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AN EQUIVALENT MULTI-PHASE SIMILITUDE LAW FOR PSEUDODYNAMIC TEST ON SMALL-SCALE R/C MODELS

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SUMMARY

Small-scale models have been frequently used for experimental test of seismic performance because of limited testing facilities and economic reasons. However, there are not enough studies on similitude law for analogizing prototype structures accurately with small-scale models, although conventional similitude law based on geometry is not well consistent in the inelastic seismic behavior. When fabricating prototype and small-scale model of reinforced concrete structures by using the same material, added mass is demanded from a volumetric change and scale factor could be limited due to size of aggregate. Therefore, it is desirable that different material is used for small-scale models. Thus, a modified similitude law could be derived depending on geometric scale factor, equivalent modulus ratio and ultimate strain ratio. In this study, compressive strength tests are conducted to analyze the equivalent modulus ratio of micro-concrete to normal-concrete. Then, equivalent modulus ratios are divided into multi-phase damage levels, which are basically dependent on ultimate strain level. Therefore, an algorithm adaptable to the pseudodynamic test, considering equivalent multi-phase similitude law based on seismic damage levels, is developed. In addition, prior to the experiment, it is numerically verified if the developed algorithm is applicable to the pseudodynamic test. It is confirmed that the equivalent multi-phase similitude law proposed in this study could be suitable for seismic performance tests on small-scale models.

INTRODUCTION

In many cases, feasibility on seismic design of civil structures has been verified by using the experimental methods, in which small-scale models have been frequently used because of limited testing facilities and economic reasons [1-3]. However, there are not enough studies on similitude laws for analogizing prototype structures accurately with small-scale models. An experimental study on seismic performance of reinforced concrete structures using micro-concrete material for small-scale models and considering bond strength of reinforcement steels [1] has been reported. And an experiment on a small-scale model of high-rise buildings with various added masses [2] has been studied. However, since conventional similitude laws [4,5] are usually derived from within the elastic range, there may arise serious errors in predicting the inelastic seismic responses of a structure.

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In this study, a modified similitude law for reinforced concrete structures, considering material nonlinearity and developing micro-concrete for small-scale models, is derived for being adaptable to the pseudodynamic testing algorithm. The inelastic behaviors of both normal-concrete and micro-concrete were identified from material tests, and the equivalent modulus ratios of micro-concrete to normal-concrete were defined.

Prior to experiments, a numerical simulation is performed by idealizing the designed specimens to a single degree of freedom system with a bilinear model, and the pseudodynamic testing algorithm is verified from seismic responses. Test specimens, consisted of prototype structures and 1/5 scaled models on a reinforced concrete column, were designed and fabricated based on the equivalent modulus ratios already defined. As a preliminary test, quasistatic tests on test specimens are carried out and their experimental results are compared using the constant and variable modulus ratios.

SIMILITUDE LAW

Applying a similitude law to small-scale model design, it should be selected according to the aim and methodology of each test. With regard to a dynamic problem, when the three basic dimensions of mass (M), length (L) and time (T) are selected, other variables are derived from them [6,7]. When a prototype structure and a small-scale model are made from different materials, the similitude law should be derived considering the equivalent modulus ratio and the ultimate strain ratio [8]. If the scale factors of a prototype structure and a small-scale model are defined as s for length, $E_r(\varepsilon)$ for equivalent modulus ratio and ε_{ur} for ultimate strain ratio, respectively, the relationship of a prototype structure and a small-scale model can be represented as shown in Table 1. In this table, the scale factors are the ratios of physical quantities of small-scale model to prototype structure.

Table 1. Similitude laws derived

Quantity	Dimensions	Scale Factor		
		Acceleration based, $E_r(\varepsilon) = 1$, $\varepsilon_{ur} = 1$	Equivalent multi-phase, $E_r(\varepsilon) \neq 1$, $\varepsilon_{ur} = 1$	Equivalent multi-phase, $E_r(\varepsilon) \neq 1$, $\varepsilon_{ur} \neq 1$
Length	L	s	S	s
Mass	M	s^2	$s^2 \cdot E_r(\varepsilon)$	$s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur}$
Time	T	$s^{0.5}$	$s^{0.5}$	$s^{0.5}$
Stress	$ML^{-1}T^{-2}$	1	$E_r(\varepsilon)$	$E_r(\varepsilon) \cdot \varepsilon_{ur}$
Velocity	LT^{-1}	$s^{0.5}$	$s^{0.5}$	$s^{0.5}$
Acceleration	LT^{-2}	1	1	1
Force	MLT^{-2}	s^2	$s^2 \cdot E_r(\varepsilon)$	$s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur}$
Stiffness	MT^{-2}	s	$s \cdot E_r(\varepsilon)$	$s \cdot E_r(\varepsilon) \cdot \varepsilon_{ur}$
Damping	MT^{-1}	$s^{3/2}$	$s^{3/2} \cdot E_r(\varepsilon)$	$s^{3/2} \cdot E_r(\varepsilon) \cdot \varepsilon_{ur}$
Frequency	T^{-1}	$1/s^{0.5}$	$1/s^{0.5}$	$1/s^{0.5}$
Added mass	-	$s^2 \cdot m_p - m_{mo}$	$s^2 \cdot E_r(\varepsilon) \cdot m_p - m_{mo}$	$s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur} \cdot m_p - m_{mo}$

* $s = L_m/L_p$, m_{mo} is the self-mass of small-scale model

Acceleration-based similitude law

Although the quantity of acceleration induced from an earthquake loading is adjustable for acceleration-based similitude law, the gravitational acceleration cannot be controlled. Therefore, the acceleration ratio, defined as a scale factor for acceleration, should be unity to reproduce exactly the gravity and inertia forces of a structure. Because scale factors for mass and time are proportional to s^2 and $s^{0.5}$, respectively, added mass is required for dynamic tests and also time should be compressed. It is concerned that the acceleration-based similitude law is suitable for the pseudodynamic test method which can treat mass and time numerically in a computer [4].

Equivalent multi-phase similitude law

The equivalent multi-phase similitude law derived from the acceleration-based similitude law considers both the equivalent modulus ratio and the ultimate strain ratio due to different materials used in small-scale models and prototype structures [8]. Depending on how much the material is damaged, a degree of structural damage can be divided into equivalent multi-phases. The equivalent modulus ratio corresponding to each phase is then applied to the equivalent multi-phase similitude law. In case of equivalent modulus ratio less than 1, an axial force of small-scale models due to both added mass and dead load could be reduced manageably. Therefore, it can be mentioned that the equivalent multi-phase similitude law is very useful for experiments using a small-scale model. In addition, the post-yielding behavior of structures can be simulated more exactly by calculating equivalent modulus ratio of concrete beyond ultimate strain and applying it to the similitude law.

MATERIAL TEST

Cylinder tests were carried out on three normal-concrete mixture ratios for prototype structure and five micro-concrete mixture ratios for small-scale model. Each cylinder is designated as N1, N2 and N3 for normal-concrete and M1, M2, M3, M4 and M5 for micro-concrete. M3 was excluded because the compressive strength was lower than 3.0MPa. Mixture ratios of normal-concrete and micro-concrete are shown in Table 2. The cylinder test results depending on water/cement ratios (w/c) are shown in Figure 1, where the compressive strength of concrete decreases as w/c increases.

Table 2. Mixture ratios of normal-concrete and micro-concrete

	Type	Mixture Ratio(C:W:S:G)
Normal-concrete	N1	1 : 0.48 : 1.94 : 2.79
	N2	1 : 0.42 : 1.66 : 2.38
	N3	1 : 0.51 : 2.07 : 2.99
	Type	**Mixture Ratio(C:W:S)**
Micro-concrete	M1	1 : 0.80 : 3.50
	M2	1 : 0.96 : 5.50
	M3	1 : 1.24 : 7.30
	M4	1 : 1.00 : 4.00
	M5	1 : 0.70 : 3.21

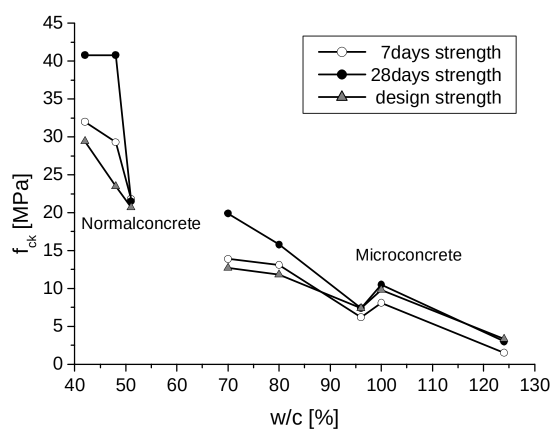


Figure 1. Ultimate strengths of concrete depending on w/c

Figure 2 shows a test apparatus of a 10 cm × 20 cm cylinder, and the stress-strain curves on each mixture ratio are presented in Figure 3. A relationship between ultimate strain and compressive strength obtained from the cylinder tests are summarized in Table 3. From cylinder test results after 28 days, it is investigated that micro-concrete M2 has the same ultimate strain as normal-concrete N1 and its strength is less than 25% of normal-concrete strength of N1.

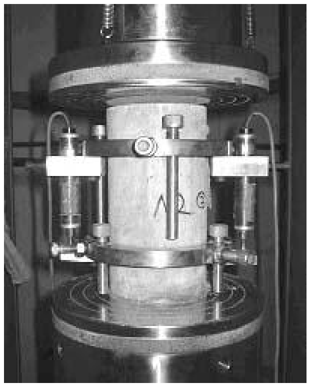


Figure 2. View of cylinder test

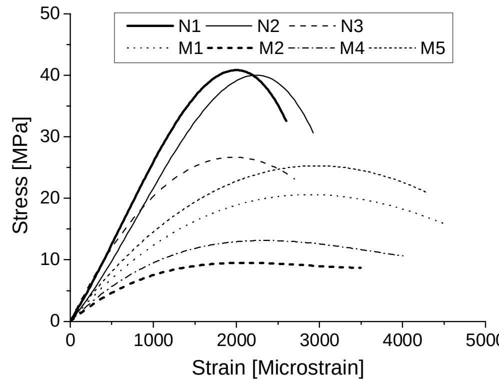
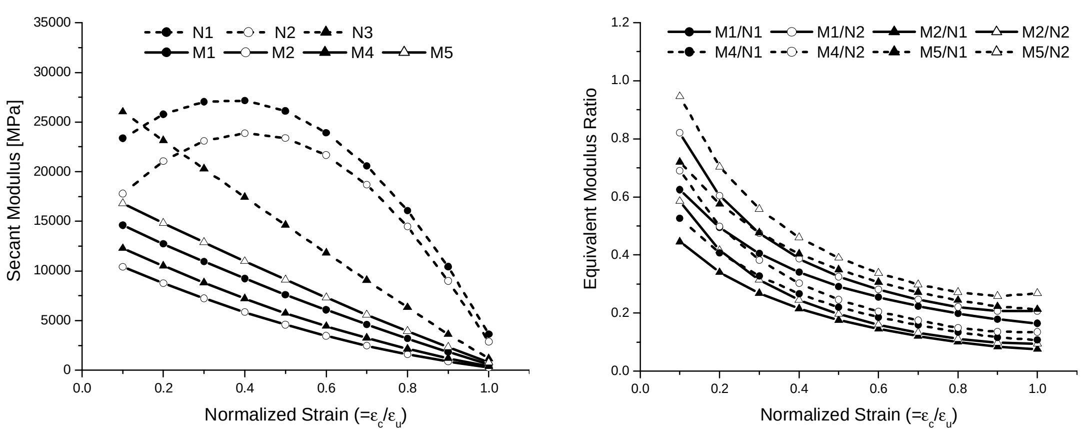


Figure 3. Stress-strain curves

Table 3. Cylinder test results after 28 days

Specimens	Ultimate Strain [Microstrain]	Ultimate Strength [MPa]
N1	**2100**	40.8
N2	2240	40.0
N3	1960	26.7
M1	2880	20.6
M2	**2100**	9.5
M4	2340	13.1
M5	2960	25.3

Variations of secant modulus and equivalent modulus ratio based on the normalized strain are shown in Figures 4(a-b), where ε_c is the strain within 10 phases divided based on the ultimate strain of concrete, and ε_u is the ultimate strain. In this study, equivalent modulus ratios are acquired from the secant modulus ratios of micro-concrete and normal-concrete in each phase and are obtained as a function of the normalized strain, as shown in Figure 4(b). From the results, it can be found that the equivalent modulus ratios are exponentially decayed varying with normalized strain levels.



(a) Secant moduli

(b) Equivalent modulus ratios

Figure 4. Material properties of normal-concrete and micro-concrete depending on strain level

MODIFIED PSEUDODYNAMIC TESTING ALGORITHM CONSIDERING EQUIVALENT MODULUS RATIO

The equivalent multi-phase similitude law considering material nonlinearity is dependent on scale factor for length, equivalent modulus ratio and ultimate strain ratio, respectively. Therefore, using equivalent modulus ratio and ultimate strain ratio obtained from the material test, stress ratio (σ_r), force ratio (F_r), mass ratio (M_r) and added mass (m_a) for designing a small-scale model can be determined as shown in Equations (1-4)

$$\sigma_r = E_r(\varepsilon) \cdot \varepsilon_{ur} \quad (1)$$

$$F_r = s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur} \quad (2)$$

$$M_r = s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur} \quad (3)$$

$$m_a = s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur} \cdot m_p - m_{mo} \quad (4)$$

where m_a is the added mass applied to small-scale models, m_p is the mass of prototype structures, and m_{mo} is the self-mass of small-scale models.

In many cases, amount of the added mass would be a critical problem in an application of the small-scale model in shaking table tests. With regard to selecting the material of small-scale models, the material strength less than that of prototype structures and the constant equivalent modulus ratio could give more exact earthquake responses in shaking table tests. From Equation (4), thus, m_a can be reduced sufficiently by selecting a suitable material. If the 1/10 scaled model is fabricated using N1 and M2, with equivalent modulus ratios ranged from 0.1 to 0.4, the added mass may be reduced to about 30%.

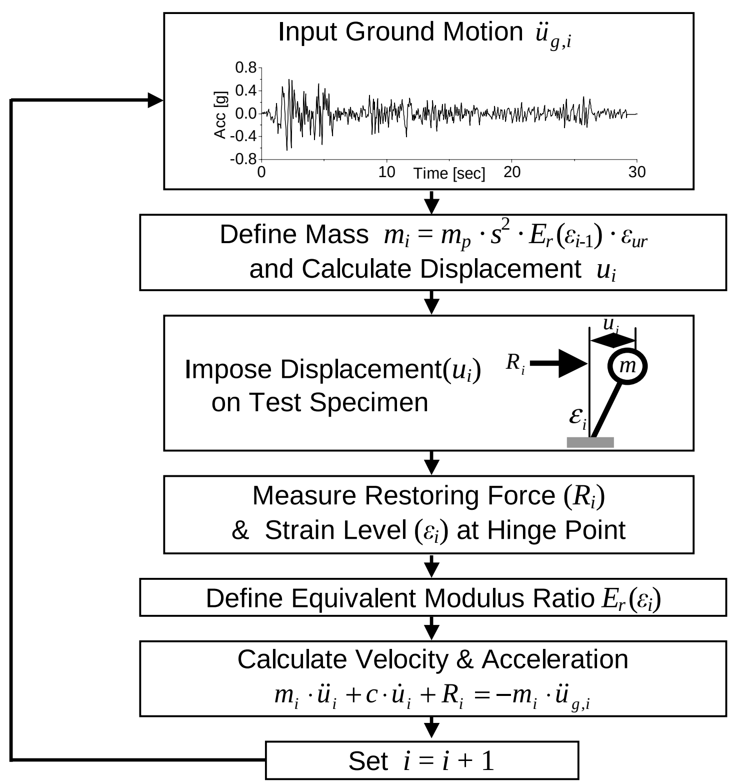


Figure 5. Numerical integration procedure for pseudodynamic test

In this study, the equivalent multi-phase similitude law considering equivalent modulus ratio is applied to the pseudodynamic testing algorithm. Comparing with the conventional pseudodynamic test method [4], strain levels at the plastic hinge zone of test specimen are determined to obtain the corresponding equivalent modulus ratios, and then the mass of test specimen considering equivalent modulus ratio is updated at each time step in order to simulate the current damaged system. Figure 5 shows a numerical integration procedure for the modified pseudodynamic testing algorithm considering equivalent multi-phase similitude law.

NUMERICAL SIMULATION OF MODIFIED PSEUDODYNAMIC TESTING ALGORITHM

Based on N1 and M2 with the same ultimate strain obtained from material tests, a numerical simulation was performed with the simplified stress-strain curves as a bilinear model, as shown in Figure 6. Each numerical model was designed according to N1 for prototype structure and M2 for 1/10 scaled model.
Stress-strain curves of two different materials can be idealized as a bilinear model, which is divided into the first phase ranging from 0 to 70 % of the ultimate strain and the second phase ranging from 70 to 100 % of the ultimate strain. Thus, secant moduli and equivalent modulus ratios in two phases are calculated to perform numerical simulation. Figure 6 shows the averaged stress-strain curves and equivalent modulus ratios for normal-concrete and micro-concrete. Also, secant moduli and equivalent modulus ratios in two phases (first & second phases) are presented in Table 4. The subscripts *p* stands for prototype structure, *m* for small-scale model, 1 for the first phase, and 2 for the second phase. As shown in Figure 6, equivalent modulus ratio of the selected materials decays exponentially as strain increases, and in normal-concrete it decreases rapidly beyond the ultimate strain. Therefore, it can be observed that the brittle fracture of normal-concrete would be more conspicuous than that of micro-concrete beyond the ultimate strain.

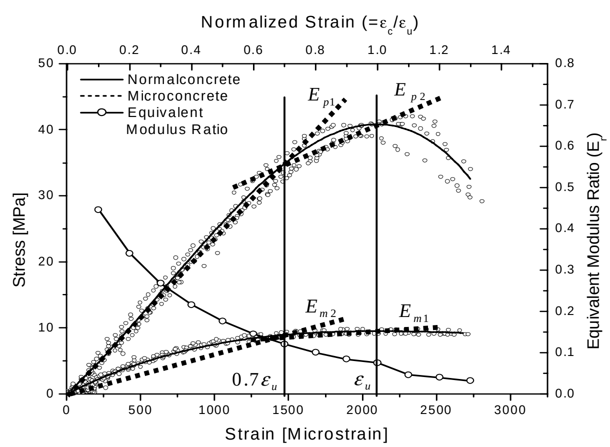


Figure 6. Stress-strain curves & equivalent modulus ratios

Table 4. Secant moduli & equivalent modulus ratios

Quantities	Phase	
	first	second
Normal-concrete Secant Modulus [GPa]	E_{p1} = 24.9	E_{p2} = 10.1
Micro-concrete Secant Modulus [GPa]	E_{m1} = 6.28	E_{m2} = 1.03
Equivalent Modulus Ratio	E_{r1} = 0.252	E_{r2} = 0.102

Bilinear material models varying with equivalent modulus ratio and structural properties of prototype structure & 1/10 scaled model are employed in numerical simulation, as in Tables 4 and 5, respectively.

Table 5. Structural properties of numerical examples

Quantities	Prototype	1/10 Scaled Model
Concrete Type	N1	M2
Height [mm]	4000	400
Mass [kg]	m_p=100.7×10^3	m_{m1}=253.9, m_{m2}=102.8
Stiffness [kN/mm]	k_{p1}=37.98, k_{p2}=15.41	k_{m1}=1.005, k_{m2}=0.160
Moment of Inertia [mm^4]	3.255×10^{10}	3.412×10^6
Horizontal yielding force [kN]	708.96	1.786

For the bilinear model, numerical simulation was performed by using the Newmark method and Newton-Raphson iteration [9]. In a range where the stiffness of 1/10 scaled model is k_{m1} or k_{m2}, the corresponding mass of m_{m1} or m_{m2} is applied to the structure. In this study, numerical simulation was performed for 1/10 scaled model, using Equations (5) and (6) satisfying the pseudodynamic testing algorithm.

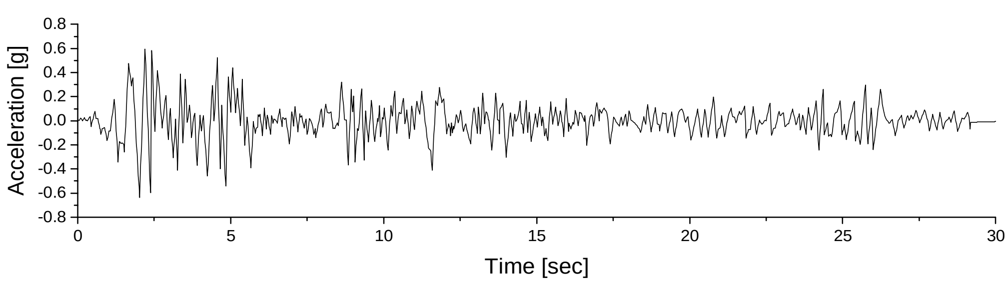
$$\text{if } \varepsilon_c \le 0.7\varepsilon_u, \quad R_m(\varepsilon, k) = k_{m1} \cdot u$$
$$m_{m1} \cdot \ddot{u} + c \cdot \dot{u} + R_m(\varepsilon, k) = -m_{m1} \cdot \ddot{u}_g \tag{5}$$
$$\text{else,} \quad R_m(\varepsilon, k) = k_{m2} \cdot u$$
$$m_{m2} \cdot \ddot{u} + c \cdot \dot{u} + R_m(\varepsilon, k) = -m_{m2} \cdot \ddot{u}_g \tag{6}$$

Here, $R_m(\varepsilon, k)$ is the restoring force of 1/10 scaled model, which is dependent on strain and stiffness. According to the modified similitude law, mass of 1/10 scaled model is proportional to $s^2 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur}$. Therefore, masses m_{m1} and m_{m2} can be obtained from Equations (7) and (8).

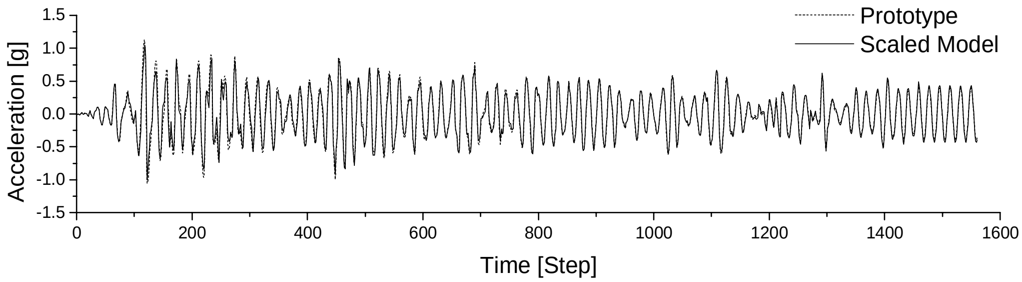
$$m_{m1} = s^2 \cdot E_{r1} \cdot \varepsilon_{ur} \cdot m_p = 0.1^2 \times 0.252 \times 1 \times 100.7 \times 10^3 = 253.94\ (kg) \tag{7}$$
$$m_{m2} = s^2 \cdot E_{r2} \cdot \varepsilon_{ur} \cdot m_p = 0.1^2 \times 0.102 \times 1 \times 100.7 \times 10^3 = 102.78\ (kg) \tag{8}$$

An input loading applied to prototype structure and 1/10 scaled model is two times of 1940 El Centro earthquake acceleration (PGA = 0.638 g), as shown in Figure 7(a). Also, seismic responses of prototype structure and 1/10 scaled model are compared in Figures 7(b-e), in which the differences on acceleration and natural frequency are within 3 %. Figure 7(f) shows that the seismic energy dissipation capacities, defined as cumulative hysteretic energy, are within difference of about 9 %. In Figure 7(g), the inelastic response spectra are obtained from the above numerical examples. It is shown that the spectral displacements of prototype structure and 1/10 scaled model are almost identical beyond 1.86Hz.

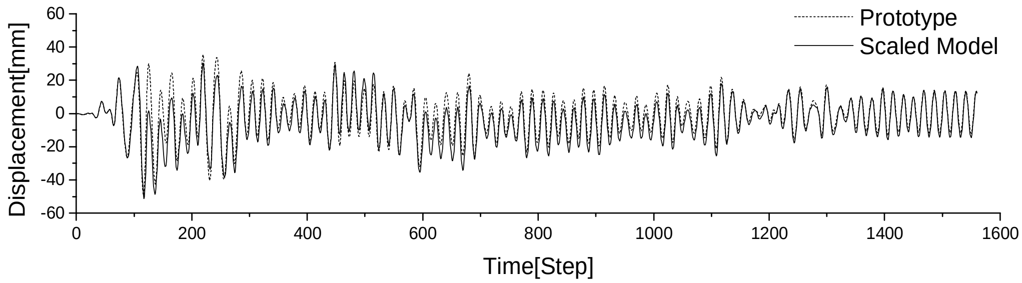
In this study, it is verified numerically that the seismic responses of 1/10 scaled model are relatively similar to those of prototype structure. Therefore, it can be mentioned that the modified pseudodynamic testing algorithm considering the equivalent multi-phase similitude law is applicable to the pseudodynamic test.



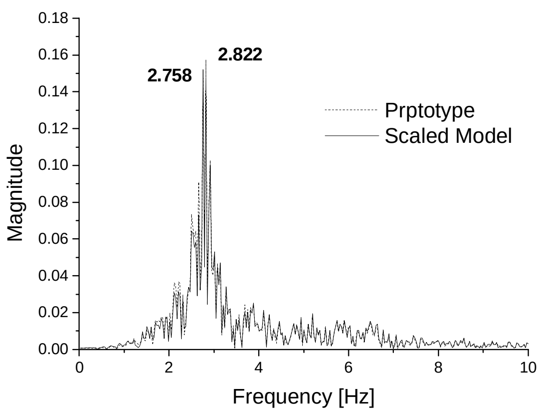
(a) Input acceleration



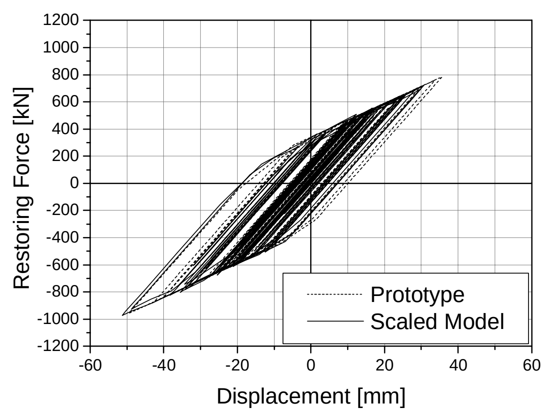
(b) Acceleration response



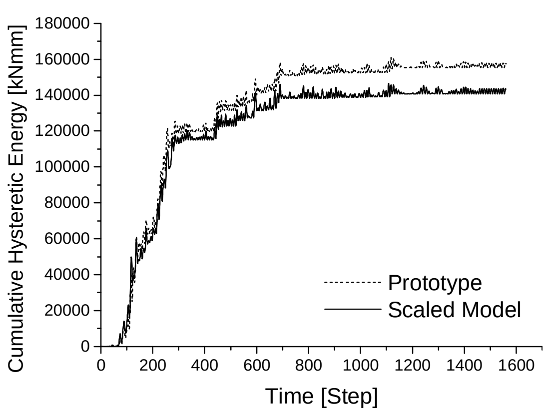
(c) Displacement response



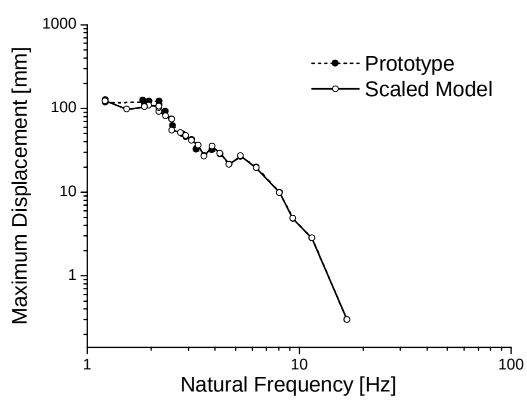
(d) Power spectrum



(e) Hysteresis loop



(f) Energy evaluation



(g) Spectral displacement response spectrum

Figure 7. Comparison of seismic responses of prototype & 1/10 scaled model

TEST MODELS

Model design

When designing a small-scale model, axial force, flexural moment and strains of concrete and reinforcement should be considered, as well as geometric scale factors. It is reasoned that concrete and reinforcement have different equivalent modulus ratio ($E_r(\varepsilon)$) and ultimate strain ratio (ε_{ur}). That is, $E_r(\varepsilon) = 1$ and $\varepsilon_{ur} = 1$ for reinforcement, which is normally used as the same material in prototype and small-scale model. However, in case of $E_r(\varepsilon) \neq 1$ and $\varepsilon_{ur} \neq 1$ for concrete, it is desirable that the difference resulted from $E_r(\varepsilon)$ and ε_{ur} is compensated by adjusting the cross section of reinforcing bar and the sectional moment arm, according to axial force, flexural moment and ε_{ur}. However, since it is not easy to control axial force, flexural moment and ε_{ur} at the same time, adjustment of axial force can be sacrificed. Although adjustment of axial force is excluded, the difference of axial force is within 5 to 10 %. Thus, it is not expected that the difference of axial force causes a severe error in the seismic performance evaluation of small-scale models.

The stress and strain diagrams in a RC column section are presented in Figure 8, in which the position of reinforcing bars in the scaled model can be determined. And the nominal flexural moments (M_n) of prototype and scaled model can be also obtained from Equation (9). Here, ε_s is the strain of reinforcing bars, ε_{up} is the ultimate strain of normal-concrete, and ε_{um} is the ultimate strain of micro-concrete.

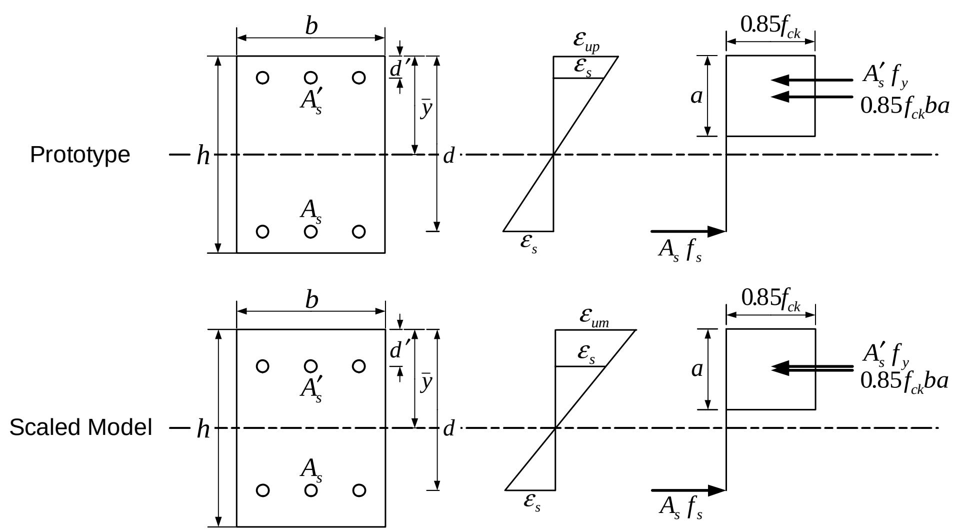


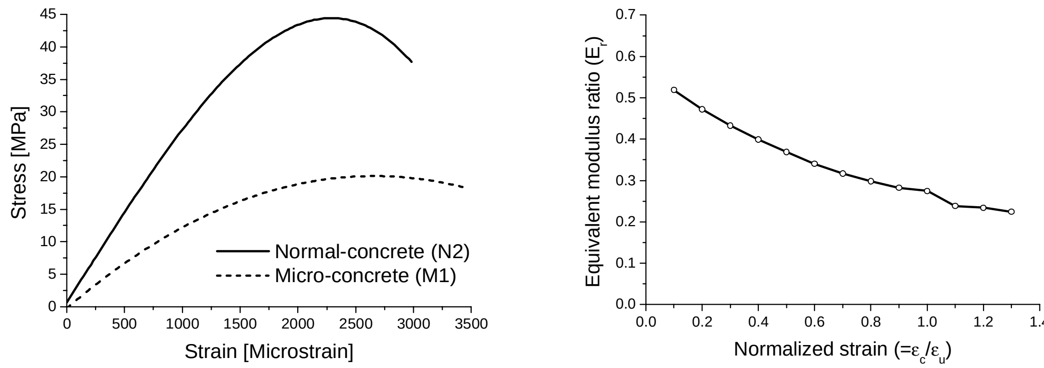
Figure 8. Stress & strain diagrams in a RC column section

$$M_n = 0.85 f_{ck} ba(\bar{y} - \frac{a}{2}) + A'_s f'_s(\bar{y} - d') - A_s f_s (d - \bar{y}) \quad (9)$$

The nominal flexural moments, M_{np} and M_{nm}, of prototype and scaled model, respectively, should be designed according to the modified similitude law satisfying Equation (10), where the tangential modulus ratio is used for $E_r(\varepsilon)$.

$$M_{nm} = s^3 \cdot E_r(\varepsilon) \cdot \varepsilon_{ur} \cdot M_{np} \quad (10)$$

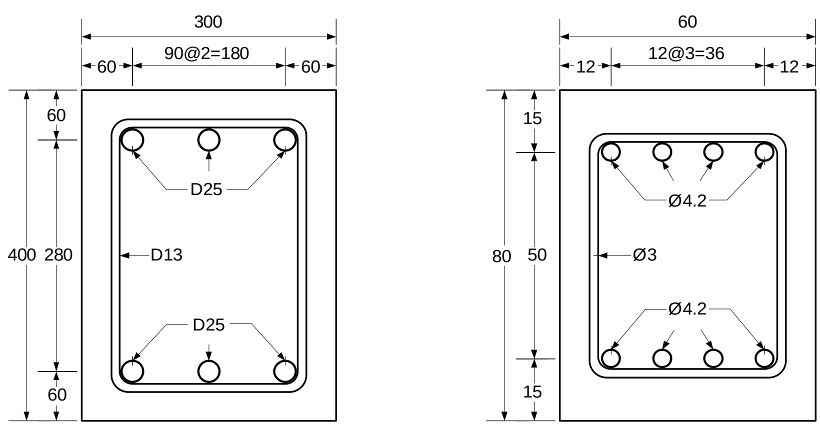
Based on the previous material tests on various mixture ratios, test specimens were fabricated by using N2 for prototype structure and M1 for small-scale model. To obtain material properties more exactly, each 9 cylinders from mixture ratios of N2 and M1 were tested. The stress-strain curves resulted from material tests are presented in Figure 9(a) and the equivalent modulus ratios of N2 to M1 are obtained as shown in Figure 9(b).



(a) Stress-strain curves (b) Equivalent modulus ratios

Figure 9. Material properties of normal-concrete(N2) and micro-concrete(M1)

In Figure 10(a), a prototype structure of a rectangular RC column of 2 meters high is designed based on equilibrium fracture. In small-scale model design, cross section of concrete is determined by the scale factor (s), and position of reinforcement (d, d') by the strain ratio. Thus, it is sufficient to determine the cross section of reinforcement (A_s, A'_s). Also, because the cross section is symmetric, $A_s = A'_s$ and $d = h - d'$. A'_s of the small-scale model can be obtained from Equations (9) and (10). Figure 10(b) shows the cross section of 1/5 scaled model designed by using micro-concrete. Structural properties of prototype and 1/5 scaled model are summarized in Table 6.



(a) Prototype (b) 1/5 scaled model

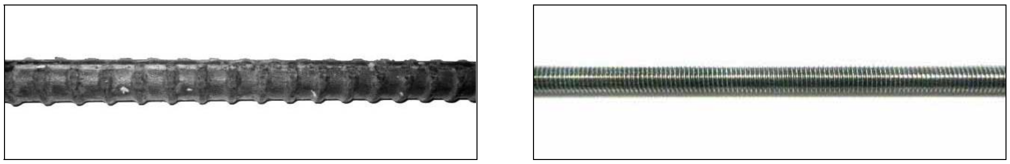
Figure 10. Cross sections of prototype & 1/5 scaled model

Table 6. Structural properties of prototype & 1/5 scaled model

Quantities		Prototype	1/5 Scaled Model
Concrete Type		N2	M1
Steel	Yielding Strain(ε_y)	0.0019	0.0019
	Yielding Stress [Mpa]	400	400
Moment of Inertia [mm^4]		2.067×10^9	3.748×10^6
Height [mm]		2000	400
Stiffness [kN/mm]		20.773	2.152

Reinforcement modeling

In 1/5 scaled models, a diameter (4.2mm) of reinforcing bars is too small to use conventional standard deformed bars. Thus, a threaded rod made by forming pitches on a round bar with the same material properties of standard deformed bars was used. Applicability of the threaded rods to small-scale models has been verified [1]. Figures 11(a-b) show the standard deformed bar for prototype and the threaded rod for 1/5 scaled model.



(a) Standard deformed bar (b) Threaded rod

Figure 11. Reinforcements of test specimens

Fabrication of specimens

For experiments, 3 and 6 sets of prototype structure and 1/5 scaled model, respectively, were fabricated as shown in Figure 12. Arrangement of reinforcing bars is also shown in Figures 13(a-b).

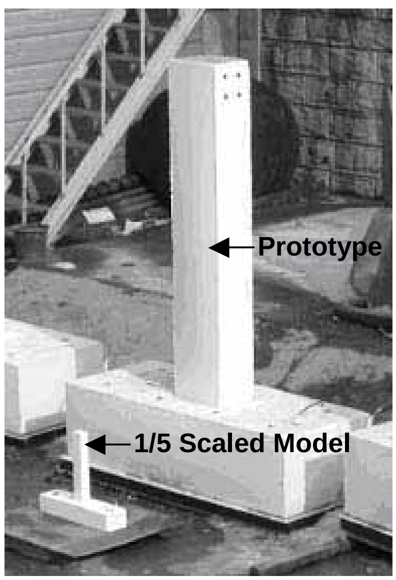
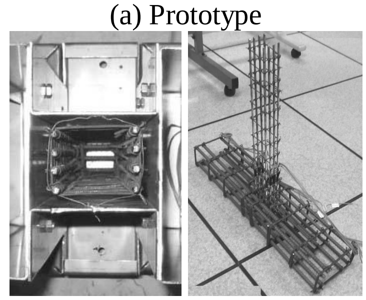


Figure 12. Fabricated specimens

(a) Prototype



(b) 1/5 scaled model

Figure 13. Arrangement of reinforcing bars

QUASISTATIC TESTS

As a preliminary test, hysteretic behavior of the test specimens was experimentally obtained from the quasistatic tests. The cyclic loadings, up to $8.0\delta_y$, in displacement control are exerted to the specimens horizontally without any axial force. A test setup for the quasistatic tests on prototype and 1/5 scaled model is shown in Figure 14, and failure patterns after the tests can be investigated in Figures 15(a-b). From the quasistatic test results, force-displacement relationships of prototype and 1/5 scaled model are derived and compared in Figures 16(a-b).

According to the modified similitude law in Table 1, a constant modulus ratio (E_r=0.519), at early stage in Figure 9(b), is applied to the test results of 1/5 scaled model. The 1/5 scaled model result converted by a constant modulus ratio is well correlated with the prototype result, as shown in Figure 16(a). On the other hand, when variable modulus ratios from Figure 9(b) are exactly applied depending on strain levels, it is observed in Figure 16(b) that the 1/5 scaled model is gradually deviated from the prototype as the exerted displacement increases.

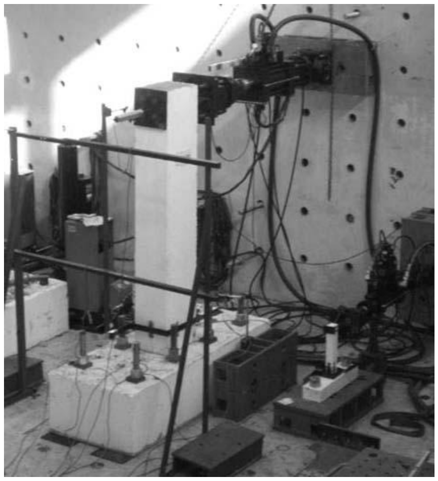
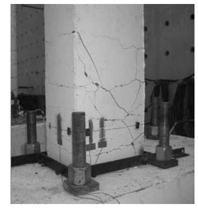
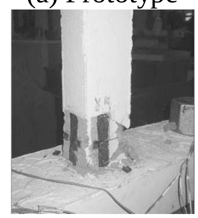


Figure 14. Test setup

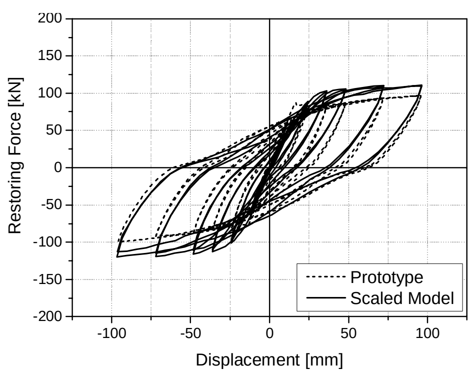


(a) Prototype

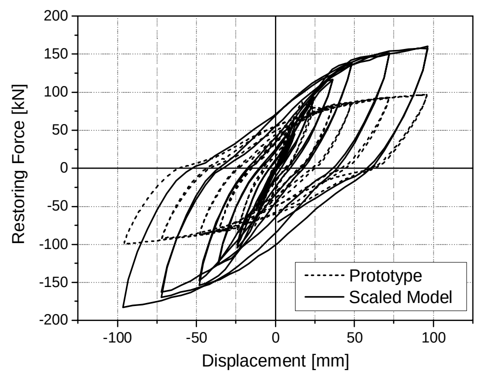


(b) 1/5 Scaled Model

Figure 15. Failure patterns



(a) Constant Modulus Ratio (E_r=0.519)



(b) Variable Modulus Ratio

Figure 16. Force-displacement relationships

Using the restoring forces measured from quasistatic tests on prototype and 1/5 scaled model, structure-based modulus ratios can be estimated inversely from Equation (2), according to the exerted displacement levels. In Figure 17, the structure-based and material-based modulus ratios are compared within the damage level of 8.0δ_y. From the figure, it is recognized that at higher damage level the structure-based modulus ratios are quite different from the material-based modulus ratios. That is, the difference between prototype and 1/5 scaled model becomes severe as the damage level increases. It can be presumed that the 1/5 scaled model may be a little stiffer than the prototype due to adhesive strength of reinforcing bars, size effect of concrete and so on.

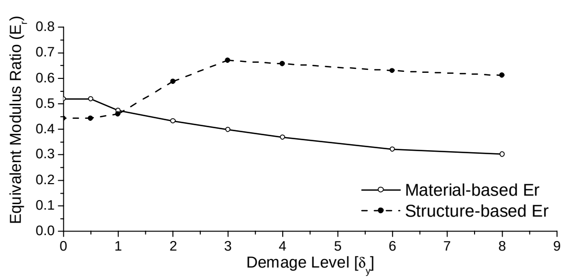


Figure 17. Equivalent modulus ratios

SUMMARY AND DISCUSSION

In this study, a modified equivalent multi-phase similitude law considering material nonlinearity is proposed. In material tests, nonlinearity of normal-concrete and micro-concrete is identified to derive the equivalent modulus ratios for multi-phases, which are based on ultimate strain level of concrete. By using a numerical simulation, the pseudodynamic testing algorithm considering the modified similitude law is verified to be applicable to the seismic simulation tests.

Prior to the pseudodynamic test, the quasistatic tests on the prototype and 1/5 scaled model of a RC column were carried out. From the test results, event though the 1/5 scaled model using a constant modulus ratio is fairly coincided with the prototype, the correlation induced from variable modulus ratios based on material tests becomes severe as the damage level increases. It can be presumed that the 1/5 scaled model may be a little stiffer than the prototype due to adhesive strength of reinforcing bars, size effect of concrete and so on. As an ongoing study, feasibility of the equivalent multi-phase similitude law will be verified by performing the pseudodynamic tests.

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