NONLINEAR SIMILITUDE LAW USED FOR STRUCTURAL SEISMIC TEST

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ABSTRACT:
The Performance-Based Seismic Design requires more accurate description for the nonlinear behavior of structure during large earthquake. Actual prototype structures tend to be very heavy and costly. Small-scaled models are usually used for shaking table test where large-scaled models for pseudodynamic test. In any case the elastic behavior can be easily simulated simply by employing classic similitude laws. However the classic similitude laws are derived on the basis of elastic theory, they can not be used to predict nonlinear behavior (such as cracks or collapse) of structures. This paper presents some suggestions as a compliment. Three quantities, i.e. Length (l), Elastic modulus (E), and Equivalent densensity (ρ) are used as fundamental variables, usually only the E is related to nonlinear deformation. The value of E will vary depending on how much nonlinear deformation occurred during an earthquake.

KEYWORDS: Nonlinear similitude law, scaled model, prototype, earthquake simulation test

1. INTRODUCTION

Usually micro-concrete model is used to simulate normal concrete structure during the earthquake simulation test. Because of the property different, especially the nonlinear stress-strain relationship, quite amount of error will present in the prediction of structure nonlinear behavior of a. However, it is absolutely necessary to understand such behavior in Performance-Based Design. Three parameters (l_r—length ratio, ρ_r—equivalent density ratio, E_r—elastic modulus ratio) are usually used as fundamental variables in earthquake simulation test. l_r and ρ_r will not vary with structural deformation, but E_r will vary with strain level. The existing similitude laws are based on constant l_r, ρ_r, and E_r, so new similitude laws have to be developed which can suit for structural nonlinear deformation during large earthquake.

The present understanding of similitude laws used for earthquake simulation can be summarized as:

(1) Micro concrete can simulate normal concrete quite well in the elastic stage, but the error grows with strain level in the nonlinear stage.

(2) based on uniaxial compression test of concrete cubic specimens with different strength level, the E_r—ε curve can be roughly divided into three stages according to strain level:

(a) Elastic stage (0—50% limit strain): The E_r represented by E_{r1};

(b) Weak nonlinear stage (50%—80% limit strain): The E_r represented by E_{r2};

(c) Strong nonlinear stage (80%—100% limit strain): The E_r represented by E_{r3}.

Usually the E_r varies with strain as indicated in figure .1.

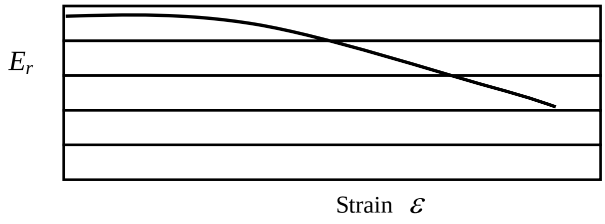

Figure 1 The equivalent elastic modulus ratio E_r decreases

if the strain level ε becomes large

2. NONLINEAR SIMILITUTE LAW

In order to include the effect caused by the degradation of E_r, two types of similitude laws are proposed as listed in table 1 and table 2 respectively. In table 1, E_r will take three values, i.e. E_{r1}, E_{r2} and E_{r3} during a complete duration of a strong earthquake instead of keeping constant. In table 2, E_r will take only one of the three values during an earthquake duration according to the maximum strain occurred in this duration, this idea is compatible with the Equivalent Linearization theory.

Table 1 Three stages of similitude law

Structure deformation level	Linear Stage	Weak nonlinear Stage	Strong nonlinear Stage
Material deformation	Linear Stage	Weak nonlinear Stage	Strong nonlinear Stage
Elastic modulus ratio	E_{r1}	E_{r2}	E_{r3}

Table 2 Three independent similitude law

Maximum structure deformation	Small deformation Linear Stage	Large deformation Quasi-elastic Stage	Large deformation Elastoplasticity Stage
Maximum material deformation	Linear Stage	Weak nonlinear Stage	Strong nonlinear Stage
Elastic modulus ratio	E_{r1}	E_{r2}	E_{r3}

The traditional similitude laws used in earthquake simulation test are listed in table 3, where the different values of E_r and m_a (attached artificial mass) can be realized by computer simulation and pseudo-dynamic equipment, but during shaking table test, E_r and m_a can not change.

Table 3 Traditional similitude laws used for earthquake simulation test

Physical quantity	Artificial mass model (different material from prototype structure)
Length	l_r
Equivalent modulus	$E_r(t)$
Density	ρ_r
Stress	$\sigma_r = E_r(t)$
Time	$t_r = l_r^{0.5}$
Deformation	$r_r = l_r$
Velocity	$\upsilon_r = l_r^{0.5}$
Acceleration	$a_r = 1$
Acceleration of gravity	$g_r = 1$
Frequency	$\omega_r = l_r^{-0.5}$
Artificial mass	$m_a = E_r(t) l_r^2 m_p - m_m$

The first method of including the degradation of E_r is to employ three values instead of one during an earthquake, corresponding similitude laws are listed in Table 4; while different E_r value is used depending on the maximum deformation during an earthquake duration, and similitude laws listed in table 5 are derived.

Table 4 Equivalent three stages similitude laws

Physical quantity	Deformed phase		
	Linear Stage	Weak nonlinear Stage	Strong nonlinear Stage
Length	l_r	l_r	l_r
Equivalent modulus	E_{r1}	E_{r2}	E_{r3}
Density	ρ_r	ρ_r	ρ_r
Stress	$\sigma_r = E_{r1}$	$\sigma_r = E_{r2}$	$\sigma_r = E_{r3}$
Time	$t_r = l_r^{0.5}$	$t_r = l_r^{0.5}$	$t_r = l_r^{0.5}$
Deformation	$r_r = l_r$	$r_r = l_r$	$r_r = l_r$
Velocity	$\upsilon_r = l_r^{0.5}$	$\upsilon_r = l_r^{0.5}$	$\upsilon_r = l_r^{0.5}$
Acceleration	$a_r = 1$	$a_r = 1$	$a_r = 1$
Acceleration of gravity	$g_r = 1$	$g_r = 1$	$g_r = 1$

Frequency	$\omega_r = l_r^{-0.5}$	$\omega_r = l_r^{-0.5}$	$\omega_r = l_r^{-0.5}$
Artificial mass	$m_a = E_{r1} l_r^2 m_p - m_m$	$m_a = E_{r2} l_r^2 m_p - m_m$	$m_a = E_{r3} l_r^2 m_p - m_m$

Table 5 Three independent equivalent similitude laws

Physical quantity	Maximum structure deformation		
	Small deformation Linear Stage	Large deformation Quasi-elastic Stage	Large deformation Elastoplasticity Stage
Length	l_r	l_r	l_r
Equivalent modulus	E_{r1}	E_{r2}	E_{r3}
Density	ρ_r	ρ_r	ρ_r
Stress	$\sigma_r = E_{r1}$	$\sigma_r = E_{r2}$	$\sigma_r = E_{r3}$
Time	$t_r = l_r^{0.5}$	$t_r = l_r^{0.5}$	$t_r = l_r^{0.5}$
Deformation	$r_r = l_r$	$r_r = l_r$	$r_r = l_r$
Velocity	$\upsilon_r = l_r^{0.5}$	$\upsilon_r = l_r^{0.5}$	$\upsilon_r = l_r^{0.5}$
Acceleration	$a_r = 1$	$a_r = 1$	$a_r = 1$
Acceleration of gravity	$g_r = 1$	$g_r = 1$	$g_r = 1$
Frequency	$\omega_r = l_r^{-0.5}$	$\omega_r = l_r^{-0.5}$	$\omega_r = l_r^{-0.5}$
Artificial mass	$m_a = E_{r1} l_r^2 m_p - m_m$	$m_a = E_{r2} l_r^2 m_p - m_m$	$m_a = E_{r3} l_r^2 m_p - m_m$

3. VALIDATION TEST

Reinforced concrete frame structure is suitable for the validation test of nonlinear similitude laws. Each of the above similitude relationship is employed in the earthquake simulation test conducted by computer program. The error for the prediction of nonlinear behavior of prototype structure varies with similitude laws, and optimal similitude laws can be determined by least error. The numerical simulation results need to be verified by further model test, so the following schedule is proposed:

3.1 Preparation

(1) Determination of test materials and their stress-strain relationships

a. Determining mixture ratio of normal concrete and micro-concrete by uniaxial compression test;

b. Determination of stress-strain relationships of selected concrete and micro-concrete;

c. Determination of stress-strain relationships of selected steel bars both for prototype and model structure.

(2) Fabrication of prototype and model structures

a. To verify equivalent three stages similitude law;
Prototype structure: single story RC frame, amount: 1
Scaled down model: l_r =1/10, single story RC frame, amount: 1

b. To verify three independent equivalent similitude law.
Prototype structure (replaced by computer simulation): three story RC frame, amount: 3
Scaled down model: l_r =1/10, three story RC frame, amount: 1

(3) Determining of parameter ratio values in similitude law used in test

During the fabrication of model structures, the micro-concrete should be uniform both model structure and test specimen, and the specimen will be used to determine the stress-strain relationships, based on these relationships, optimal similitude law can be determined.

3.2 Test Procedure

(1) To verify the equivalent three-phase similitude law by shaking table Test, we can only set a constant E_r and m_a, but we can realize varied E_r in the whole process of an earthquake by Pseudo-Dynamic equipment.

a. To test prototype structure, until completely failure

b. To test model structure: Deformation phase can be determined by measured hysteretic loop, and the load of each step can thus be determined by the corresponding phase E_r.

(2) To verify three independent similitude laws, such test can be conducted by shaking table:

Small earthquake test: The input level will be control under certain value, so that the maximum structure deformation lies in small deformation linear stage;

Moderate earthquake test: To control the input record so as to make maximum structure deformation lie in large deformation quasi-elastic stage;

Large earthquake test: To control the input record so as to make the maximum structure deformation lie in large deformation elastoplasticity Stage.

a. Prototype structures (can be conducted by computer simulation): 3 structures for small, moderate and large earthquake respectively;

b. Model structures
Model 1: For small earthquake input, let $E_r = E_{r1}$, in the whole process.
Model 2: For moderate earthquake input, let $E_r = E_{r2}$, in the whole process.
Model 1: For large earthquake input, let $E_r = E_{r3}$, in the whole process;

c. Complemented test
After small earthquake input, model 1 will be adjusted to satisfied $E_r = E_{r2}$, and input moderate earthquake. After then, model 1 will be adjusted to satisfied $E_r = E_{r3}$, and input large earthquake.

3.2 Data Cooking

The response of prototype structure will regarded as a standard, errors for all test cases will be calculated, thus the optimal similitude law will derived. And we can also recommend suitable similitude law for different purposes of experiment, for example, to test elastic behavior or nonlinear behavior.

4. CONCLUTIONS AND REMARKS

Performance Based Earthquake Design Method needs clearly understanding of the nonlinear behavior of structures, which is usually studied by model test, thus nonlinear similitude law has to be developed. For concrete structures, high strength concrete is employed in prototype structures while micro-concrete is usually employed in model structures. The elastic modulus ratio E_r will decrease with larger strain, and this leads to the variation of similitude ratio values, such as less a_r and m_r. This phenomenon should be reflected in the prediction of dynamic response of prototype structure.

Based on the preliminary study, the authors suggested two ways to involve the E_r degradation effect during model structure designing, they are three stages of similitude law and three independent similitude laws. Further validation test schedule is also proposed.

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