Predictive Models for Damping in Buildings: The Role of Structural System Characteristics

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ABSTRACT

Damping is dependent on many variables and complex mechanisms that are not yet fully quantifiable in the design stage. This has led to generic assignments of viscous damping usually based on material type and at best based on height with reference to existing databases. This study will employ recent full-scale observations to demonstrate the role of the structural system's dominant deformation mechanism - frame racking vs. cantilever action – in energy dissipation capability. Specifically, it is shown that frame racking and other shear deformations dissipate more energy than the axial shortening associated with cantilever action. As such, the ratio of frame racking to cantilever action may offer a more robust and intuitive parameter better suited for use in predictive viscous damping models. This study serves as the first step in the development of such models, with a specific focus on serviceability design.

INTRODUCTION

As building systems become increasingly more lightweight and efficient, accurate prediction of dynamic responses characterized by structural mass, stiffness and damping becomes increasingly critical. While mass and stiffness are readily determined in the design stage, damping continues to elude structural engineers, who remain reliant on rudimentary estimates that are largely based on the building's primary material: steel or reinforced concrete. This often proves problematic as damping is a particularly critical parameter in serviceability and habitability design. The resultant uncertainty surrounding these assumed damping levels often thwarts design efforts to evaluate a building's habitability and serviceability with accuracy and may even result in the need for an auxiliary damping device. Clearly a better understanding of the structure's inherent damping is needed to insure that economy and efficiency can be balanced with serviceability and habitability performance.

For this reason there has been a greater attempt to quantify the viscous damping ratio of tall buildings under the action of wind and ambient excitation, generating empirical predictive models based on databases of full-scale values [Jeary, 1986; Lagomarsino, 1993; Satake et al., 2003]. These databases are quite regional in nature, limited in scope, and only occasionally consulted by practitioners. The lack of a definitive parameter influencing damping requires trends to be generally parameterized as a function of single variables like building height or period for a given material, though considerable scatter is apparent. This is not only attributed to difficulties in estimating damping from full-scale data, but also results from the fact that height may not be an appropriate regression parameter. For example, as demonstrated by Erwin et al.

[2007], a collection of buildings with the same fundamental structural system were observed to manifest significantly different damping values in their two lateral directions, which will later be shown to depend upon aspect ratio. The question may then be posed: is there a more appropriate way to characterize a building that is robust enough to be applied to a wide class of structural systems and thereby be used as a regression parameter in predictive damping models?

HYPOTHESIS AND BACKGROUND

The authors propose that such a robust parameter may be found in the relative participation of the structural system's dominant deformation mechanisms: frame racking (shear) vs. cantilever (axial) action. Both are present in every structural system, though the degree to which depends not only on the height of the structure but also upon member stiffnesses and system geometry. For example, frame racking generally dominates in moment resisting frames (MRFs) and leads to increasingly large deformations as height increases, while in shear wall systems, the transition to a cantilever dominated behavior depends more so on aspect ratio than height itself [Taranath, 1998]. Thus the ratio of these mechanisms appears to posses the capability to characterize the uniqueness of a structural system with a single parameter, while being robust enough to be applied to a variety of structural system types.

The feasibility of dominant deformation mechanism as a parameter in viscous damping characterization has been supported by preliminary research demonstrating that frame racking and other shear-based deformations dissipate relatively more energy than the axial shortening associated with cantilever behavior [Kijewski-Correa et al., 2006; Erwin et al., 2007]. Furthermore, this hypothesis finds support in fundamental mechanics. This can be demonstrated simply using a cantilever beam with a rectangular cross section under a uniformly distributed load of magnitude q [Solecki and Conant, 2003]. The moment and shear at any location x along the length of the beam h are given by:

$$M = -\frac{1}{2}qx^2 \text{ and } V = qx \qquad \text{(1 a,b)}$$

Then evaluating the strain energy as a generic measure of energy dissipation potential:

$$U = \int_0^h \left(\frac{M^2}{2EI} + \frac{F^2}{2EA} + \frac{\kappa V^2}{2GA} \right) dx \qquad (2)$$

for the case of zero axial load ($F=0$) yields

$$U = \frac{q^2 h^5}{40EI} + \frac{\kappa q^2 h^3}{6GA} \qquad (3)$$

where I=moment of inertia about the axis of bending ($I=bd^3/12$), A=cross sectional area ($A=bd$), κ =form factor ($\kappa=1.2$), E=Young's Modulus, and G=Shear Modulus ($G=0.5E/(1+\nu)$), where ν is Poisson's ratio. Taking $\nu=0.3$, the strain energy becomes:

$$U = \frac{q^2 h^5}{40EI}\left(1 + 1.73\frac{d^2}{h^2} \right). \qquad (4)$$

Note that the first term in parentheses is the strain energy due to bending and the second term is the strain energy due to shear, which is additionally dependent upon the ratio between depth d and length h of the beam. From this equation, the shear contributions to the strain energy will be greatest when the aspect ratio h/d is close to 1 and will be negligible when the beam is long and slender. This reflects the tendency for taller structures to experience lesser energy dissipation.

The quantification of these deformation mechanisms in practice can be accomplished in one of two ways. The more precise quantification can be extracted from finite element models (FEM), specifically from mode shapes, using the assumption that the i^{th} mode shape is comprised of three components:

$$\phi_i(z) = \phi_{i,A}(z) + \phi_{i,V}(z) + \phi_{i,PZ}(z) \tag{5}$$

An axial component associated with cantilever action ($\phi_{i,A}$), a shear component associated with frame racking in the beams and columns ($\phi_{i,V}$), and a component tied to joint deformations or so called panel zone effects ($\phi_{i,PZ}$). After determining the overall mode shape (ϕ_i), the axial component can be eliminated by using a rod constraint on all columns, thus preventing any axial deformation. The resulting mode shape then represents the overall shear contributions from the beams, columns or joints ($\phi_{i,V} + \phi_{i,PZ}$). With this in hand, $\phi_{i,A}$ can then be computed from (5).

This concept is demonstrated using two-dimensional MRFs modeled in SAP 2000 for three different aspect ratios: *h/d*=1, 5, and 10 and loaded laterally at the top floor. The lateral deformations are modally characterized and plotted in Figure 1 for the two extreme aspect ratios, isolating the shear and axial contributions. As Figure 1 demonstrates, the contributions are height dependent, with shear dominating the lower half of the structure and cantilever effects dominating the upper half. Table 1 summarizes the relative contributions of the axial and shear deformations to the overall mode shape for the first 2 modes, averaged over the height of the model. Clearly, the cantilever or axial contribution increases with aspect ratio, as expected, particularly in the fundamental mode.

Aspect Ratio	AXIAL		SHEAR		
	Mode 1	Mode 2	Mode 1	Mode 2	α
1	1%	22%	99%	78%	0.33
5	15%	9%	85%	91%	0.63
10	40%	49%	60%	51%	0.88

TABLE 1- AVERAGE PERCENT CONTRIBUTIONS AND MODE SHAPE POWER FOR FEM PARAMETER STUDY

In many cases, when analyzing published full scale dynamic properties, the full finite element model of a structure is not available for such an analysis or would require too much effort to generate. Still, a basic fit of the overall mode shape by a power-law expression can yield qualitative insights into the degree of cantilever action present. Thus the i^{th} normalized mode shape is described by

$$\widetilde{\phi}(z)_i = (z/h)^{\alpha} \tag{6}$$

and least squares minimization can be used to identify a best-fit power (α). For $\alpha<1$, there is a general lack of cantilever action and as $\alpha \rightarrow 2$, there is an increasing presence of cantilever action. Often, $\alpha=1$ is termed a "shear building" and $\alpha=2$ is termed a "cantilever building," as these signify benchmarks where around 75-80% of the deformations are contributed by the namesake. As such, the authors have adopted the following characterization of buildings based on the mode shape power:

Type V (Shear): $\alpha \leq 1.25$
Type A-V (Interactive): $1.25 > \alpha > 1.5$ (7 a,b,c)
Type A (Cantilever): $\alpha \geq 1.5$

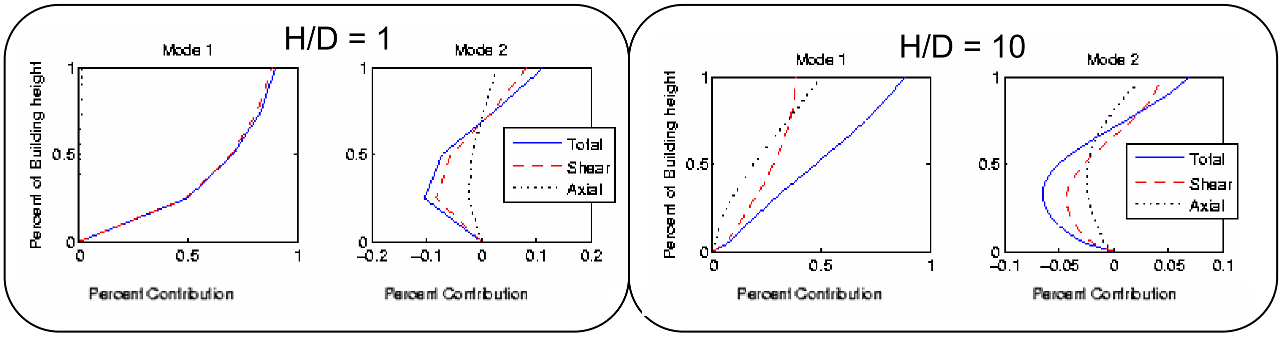

FIGURE 1 AXIAL AND SHEAR CONTRIBUTIONS IN EACH MODE FOR H/D=1 (LEFT) AND H/D = 10

To evaluate the effectiveness of this approximate characterization, the mode shapes from the finite element model for three aspect ratios are best fit by (6), and the associated powers are reported in Table 1. Based on the general rules of thumb for MRFs, for $h/d = 1$, $\alpha << 1$ indicates a lack of cantilever action, which is clearly demonstrated by the percent contributions introduced previously in Table 1. Comparatively, for $h/d = 10$, $\alpha \rightarrow 1$ still signifies dominant shear deformations, but with increasingly substantive cantilever action. Still, irregardless of aspect ratio, MRFs have difficulty achieving any more significant cantilever action ($\alpha > 1$) due to the excessive shears that accumulate as height increases, thus limiting the utility of these FEMs in demonstrating the concept at hand.

To further examine the effects of this approximation on actual building systems, a similar finite element analysis was conducted on Building 3 of the Chicago Full-Scale Monitoring program, which is reported to be a "steel moment-connected, framed tubular system…[that] behaves fundamentally as a vertical cantilever fixed at the base to resist wind loads. The system is comprised of closely-spaced, wide columns and deep spandrel beams along multiple frame lines. Deformations of the structure are due to a combination of axial shortening, shearing…in the frame members, and beam-column panel zone distortions" [Kijewski-Correa et al., 2006]. As such, Building 3 identically embodies the idealization in (5). Figure 2 demonstrates the increasing role of cantilever effects as height increases, for the two orthogonal sway responses (1 and 2), from less than 20% of the overall deformations near the base of the structure to 50% at the roof in mode 1 and 46% at the roof in mode 2. These relative contributions were averaged and reported in Table 2, demonstrating a near 60-40 split of shear to axial deformations in both orthogonal directions. Fitting the normalized mode shape of Building 3 with (6), the optimal mode shape powers are 1.39 and 1.41, as also reported in Table 2. According to (7), the system is classified as *Interactive*, with near equal contributions of shear and axial deformations. This indicates that when lacking a full FEM, a qualitative measure of the contributions of shear vs. cantilever action can be gauged from the mode shape powers themselves. This will now be exploited in the following section.

	Shear	Axial	α
Mode 1	66%	34%	1.39
Mode 2	63%	37%	1.41

TABLE 2- BUILDING 3 SHEAR AND AXIAL DEFORMATIONS AVERAGED OVER HEIGHT AND MODE SHAPE POWER

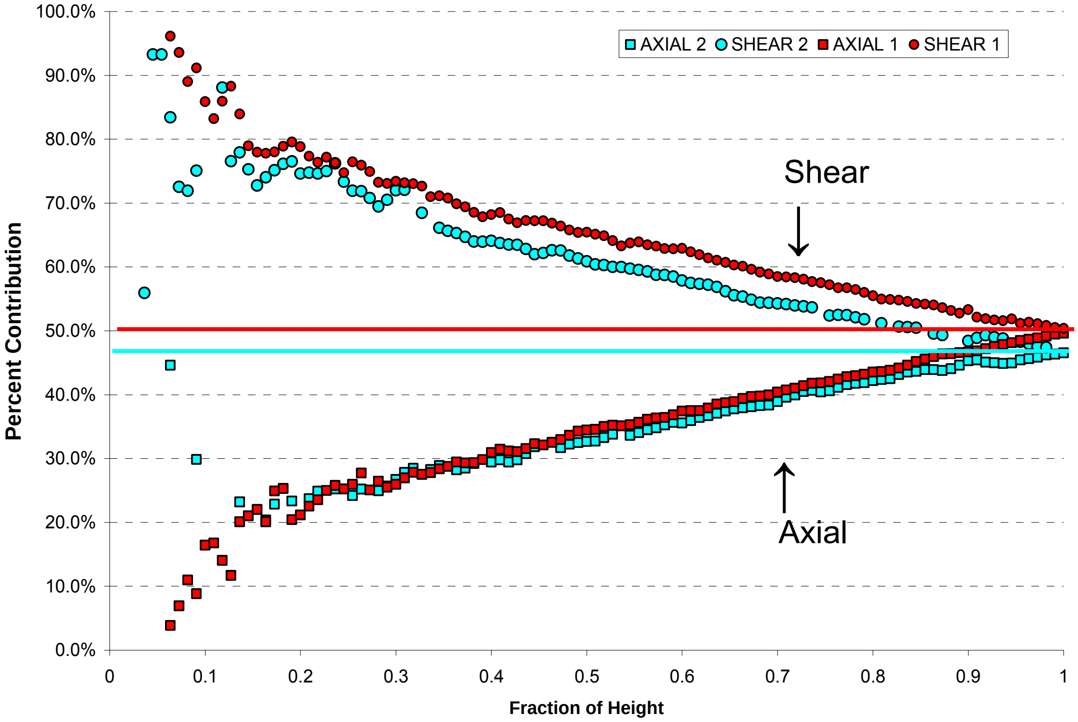

FIGURE 2- BUILDING 3 CONTIRIBUTION OF AXIAL VS. SHEAR WITH HEIGHT

FULL-SCALE CASE STUDIES OF TALL BUILDINGS

Full-scale damping data has been recently published on nine tall buildings, which are expected to have noteworthy axial shortening. In most cases, sufficient detail is available from the literature to characterize the buildings via their mode shapes, in accordance with (6). As such, each published mode shape was digitized and mode shape powers (α) were determined by least squares analysis. Table 3 summarizes the details of the building's structural systems, their use of steel (S), reinforced concrete (RC) or composite (SRC) lateral systems, the published damping values and the estimated mode shape powers. One can note the interactive systems as those that utilize dual systems (cores and frames) or that employ tube-concepts with substantive shear lag or panel zone deformation. The few cantilever structures rely on tubes with stiffening elements to reduce shear lag or outriggers to further engage perimeter elements in resisting overturning.

The critical damping ratios (ξ) in Table 3 are the average of the values reported in the referenced papers. In cases where amplitude dependent damping was reported, the high amplitude plateau is used. The reported methods used to evaluate damping include the Half Power Bandwidth and Random Decrement Technique. At this point it is important to emphasize that amplitude dependence, as discussed in greater detail later, and a number of bias and variance errors can affect damping estimates and thus the reliability of the values reported in the literature is uncertain. In addition, since only mode shapes are available, the exact quantification of the extent of shear vs. cantilever action is not known precisely. Still it is interesting to see if the general trend of decreasing damping with increasing role of cantilever action holds true. Indeed, as shown in Figure 3, damping values are more scattered and larger for interactive systems and as the systems become more cantilever, the damping values collapse and decrease. The

Building	h [m]	Mat'l Type	Structural System Type	Lateral Mode #1			Lateral Mode #2		
				α	Type	ξ [%]	α	Type	ξ [%]
Building 1 Chicago[1]	N/A	S	Stiffened Tube	1.73	A	1.01	1.72	A	0.77
Building 2 Chicago[1]	N/A	RC	Shear wall/outrigger*	1.40	A-V	1.52	1.34	A-V	2.24
Building 3 Chicago[1]	N/A	S	Framed Tube*	1.32	A-V	1.13	1.29	A-V	1.25
Building 4 Seoul, South Korea[2]	264	SRC	RC core, indirect outrigger belt wall system*	1.36	A-V	1.26	1.36	A-V	0.89
Republic Plaza, Singapore[3]	280	SRC	RC core, S framed tube	1.45	A-V	<0.70	1.45	A-V	<0.70
Building 5* Hong Kong[4]	367	SRC	Trussed tube	1.33	A-V	0.46	1.04	V	N/A
DiWang Tower, Shenzhen (PRC)[5]	384	SRC	RC Core, S frame and outriggers	1.73	A	1.05	1.62	A	0.94
Central Plaza, Hong Kong[6]	374	RC	Core and perimeter tube	N/A	A-V	0.86	N/A	A-V	0.66
Jin Mao, Shanghai[7]	420	SRC	Core, outriggers tied to megacolumns	1.50	A	0.55	1.50	A	0.57

*coupled system, mode is SRSS combination

[1] [Kijewski-Correa et al., 2006]

[2] [Pirnia et al., 2007]

[3] [Brownjohn et al., 2000; Brownjohn, 2005]

[4] [Li et al., 2003]

[5] [Xu & Zhan, 2001; Li & Wu, 2004; Li et al., 2004]

[6] [Li et al., 2005]

[7] [Zhou & Kareem, 2003; Li et. al., 2006]

TABLE 3 - Summary of full-scale dynamic properties and structural system characteristics for nine tall buildings

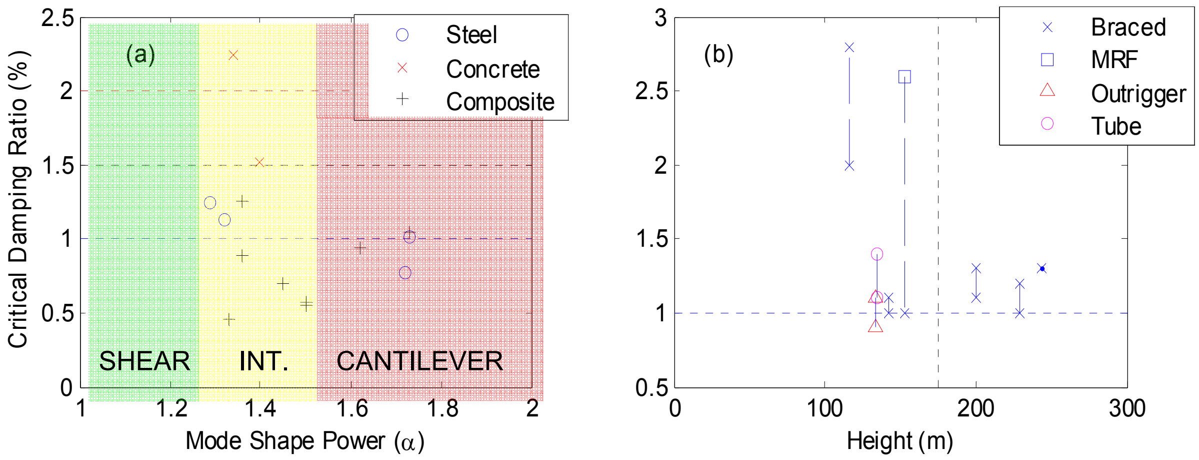

FIGURE 3- Full-scale damping trends (a) as a function of mode shape power for nine tall buildings and (b) as a function of height for steel buildings in South Korean Database

composite construction lacks a definitive trend, though the damping appears to decrease with aspect ratio for the interactive systems. Again explicit knowledge of the degree of axial and shear deformation and the amount of concrete vs. steel within those systems is truly required to make more meaningful determinations about their effects on energy dissipation. For reference, the traditionally assumed serviceability critical damping ratios of 1% for steel, 1.5% for composite and 2% for reinforced concrete are also displayed.

FULL-SCALE CASE STUDIES IN SOUTH KOREA

While the previous analysis supports the authors' hypothesis for tall structures characterized by significant cantilever action, it is interesting to see if it still holds true for lower rise buildings with greater reliance on frame action. The recently acquired South Korean database of full-scale dynamic properties for over 60 buildings [Yoon and Ju, 2004] provides a unique opportunity for such an investigation, particularly since all the buildings were analyzed by the same system identification algorithms and includes multiple RC buildings employing the same structural system, foundation type and occupancy. Erwin et al. [2007] focused on a subset of 22 RC apartment buildings with heights of 9- to 25-stories. The structural system employed (shown in Figure 4) is fundamentally a modular shear wall system tied to a reinforced concrete slab and perimeter frames, in many cases characterized by elongated floor plates [Erwin et al., 2007]. The study found that damping in the short direction of these buildings, whose lateral resistance was primarily derived from shear walls, manifested damping values that *decreased with height*, as the cantilever contribution to the shear wall deformation increased.

In the long direction, Erwin et al. [2007] observed little correlation between damping and height, and instead observed an *increase* in damping *with floorplate aspect ratio*. In the long direction of these modular buildings, slab action is the primary means to engage the various shear wall cores, thus generating more frame action. Since the area of slab present in the building increases with the floorplate aspect ratio, it is logical that the energy dissipation would also increase in direct proportion. Again, since the construction materials, usage, structural system, and foundation type do not vary significantly between these 22 RC apartment buildings, this subset provides an excellent controlled population on which the role of deformation mechanism in energy dissipation can be demonstrated.

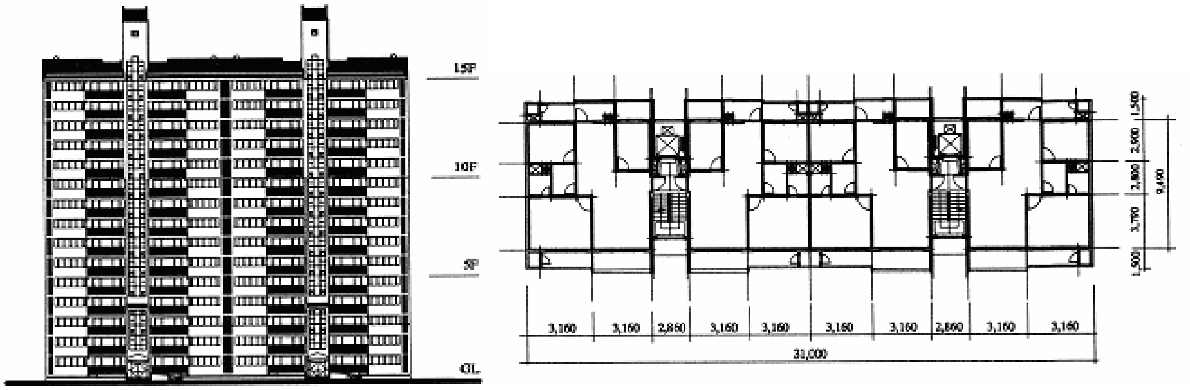

FIGURE 4- ELEVATION AND PLAN VIEW OF TYPICAL RC APARTMENT BUILDING IN SOUTH KOREAN DATASET

The same system identification techniques were applied to the steel and composite subsets of this South Korean database to determine the influence of structural system deformation characteristics on inherent viscous damping. The eight steel buildings presented here have heights from 31-60 stories (116-243m) and include braced/moment frames, outriggers, and tube systems. Table 4 provides a summary of the building properties and the average damping values determined by Erwin [2008]. As mode shape information was not available, the degree of cantilever action is assumed to be correlated to other known physical parameters such as height and aspect ratio (*h/d)*. The buildings' fundamental critical damping ratio in each direction is plotted with height and denoted by structural system type (Figure 3b). The vertical lines connect damping values for a given building in its two orthogonal directions. It is immediately obvious that damping is not tied solely to material type or structural height, as only one building exhibits the same damping value on both axes.

Several interesting observations can be drawn from Figure 3b. The vertical dotted line was included to highlight the fact that only braced frames are used for the taller buildings in this subset. This conscious choice is required to eliminate excessive frame action in tall MRFs and invoke the axial stiffness of the braces and tied columns in vertical cantilever action [Taranath, 1998]. Thus it is not surprising to note that the damping values on the right side of the graph do not exceed 1.5%, consistent with the hypothesis that the increasing role of axial deformations results in less energy dissipation. Braced frames can be characterized as interactive systems where the braced bays serve as vertical cantilevers helping to restrain the excessive shear deformations of the unbraced bays. The limited data herein appear to suggest that beyond a height of 125 m, the damping falls off considerably, potentially due to the transition to a more cantilever-dominated mechanism. In this 125m+ range, the damping values cluster between 1 and 1.25%, potentially suggesting a plateau for braced frames. Still it should be cautioned that since the stiffness of the columns, beams and braces is unknown, it is impossible to quantify the relative roles of axial vs. shear deformation.

The outrigger and tube buildings (S-3 & S-4) are of comparable height and aspect ratio and again made of the same material, yet the outrigger structure has considerably less damping than its counterpart. As an outrigger engages the perimeter columns to resist overturning moments, it increases the degree of cantilever action. On the other hand, a tube structure, though intended to behave as a vertical cantilever, can suffer from a significant amount of shear lag unless diagonal bracing is provided (e.g., John Hancock Center, Chicago) or exceptionally small column spacing is employed (e.g., World Trade Center, New York). Thus, although exact measures of the degree of frame vs. cantilever action are not available for these buildings, it is plausible that shear lag (frame action) has contributed to the increased energy dissipation in S-3.

The traditional MRF makes one appearance in this subset of buildings, as the system used in the long direction of S-7. This particular building has a long-direction aspect ratio of 2.9 and a short-direction aspect ratio of 6.7. The drastic difference in damping values on the two axes of this building further underscores the importance of considering structural system type in damping characterization. It is safe to presume that the moment frame in the long direction deforms primarily due to shear racking, where as the addition of braces in the more slender direction can be similarly be presumed to result in a greater degree of chord drift. The latter mechanism contributes significantly less energy dissipation capability.

A similar analysis is conducted on the SRC buildings and reported in Table 5 and Figure 5. The five SRC buildings investigated here feature steel beams and concrete-encased steel columns

Building	h [m]	Long Direction			Short Direction		
		System	h/d	ξ [%]	System	h/d	ξ [%]
S-2	116.2	Braced	3.6	2.8	Braced	7.7	2.0
S-3	133.9	Outrigger	3.0	1.1	Outrigger	3.0	0.9
S-4	134.3	Tube	3.3	1.1	Tube	3.3	1.4
S-6	142.5	Braced	2.9	1.1	Braced	5.7	1.0
S-7	152.7	Moment	2.9	2.6	Braced	6.7	1.0
S-9	200.2	Braced	2.9	1.1	Braced	4.6	1.3
S-10	229	Braced	3.8	1.2	Braced	4.6	1.0
S-11	243.3	Braced	4.5	1.3	Braced	7.4	1.3

TABLE 4 - Average Full-Scale Critical Damping Ratios in the Two Lateral Directions of the Steel Buildings in the South Korean Database

Building	h [m]	Long Direction			Short Direction		
		System	h/d	ξ [%]	System	h/d	ξ [%]
SRC-1	80.2	Moment	1.3	1.1	Braced	3.2	1.0
SRC-2	85.6	Moment	2.8	1.0	Braced	2.9	1.4
SRC-3	96.0	Moment	2.3	1.5	Braced	5.5	1.3
SRC-9	210.4	Outrigger	4.9	1.4	Outrigger	6.0	0.8
SRC-10	233.9	Outrigger	5.5	1.3	Outrigger	6.7	1.0

TABLE 5 - Average Full-Scale Critical Damping Ratios in the Two Lateral Directions of the SRC Buildings in the South Korean Database

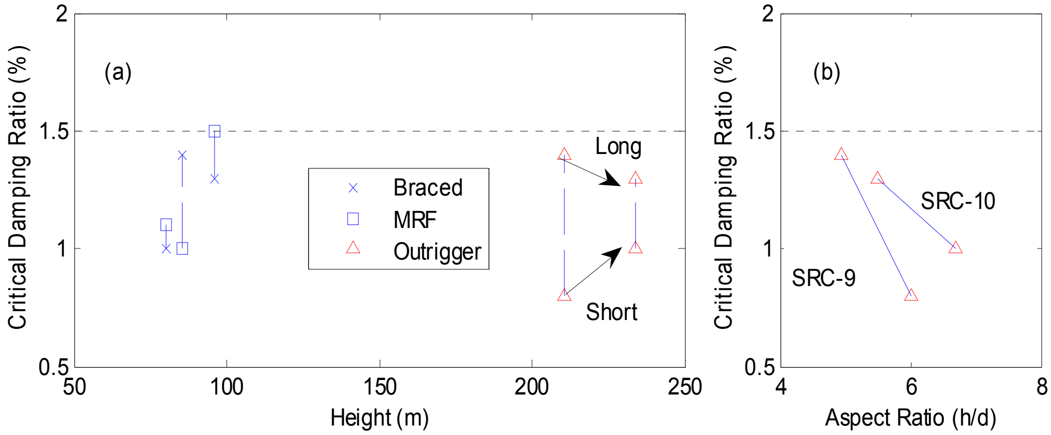

FIGURE 5 - (a) Full-Scale Critical Damping Ratios with Height for SRC Buildings in South Korean Database, (b) Effect of Aspect Ratio on Outrigger Class

with heights ranging from 22-66 stories (80-234 m). The composite columns and steel beams participate in a number of traditional system configurations, including braced and moment frames as well as outrigger systems. Again without specifics on the beam, column and brace sizing and placement, the exact degree of cantilever action is not known. This uncertainty is further compounded by the presence of two materials with known differences in inherent energy dissipation capability in the lateral systems of these buildings. The role of each would have to be ultimately quantified before any definitive conclusions are made. Still, some interesting features can be noted in support of this study's hypothesis. In three buildings (SRC-1,2,3), a braced frame is used in the short direction and an MRF in the long, and with the exception of SRC-2, the MRF produces greater damping values, consistent with the analysis performed on the steel buildings. The two outrigger buildings have a height difference of more than 20m, but have the exact same cross-sectional dimensions. This provides an interesting case study to investigate the role of aspect ratio for what is assumedly a system with significant cantilever action. In each building, the greatest amount of damping occurs in the long direction, characterized by the smaller aspect ratios of 4.9 and 5.5 in SRC-9 and 10, respectively. This can be attributed to the comparatively greater presence of frame action (recall Figure 1). Furthermore, as the aspect ratio increases, the degree of cantilever action similarly increases, as demonstrated earlier in this study. Note that in the case of this outrigger pair, this results in a reduction in damping, as demonstrated in Figure 5b.

ON AMPLITUDE DEPENDENCE

While the introduction of a unifying parameterization for energy dissipation, suitable for a wide class of structural systems, may help to alleviate some of the scatter noted in damping databases, there remain other issues associated with the imposition of a linear model on a mechanism that is tied to multiple nonlinearities [Li et al., 2000]. The equivalent viscous damping model is used for convenience in maintaining a linear equation of motion, yet, inherently, even at small levels of response, actual structures exhibit nonlinearity in both stiffness and damping [e.g., Fang et al., 1999; Li et al., 2000; Pirnia et al., 2007; Kijewski-Correa and Pirnia, 2007]. So while nonlinear analyses, primarily associated with seismic design, adopt hysteretic models to characterize these features, simplified linear analyses common to design practice maintain the viscous damping model and accordingly adjust the critical damping ratio to reflect this amplitude dependence. This philosophy is reflected in codes and standards, where 1-2% critical damping is customary for wind gust effect factors associated with serviceability design (C6.5.8) and 5% critical damping is employed in the generation of seismic response spectra (Ch. 22) [ASCE 7-05, 2006]. Similar trends are also evident in full-scale damping databases, e.g., Japanese [Satake et al., 2003]. Table 6 shows the damping values associated with seismic and ambient excitations for different construction materials in the Japanese database. It can be seen that the damping values under seismic excitations are larger than their ambient counterparts, particularly for reinforced concrete construction that experienced generally larger amplitude levels than the steel buildings in the database. As such, any attempt to develop predictive models for viscous damping levels in structures from this or other databases must be cognizant of this amplitude-dependence. In the context of this study, amplitude-dependence was not explicitly investigated, but since the full-scale data considered were collected under ambient vibrations or lower-return-period wind events, particularly in the case of the South Korean database, the values should all be resigned to the low-frequency plateau in the three-stage model proposed by Jeary [1986] and therefore should be suitable for comparison.

Primary Construction Material	Seismic	Ambient
Steel	1.6%	1.5%
Steel & Reinforced Concrete	3.6%	2.1%

TABLE 6- AVERAGE DAMPING VALUES FOR SEISMIC AND AMBIENT EXCITATIONS IN JAPANESE DATABASE

CONCLUSIONS

This study investigated the influence of the structural system's primary deformation mechanism (frame racking vs. cantilever action) on energy dissipation using basic mechanics, finite element models and full-scale databases, with a specific focus on serviceability limit states most critical to tall building design. Preliminary findings presented herein help to support the hypothesis that damping increases with increasing relative contributions of the shear mechanisms. Thus a more robust and intuitive parameter for use in predictive viscous damping models would include some measure of these relative contributions, with specific consideration of the structural material (steel, concrete or composite). In lieu of explicit information on the relative contributions of these mechanisms in instrumented buildings, analysis of mode shape powers and building aspect ratios helped to demonstrate the reliance of damping on factors outside of material type and height, which are normally used to parameterize databases. It is expected that continued efforts to further quantify the participation of cantilever and frame action in the overall response, which will require access to actual finite element models of instrumented buildings, will further the understanding of the role of structural system behavior in overall energy dissipation.

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