposed method was verified through comparison with the elastoplastic analysis results obtained by FEM-NL and SDOF-NL. The obtained findings are as follows.



(a) FEM-NL vs. FEM-EQ (a) FEM-NL vs. SDOF-NL

Fig. 9 *Q*–*γ* waveform relationship (RP1): (a) FEM-NL vs. FEM EQ, (b) FEM-NL vs. SDOF-NL

1) In our novel equivalent linear 3D FEM analysis method, we proposed an evaluation approach for the h–γ relationship, which is a parameter of the strain-dependent characteristics of FEM-EQ. Our approach is based on γ_{max}, which is obtained by SDOF-NL using threefold skeleton curves and maximum point-oriented hysteresis curves containing almost no hysteresis area provided by JEA (2023). In the proposed method, the G/G_0–γ relationship obtained from the JEA (2023) skeleton curve and the h–γ relationship obtained from the calculation formula of h were used to calculate the convergence of G_e and h_e directly from γ_{ave}, obtained from the relative displacements at the four corners of the seismic wall set up in the 3D FEM. G_e and h_e obtained from the convergence calculations were extended to equivalent linear 3D FEM by applying the same values uniformly within the range set for the seismic wall.
2) To validate the proposed method, the analysis accuracy for FEM-NL was evaluated for seismic motions in the weakly nonlinear region between the first and second breakpoints of the skeleton curve. The results indicated that Q_{max} and γ_{max} obtained by FEM-EQ tended to be slightly larger than those obtained by FEM-NL, including variations in individual responses. This may be because the equivalent damping in FEM-EQ is obtained from the h–γ relationship proposed in this study, which tends to evaluate the damping effect at γ, where plasticization has developed, to a larger extent than SDO-NL, which has a maximum point-oriented hysteresis curve. In addition, in comparison with γ_{max} obtained by SDOF-NL, which is similar to the conventional design model, γ_{max} obtained by FEM-EQ is closer to that obtained by FEM-NL, indicating that the accuracy of γ_{max} tends to improve with the application of the proposed method.

By applying the proposed method and the equation for calculating h presented in this study to equivalent linear 3D FEM analysis using FEM-EQ, we found that Q_{max} and γ_{max} can be conservatively evaluated as larger values compared to those obtained by nonlinear analysis using FEM-NL, which considers the stress–strain relationship in RC materials. In this study, verification results were presented for RC seismic walls provided by NUPEC in OECD/NEA (1996). By applying the same concept to 3D FEM for buildings, the proposed method can be applied to major facilities such as RBs. However, this study was limited to RC seismic walls provided by NUPEC. FEM-EQ validation for complex structures and strongly nonlinear regions, as encountered in actual design, has not been performed. For practical application of the proposed method, it is necessary to acquire sufficient knowledge of RC structures and their scope of applications through verification with FEM-NL. This will be addressed in future work.

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