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SCALE MODELING OF REINFORCED CONCRETE CATEGORY I STRUCTURES SUBJECTED TO SEISMIC LOADING

by

Richard C. Dove and Joel G. Bennett

ABSTRACT

The laws that govern the scale-model requirements for reinforced concrete Category I structures over a full range of seismic loading extending from the elastic through the inelastic ranges of response are developed. Three types of scaling are then examined. The third type, called "Q" scaling in this report, is the most useful for tailoring structural models to existing seismic test facilities. Finally, the way in which the three types of commonly used damping (viscous, structural, and Coulomb) scale in these models is derived.

INTRODUCTION

The Seismic Category I Structures Program currently being carried out at the Los Alamos National Laboratory is intended to provide experimentally determined data on the structural behavior of very large, reinforced concrete structures when subjected to seismic loads which are larger than those considered in the structure's original design.

Unfortunately, these Category I structures are so large that the possibility of seismically testing the prototype structures under controlled conditions is essentially nonexistent. As a result, seismic experiments on scale models are being used in this program.

The use of scale models for the linear/elastic region design of concrete structures is a well-established and growing practice. The Commentary on Building Code Requirements for Reinforced Concrete (ACI 318-77)[1] states:

"The code permits model analysis to be used to supplement structural analysis and design calculations. Documentation of the model analysis should be provided with the related calculations. Model analysis is most effective as a tool for predicting the behavior of actual structures when performed by an engineer or architect having experience in this technique."

In Chapter 19 (Shells and Folded Plate Members) of the 1977 Building Code Requirements,[2] model analysis is specifically discussed; Section 19.2.6.1 states:

"Analyses based on results of elastic model tests approved by the Building Official shall be considered as valid elastic analyses."

In the discussion of this section, the reader is cautioned:

"Many factors enter into model tests besides shape and direct scale. Thus, the Building Official should accept results of model tests in lieu of mathematical analysis only when the model tests have been performed under the direction of a recognized expert in this area of structural engineering, including expertise in the theory of models and similitude of model and prototype."[3]

In Australia, the current Concrete Code permits design based on model analysis without supplementary calculations.[4]

It is clear that the use of models for the design and analysis of reinforced concrete structures in the elastic load range is well accepted. Although the use of models to design and analyze reinforced concrete structures loaded into the inelastic range is more complicated and more expensive, the methodology is well known, and numerous ultimate load tests have been successfully carried out. References 3 and 5 contain information on reinforced concrete models for inelastic and ultimate load studies. Subjects discussed in detail include:

1. required scaling laws
2. material selection, including modeling of the reinforcement
3. test techniques

4. accuracy of model tests, and
5. costs

Studies reported on include multistory buildings, bridges, pressure vessels, dams and many of the usual structural elements.

When reinforced concrete models are used to investigate inelastic behavior and/or ultimate load capacity under dynamic load conditions, the problem is further complicated as compared to quasistatic loading. Here again, however, the methodology is well established.[6] The ACI special publication titled Dynamic Modeling of Concrete Structures,[7] is, as the title suggests, devoted exclusively to this subject and, as its publication date (1982) indicates, there is a rapid growth of interest in this area. A large number of tests have been conducted on reinforced concrete models subjected to air blast, ground shock, and missile impact loading. References 7 and 8 both report on this type of test, and many more examples are reported in the classified literature. It is interesting to note that facilities for blast or impact loading of models are relatively simple to construct on an ad hoc basis.

Simulated seismic loading is no more complicated, in theory, than other types of dynamic loading (such as air blast or ground shock); but, in fact, a facility that will simulate seismic loading is more difficult and expensive to construct and, as a result, there are a very limited number of seismic simulation facilities that will accommodate larger scale models. Reference 9 contains a list of seismic test facilities in the US that are potentially useful for testing structural models, together with a discussion of the characteristics and limitations of these facilities.

Papers by Clough and Niwa and by Godden* give examples of concrete structures tested on the seismic simulator at the University of California at Berkeley. In our research on reinforced concrete models of Category I nuclear power plant structures we have used the seismic simulation facility at the Construction Engineering Research Laboratory, Champaign, Illinois. This facility is the largest, both in applied force and maximum test item weight, available in the US. Further, the control system on this shaker has recently (January 1984) been significantly upgraded.

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*Both papers can be found in Ref. 7.

There are a number of large seismic simulation test facilities in Japan, including the world's largest facility (the Nuclear Power Engineering Test Center, NUPEC, facility at Tadotsu Town on Shikoku Island). Most Japanese facilities are listed and their characteristics discussed in Ref. 10. References 11-16 are indicative of Japanese activity in the seismic testing of concrete models.

As the preceding review demonstrates, there is a great deal of relevant research on which a scale model program for the seismic response of Category I structures can build. However, the use of scaled models for studying the seismic response of very large reinforced concrete structures loaded into the inelastic region remains a challenging problem. First of all, since the prototype structures are very large and the seismic simulation test facilities are relatively small, the required dimension scale factor is large. It is sad, but true, that experience teaches that the larger the scale factor, the more difficult it is to construct a true scale model.

It is also true that modeling for dynamic experiments is more difficult than modeling for static experiments; time, all time dependent inputs (acceleration and velocity for example), and time dependent properties (viscous effects for example) must be properly scaled in dynamic experiments.

When models are used to study structural response in the inelastic region, the materials used in the construction of the model must have the required similarity to the prototype materials over the entire load range; it is <u>not</u> sufficient to model elastic modulus as is often done when only elastic response is to be modeled. As a result, models for the study of reinforced concrete structures, loaded into the inelastic region, must be constructed using the same materials (concrete and steel) as are used in the prototype. Even when this is done, there will be differences between the model and prototype material behavior in the inelastic region because of our inability to completely scale crack formation and growth, bonding mechanisms, etc.

These difficulties do not invalidate the use of model studies to aid in our understanding of the inelastic response of reinforced concrete structures; however, if valid results are to be obtained, it is essential that these scaling difficulties be recognized and their effects minimized and/or accounted for.

In the material which follows, the scaling laws are developed in some detail so that assumptions and choices based on judgment can be clearly recognized and their effects discussed. The scaling laws developed are then used to design a reinforced concrete model of a Category I structure. Finally, how scaling is affected by various types of damping (viscous, structural, and Coulomb) is discussed.

Development of the Scaling Laws

The typical structure of interest is shown in Fig. 1. The terms used in the development are defined as follows.

- $\ddot{x}$ - response acceleration at any point on the structure.
- E - the symbol used to indicate the material force vs deformation characteristic; not a constant over entire loading region of interest.
- M - the mass of the structure or any mass attached to the structure.
- h - any linear dimension. Since only one term is used, no geometric distortion is allowed.
- $\ddot{y}$ - the input, or driving, acceleration.
- t - time; necessary since both input and response motions are functions of time.
- F - force; any force, including gravitational forces, except damping forces.

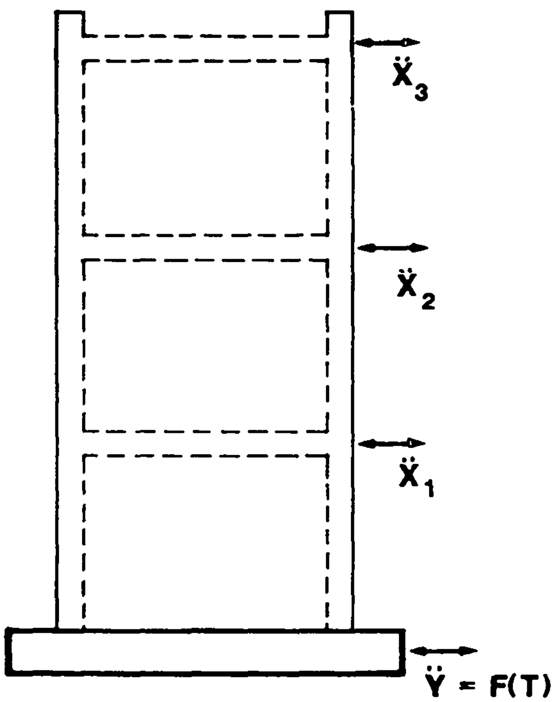

Fig. 1. Idealized elevation view of a typical structure of interest.

Material properties that govern damping forces (viscous, structural, or Coulomb) have deliberately been omitted and hence damping forces are neglected. This has been done to simplify the establishment of the acceleration, time, mass, and force scales; however, following this simplified development damping will be addressed.

For this system the basic functional equation is

$$\ddot{x} = \phi\,(E, M, h, \ddot{y}, t, F). \tag{1}$$

Equation (1) can be reduced to a dimensionless functional equation as follows.

All of the terms in Eq. (1) can be expressed using three fundamental dimensions

(F - force, L - length, T - time).

Thus, $\ddot{x}$ - LT^{-2}
E - FL^{-2}
M - $FT^{2}L^{-1}$
h - L
$\ddot{y}$ - LT^{-2}
t - T
F - F

Equation (1), with seven quantities involving 3 fundamental dimensions, can be reduced to a dimensionless equation containing 4 dimensionless groups (7 - 3 = 4, the so called Buckingham 'π' theorem). Thus,

$$\frac{\ddot{x}}{\ddot{y}} = \phi'\left(\frac{Eh^2}{M\ddot{y}}, \frac{h}{\ddot{y}t^2}, \frac{F}{M\ddot{y}}\right) . \tag{2}$$

These dimensionless groups are known as 'π' terms and defining $\ddot{x}/\ddot{y}$ as π_1, $Eh^2/M\ddot{y}$ as π_2, etc. we can write

$$\pi_1 = \phi'\,(\pi_2, \pi_3, \pi_4) . \tag{3}$$

Scale model theory can now be easily stated.

"Since the same functional equation (Eq. 3) governs both the model and the prototype, we see that if we design and test the model so that π_2 of the model (π_{2_m}) equals π_2 of the prototype (π_{2_p}) i.e.,

$\pi_{2_m} = \pi_{2_p}$; and, likewise

$\pi_{3_m} = \pi_{3_p}$, and $\pi_{4_m} = \pi_{4_p}$ then π_{1_m} must equal π_{1_p}."[17]

These conditions

$(\pi_{2_m} = \pi_{2_p})$, etc.,

establish the required scales (i.e. the scaling laws). Writing these design and operating conditions out we have

$$\left(\frac{Eh^2}{M\ddot{y}}\right)_m = \left(\frac{Eh^2}{M\ddot{y}}\right)_p , \tag{4}$$

$$\left(\frac{h}{\ddot{y}t^2}\right)_m = \left(\frac{h}{\ddot{y}t^2}\right)_p , \quad \text{and} \tag{5}$$

$$\left(\frac{F}{M\ddot{y}}\right)_m = \left(\frac{F}{M\ddot{y}}\right)_p , \tag{6}$$

where m and p refer to model and prototype respectively. Each of the three can be rearranged in the following way (using Eq. (4) as an example),

$$\frac{E_p}{E_m} = \left(\frac{h_m}{h_p}\right)^2 \left(\frac{M_p}{M_m}\right) \left(\frac{\ddot{y}_p}{\ddot{y}_m}\right) . \tag{7}$$

We now define scales as follows. Let N_E, the basic material stiffness property scale, be E_p/E_m; let N_h, the length scale, be h_p/h_m, etc. Then Eq. (7) becomes

$$N_E = \frac{N_M N_{\ddot{y}}}{N_h^2} . \qquad (8)$$

In the same way, using Eqs. (5) and (6), we can write all of the required scale relationships.

$$N_h = N_{\ddot{y}} N_t^2 \text{, and} \qquad (9)$$

$$N_F = N_M N_{\ddot{y}} . \qquad (10)$$

These three equations are the scaling requirements (or laws) that dictate how the model must be designed and operated. If these scaling laws are satisfied the prediction equation,

$$(\pi_{1_m} = \pi_{1_p}), \quad \text{yields} \quad \ddot{x}_p = N_{\ddot{y}} \ddot{X}_m .$$

Since the six scales (N_E, N_M, etc.) are related by only three equations, any three scales can be selected arbitrarily; hence, in theory, the required scaling can be accomplished in any number of ways. In fact, even in this simple case, the choice of which scales are to be 'arbitrarily' selected and what values are assigned is very important and will determine whether or not the model can be constructed and tested.

In general, the length scale (N_h) is dictated by the size of the prototype and the maximum size of the model that can be tested in an existing test facility or a facility to be constructed. Without assigning a numerical value at this point, let us agree that N_h will have to be assigned a specific value, say $\overline{N}_h$.

Remembering that the term E does not represent a constant but, rather, the entire shape of the stress vs strain diagrams of all of the materials used in the model and the prototype, we can anticipate that there is little chance of selecting model materials that are different from the prototype materials while still retaining the required similarity over the entire loading range. Therefore, when models are designed to predict prototype behavior when the materials are loading into their inelastic regions, it is almost always necessary to use the same materials in the model as are used in the prototype (steel reinforcement and concrete, in this case). Hence, $N_E = 1$.*

The remaining choice of the scale to which we will assign a value is not so clear cut. Let us consider several possibilities.

Case I. Let $N_M = \bar{N}_h^3$. This would appear to be a logical choice since having already decided to use the same materials in model and prototype, their densities will be equal and all masses will be scaled by volume (i.e. L^3), hence $N_m = \bar{N}_h^3$. With these three choices ($N_h = \bar{N}_h$, $N_E = 1$, and $N_M = \bar{N}_h^3$) the remaining required scales become

$$N_{\ddot{y}} = \frac{1}{\bar{N}_h} ,$$

$$N_t = \bar{N}_h , \text{ and}$$

$$N_F = \bar{N}_h^2 .$$

The first two requirements (the acceleration and time scaling) appear to pose no special problems. If the prototype is to be subjected to a peak acceleration of 1 g, the peak acceleration applied to the model can (given an appropriate test facility) be adjusted to ($\bar{N}_h$ x 1) g, i.e.,

$$N_{\ddot{y}} = \frac{\ddot{y}_p}{\ddot{y}_m} , \text{ or } \ddot{y}_m = \bar{N}_h \times \ddot{y}_p .$$

*Even when steel and concrete are used in the models and the elastic modulus of the model concrete is the same as the prototype concrete, it is doubtful if the desired similarity over the entire loading range is achieved--it is simply the best we can do.

Further, if the prototype is to be subjected to a certain seismic history lasting 12 seconds, that seismic history can be time scaled by a factor of N_t so that for the model test the duration of the test signal would be $12/\bar{N}_h$ s.*

The third scale requirement, $N_F = \bar{N}_h^2$, is troublesome. In the problem being considered the only external forces that act on the system are the gravitational forces and it is clear that if the model is tested in the same gravitational field (the Earth's) as the prototype, then the gravity forces (weights) will be scaled as the masses are scaled

$$\left(\text{i.e. } F_{\text{gravity}_m} = \frac{F_{\text{gravity}_p}}{\bar{N}_h^{\,3}}\right),$$

instead of being scaled by a factor $\bar{N}_h^2$.

The type of scaling just discussed (to be referred to as Case I in this paper) is widely used in spite of this distortion. The assumption is that the distortion of gravity forces has little effect upon the response of the model. We can be somewhat more specific in our thinking about the effect of this distortion if we realize that in this system gravity forces affect (1) the vertical stresses in the structure, (2) the overturning moment when the structure is displaced from equilibrium, (3) the period of free vibration (P) and (4) any Coulomb friction effects, since these depend on normal forces. We now see that if the gravitational forces are small compared to other forces (inertia and restoring forces), the vertical stress field and the overturning moment may not be greatly altered by distorting these forces. Furthermore if the system is 'stiff,' the influence of gravity on the period of vibration will be small, and finally if there are no Coulomb effects (presumably because the coefficient of friction is small or no slippage occurs), distorting gravity forces has no effect. Calculations show that, for the structures of interest in this study (low profile, thick walls, limited number of stories), the vertical stress, overturning moment, and natural period are not greatly affected by

*Thinking in terms of frequency (f) content, all components of the signal applied to the model will be frequency shifted up by a factor of N_h since the frequency scale N_f is the reciprocal of the time scale N_t.

gravitational forces. How important Coulomb damping may be in affecting the response of cracked concrete is unknown.

Case II. Let $N_{\ddot{y}} = 1$. This too appears to be a logical choice since testing the model in the same gravitational field as affects the prototype suggests that $\ddot{y}_m = \ddot{y}_p$. With these three choices

$$(N_h = \bar{N}_h, \quad N_E = 1, \text{ and } \quad N_{\ddot{y}} = 1)$$

the remaining scales become

$$N_t = \sqrt{\bar{N}_h} ,$$

$$N_F = \bar{N}_h^{\,2} , \text{ and}$$

$$N_M = \bar{N}_h^{\,2} .$$

Now the problem is that, unless we find some way to adjust (increase) the density of the model material, the distributed mass will be scaled as $N_M = \bar{N}_h^3$ (as before) rather than the required value of $\bar{N}_h^2$. The usual way to make this adjustment is to attach lumped masses to the model.* There are several difficulties with this approach. (1) Attached lumped masses can never truly model distributed mass even if the total mass is correct; centers of gravity of components and hence moments are changed. (2) Stress distribution is affected. (3) Attachment can be difficult under severe dynamic load conditions. (4) As the model becomes smaller (larger $\bar{N}_h$), relatively more mass must be added, since the mass that must be added is directly proportional to $\bar{N}_h$.

Case III. Let $N_{\ddot{y}} = Q$. Q represents either a constant or a function of $\bar{N}_h$, and it is intended that $1/N_h < Q < 1$. For this case the scales are

*Some authors have suggested using heavy aggregate material for the model concrete, but the fact is that, even if this modification did not change the material properties, (N_E), not enough adjustment can be made except when the models are very large, i.e., $\bar{N}_h$ is small.

$$N_h = \bar{N}_h,$$

$$N_E = 1,$$

$$N_{\ddot{y}} = Q,$$

$$N_M = \bar{N}_h^2/Q$$

$$N_t = \sqrt{N_h/Q}, \text{ and}$$

$$N_F = \bar{N}_h^2.$$

Clearly this is a case somewhat intermediate to Cases I and II, and as you would expect, all of the difficulties that were discussed for both of the first two cases will apply to this case. Gravity forces in the model will be distorted, as in Case I, but the amount of distortion will depend upon the value selected for Q. Mass will still have to be attached to the model, as in Case II, but the amount will depend upon the value selected for Q. Perhaps the most important feature of Case III modeling is that the value of the acceleration scale can be selected to match the capabilities of the model test facility. In designing and testing small models, the authors have found that it is usually not convenient to use acceleration scales of either $1/N_h$ (Case I) or unity (Case II).

Application of the Scaling Laws to the Design and Testing of a Typical Category I Structure

For the purpose of this example, we begin by assuming that the prototype Category I structure has a wall thickness (h_p) of 30 inches and all other dimensions are proportioned accordingly. Because of cost, size, and weight limitations, we decide that the model structure will have a wall thickness (h_m) of 1 inch; hence, $N_h = 30$. Because we wish to investigate the behavior of the prototype when the seismic input is large enough to produce inelastic deformation of the structure, we will use steel reinforced concrete for the model in an attempt to obtain the desired similarity of material behavior over the entire loading range; hence, $N_E = 1$.

We now assume the largest peak acceleration value to which the prototype will be subjected ($\ddot{Y}_{PK}$) is 1 g. A study of the available seismic test facility's capabilities indicates that for the mass of the model we are considering, together with the mass of all the necessary mounting hardware, the peak acceleration value that can be applied to the model ($\ddot{Y}_{PK}$) while still maintaining good pulse shape (or frequency content) control is 5 g. Therefore we select N_y = 1/5, i.e., Q = 1/5.

This will be a Case III model and the other required scales are

$$N_M = \bar{N}_h^2/Q = \frac{30^2}{1/5} = 4500$$

$$N_t = \sqrt{\bar{N}_h/Q} = \sqrt{\frac{30}{1/5}} = 12.25$$

$$N_F = \bar{N}_h^2 = 30^2 = 900.$$

These scaling laws are now used to design and test the model. First, the model is constructed as a 1/30-scale version of the prototype. Second, the amount of mass that must be added to the model to achieve the required mass scale is computed. The mass of the model desired is

$$M_{m.d.} = \frac{M_p}{N_M} .$$

The mass of the prototype (M_p) can be computed from the prototype volume and density, but an easier method (assuming the model has been fabricated) is to write $M_p = M_{m'} \times \bar{N}_h^3$, where $M_{m'}$ is the mass of the model as fabricated without any added mass. Then the mass to be added to the model is

$$M_A = M_{m.d.} - M_{m'} ,$$

$$M_A = \frac{M_{m'} \bar{N}_h^{\,3}}{N_M} - M_{m'} , \quad \text{or}$$

$$M_A = M_{m'} \left(\frac{\bar{N}_h^{\,3}}{N_M} - 1 \right) . \tag{11}$$

For the example being considered ($N_h = 30$, $N_M = 4500$), this reduces to $M_A = 5 M_{m'}$. This added mass should, of course, be uniformly distributed throughout the model since its purpose is to properly scale the effect of the structure's distributed mass. In general, this will not be possible, and in the example being considered, the added mass will be located at each floor level as shown in Fig. 2. Since the location of this added mass has considerable effect on the system's dynamic response, it is important that the value substituted for $M_{m'}$ (the model's mass) be the effective value of mass ($M_{me'}$) lumped at the location where the added mass is to be attached. This value of lumped mass, which is dynamically equivalent to the distributed mass it replaces, can be computed (using energy methods or Rayleigh's method) or (assuming the model is available) from measured values of the structure's natural frequency with and without added mass.

The appropriate test signal is now determined by amplitude and time scaling the seismic history of interest by the required acceleration and time scales. Assuming that the 1940 El Centro N-S seismic history, edited to 16 s and one g peak acceleration, is chosen as the prototype excitation, the model test signal is obtained by amplitude scaling this record by $N_{\ddot{y}} = 1/5$, which produces a peak acceleration of 5 g's, and by time scaling the record by $N_t = 12.25$, which produces a record of 1.306 s duration and containing frequency components that have been increased by a factor of 12.25.

<u>Investigation of the Effect of Damping on Reinforced Concrete Models</u>

In the preceding discussion, the effect of damping on a scale model's behavior was deliberately neglected because its inclusion complicates the analysis but does not affect the establishment of the important scaling laws. Now,

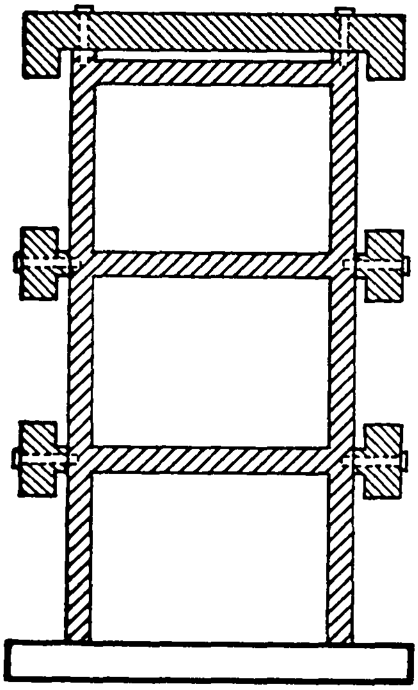

Fig. 2. Method of attaching mass to a typical structure.

however, we are obligated to investigate how damping forces should be scaled, whether they can be scaled, and, if not, what is the effect of this distortion.

In this discussion, damping is used to mean energy loss during cyclic loading. Three damping mechanisms are considered: (a) viscous, or frequency dependent, damping, (b) structural, or solid, damping, and (c) Coulomb, or dry friction, damping. For these three types of damping, the damping forces are defined as follows:

Viscous damping force; $F_\nu = \nu VA/b$ in which

ν is the material viscous damping coefficient,

V is relative velocity between surfaces,

A is surface area, and

b is perpendicular distance between the surfaces.

Note that the usual system, or element, viscous damping coefficient (c), for which $F_\nu = c V$, is related to ν as $c = \nu A/b$. A and b are, of course, not material properties and hence c is not a material property. Also note that the widely used viscous damping ratio, $\zeta = c/c_c = c/2\sqrt{KM}$, in which c_c is the 'critical' damping equal to $2\sqrt{KM}$, where K is stiffness and M is mass, is not a material property.

Structural damping force; $F_\beta = \beta uA/b$* in which

β is the material structural damping coefficient,

u is relative displacement between surfaces, and

A and b are as previously defined.

Note that the usual system, or element, structural damping coefficient (υ), for which $F_\beta = \upsilon u$, is related to β as $\upsilon = \beta A/b$. Obviously, υ is not a material property. In structural damping calculations the damping force is also often written as $F_\beta = \upsilon' KU$ and υ' is called a "proportional" structural damping coefficient. Obviously $\upsilon' = \upsilon/K$, where K is the element stiffness and, again, υ' is not a material property.

Coulomb damping force; $F_\mu = \mu F_N$ in which

μ is the Coulomb damping coefficient, and

F_N is the force normal to the surface on which slipping occurs.

μ is usually assumed to be a material property; that is, the value of μ is assumed to be dependent upon the two materials in contact at the sliding interface. Actually, μ, and hence F_μ, does depend upon surface geometry. This may be of considerable importance in scaling; however, in the analysis which follows, μ will be taken as a material property and, hence, if the same materials are used in the model and prototype, $\mu_m = \mu_p$.

If we assume that by using the same material for model and prototype, all of the basic material damping coefficients (ν, β, μ) are the same in the model and the prototype, we may write

$\nu_m = \nu_p$,
$\beta_m = \beta_p$, and
$\mu_m = \mu_p$.

Now the ratio of damping forces in the model to those in the prototype can be written using the fundamental equations for the damping forces and the scales previously defined.

*Although the magnitude of structural, or solid, damping force (F_β) is not considered to be velocity dependent, this type of damping is assumed to oppose relative velocity, and the damping force exists only for relative velocities greater than zero.

For viscous damping forces, F_ν

$$F_{\nu_m} = \frac{\nu_m V_m A_m}{b_m} \text{ , and}$$

$$F_{\nu_p} = \frac{\nu_p V_p A_p}{b_p} \text{ .}$$

Dividing and noting that $\nu_m = \nu_p$,

$$\frac{F_{\nu_p}}{F_{\nu_m}} = \frac{V_p}{V_m} \frac{A_p}{A_m} \frac{b_m}{b_p} \text{ , and}$$

substituting

$$b_m = b_p/N_h,$$

$$A_m = A_p/N_h^{\ 2}, \text{ and}$$

$$V_m = V_p/N_{\ddot{y}}N_t,\text{*}$$

we have

$$\frac{F_{\nu_p}}{F_{\nu_m}} = N_{\ddot{y}} \, N_t \, N_h \quad . \tag{12}$$

How this ratio of viscous forces compares to the required force scale (N_F) of N_h^2 previously established depends upon how the model has been scaled. The ratios of viscous forces for the three modeling cases previously discussed are shown in Table I. Note that viscous damping forces are distorted in every

*The velocity scale ($N_{\dot{y}}$) is the acceleration scale ($N_{\ddot{y}}$) times the time scale (N_t).

case; specifically, viscous damping forces in the models are too large (as compared to the viscous damping forces in the prototype).

Proceeding in the same manner, we can write the ratio of the structural damping forces involved, thus

$$\frac{F_{\beta_p}}{F_{\beta_m}} = N_h^2 \; . \tag{13}$$

Equation (13) shows that structural damping is correctly scaled for all modeling cases (see Table I).

How Coulomb damping forces (F_μ) are scaled depends upon how normal forces (F_n) are scaled since $F_\mu = \mu \, F_n$ and we have assumed that "μ" is the same in both model and prototype. Since in buildings the vertical normal forces include gravity forces, and since gravity forces are only correctly scaled (as N_h^2), in Case II models we note that Coulomb damping forces are only correctly scaled in Case II models. Since the vertical normal forces in a structure depend not only on gravitation forces but upon vertical inertia forces and forces developed by flexure and since, in general, we do not know the relative magnitude of these forces, the distortion of Coulomb damping forces in the other two modeling cases remains unknown. However, with Case I and Case III models, the gravitational forces are too small (as compared to gravitational forces in the prototype); hence we know that the Coulomb forces will also be too small in the model.

This analysis demonstrates that the effect of scaling on damping is understood and can be accounted for provided that the nature of the damping forces is known. This then is the problem with reinforced concrete, especially when loaded into the inelastic range; the exact nature of the damping mechanism is unknown. If, as is often assumed in analysis of structures, the damping is structural, or solid damping, then damping forces are not distorted. Further, if Case II scaling is used, neither structural nor Coulomb damping forces are distorted, and the viscous damping forces are distorted by a minimum amount (the viscous forces in the model are too large by a factor of $\bar{N}_h^{1/2}$).

TABLE I

DAMPING FORCE RATIOS

Type of Modeling	Viscous Force Ratio F_{ν_p}/F_{ν_m}	Structural Force Ratio F_{ρ_p}/F_{ρ_m}	Coulomb Force Ratio F_{μ_p}/F_{μ_m}
Case I	$\bar{N}_h$	$\bar{N}_h^2$	?
Case II	$\bar{N}_h^{3/2}$	$\bar{N}_h^2$	$\bar{N}_h^2$
Case III	$\bar{N}_h^{3/2}\, Q^{1/2}$	$\bar{N}_h^2$	?

Since the concept of viscous damping ratio, ζ, is used in most design and analysis methods applied to Category I structures,* it is useful to rethink the preceding analysis of viscous damping forces in terms of ζ.

Using the terms defined in the preceding paragraphs,

$$\zeta = \frac{\nu A}{2b\sqrt{KM}} \;.$$

Writing this expression for the model (subscript m) and the prototype (subscript p) and dividing, we have

$$\frac{\zeta_p}{\zeta_m} = \frac{\nu_p}{\nu_m} \cdot \frac{A_p}{A_m} \cdot \frac{b_m}{b_p} \cdot \left(\frac{K_m}{K_p} \cdot \frac{M_m}{M_p}\right)^{1/2} \;.$$

Now if the model and prototype are of identical materials and $\nu_p = \nu_m$ (as was previously assumed), and we substitute scale definitions we have

$$\frac{\zeta_p}{\zeta_m} = 1 \cdot \bar{N}_h^2 \cdot \frac{1}{\bar{N}_h} \cdot \left(\frac{1}{\bar{N}_h} \cdot \frac{1}{\bar{N}_h^2/Q}\right)^{1/2}$$

*ζ is used because of its convenience in computations, not because designers believe that the damping mechanism is viscous.

or

$$\frac{\zeta_p}{\zeta_m} = \sqrt{\bar{Q}/N_h}\ .^{**} \tag{14}$$

Equation (14) tells us how the viscous damping ratio, ζ, of two structures (model and prototype) will be related _if_ the damping is viscous. This suggests that, if we build two structures of different sizes (two different scale models) and test and measure ζ on each one, we can compare the ratio of measured results to the ratio predicted by Eq.(14) to investigate whether or not the damping is indeed viscous.

For example, we might build and test 1/30 and 1/10-scale models of a Category I structure and design and test them so that the smaller structure is a Case II (Q=1), 1/3 scale ($N_h = 3$) model of the larger structure. Then Eq. (14) would predict that the measured values of ζ would be related as

$$\frac{\zeta_{larger}}{\zeta_{smaller}} = \sqrt{1/3}$$

or

$$\zeta_{larger} = 0.58\ \zeta_{smaller},$$

if the damping is viscous.

**Note that the area scale, $N_A = \bar{N}_h^2$; that the stiffness scale, $N_K = N_F/\bar{N}_h = \bar{N}_h^2/\bar{N}_h = \bar{N}_h$; and that when the mass scale, N_m, is written as $\bar{N}_h^2/Q$, we cover all three model cases since for a Case I model $Q = 1/\bar{N}_h$ and for a Case II model $Q = 1$.

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The laws that govern the scale-model requirements for reinforced concrete Category I structures over a full range of seismic loading extending from the elastic through the inelastic ranges of response are developed. Three types of scaling are then examined. The third type, called "Q" scaling in this report, is the most useful for tailoring structural models to existing seismic test facilities. Finally, the way in which the three types of commonly used damping (viscous, structural, and Coulomb) scale in these models is derived.

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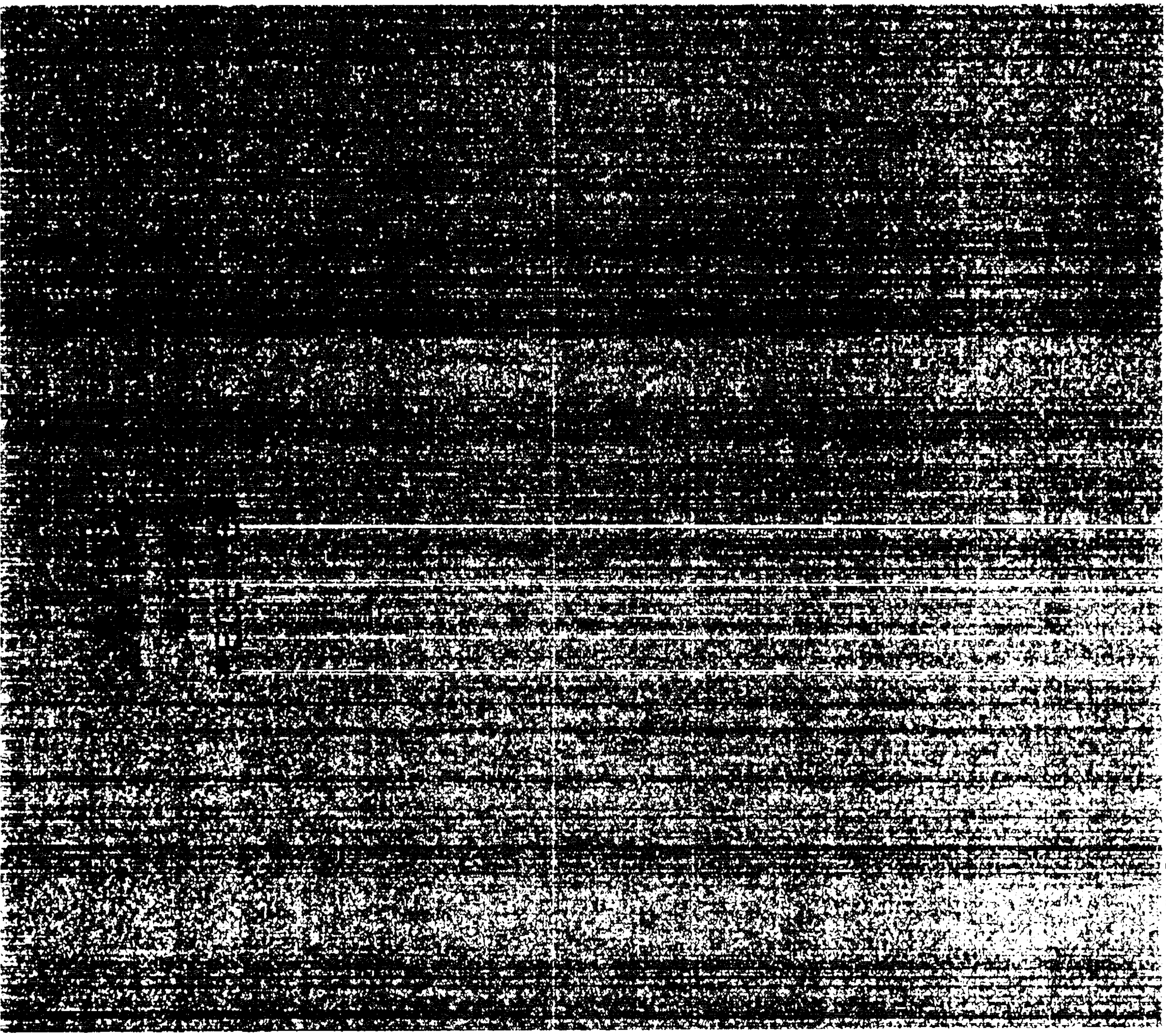

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