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Forecast models for damping and vibration periods of buildings

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Summary

The building's dynamic parameters (vibration periods, damping) are examined in three sequential phases: (a) the study of physical-theoretical aspects and of the existing forecast models; (b) the collection of a broad experimental data base; (c) the definition of new simple forecast models. The bending and torsion periods are, with a good approximation, related to the height of the building. The damping resulting from low intensity vibrations follows Rayleigh's law; growth of the damping due to the increase of vibration amplitude depends on the structural material. The confidence intervals are supplied to all proposed models with the scope of defining cautionary criteria for application in the codes.

1. Introduction

The building's response to dynamic forces such as wind or earthquake can be evaluated using techniques ranging from the direct integration of equations of motion, to modal analysis, to the use of response spectra. In each case the correct definition of the structural (stiffness) and dynamic (inertia and dissipative capacity) parameters turns out to be anything but simple.

With regards to the stiffness, only the contribution of structural elements is usually considered; however, a significant share, though difficult to quantify, can be supplied from partition walls and to disregard it could create noticeable errors.

The uncertainties in the definition of damping are still greater, since the sources of dissipation in a building are many and varied in nature; in the case of direct integration of the equations of motion it is necessary to know the damping matrix of the system while, in the case of modal analysis, the modal damping coefficients must be available.

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This paper outlines the state of progress of a research which has been conducted now for several years [1] and whose aim has been to define forecast criteria for the dynamic parameters of buildings based on experimental measurements and on specific theoretical models; the paper develops according to three distinct but closely interconnected phases.

The first phase concerns the analysis of the theoretical aspects linked to the formulation of the problem; this includes the development of approximated formulae for the forecast of vibration periods and the description of dissipative phenomena with suitable mechanical models. Moreover forecast models available in literature or used in codes are examined. The result is the definition of theoretical qualitative models to be verified with experimental data.

In the second phase data are collected from full-scale tests conducted on buildings in order to measure periods of vibration and damping coefficients. A data base has been created in order to allow statistic processing and correlations; the choice of which parameters to file is made on the basis of previous theoretical considerations.

In the final phase there is the formulation of new criteria for the forecast of vibration periods and damping, deduced from statistic analysis conducted on reported data in accordance with the theoretical considerations.

With regards to vibration periods, simple formulae, analogous to others already proposed in literature, are used for bending modes and for the first torsion mode; considering the confidence intervals it is possible to define distinct reliable formulae in cases of check to wind or seismic actions.

The available data on damping allow us to formulate a model for medium intensity vibrations (initial damping), differentiated by the building's characteristics; damping corresponding to more significant vibrations is deduced on the basis of theoretical considerations. Initial damping is related to the building's vibration periods, according to Rayleigh's law; the two law's parameters are estimated which allow the definition of the modal damping coefficients or of the entire viscous equivalent damping matrix. The commission appointed to the drafting of the Eurocode 1 [2] has proposed a model directly derived from the one presented in this paper.

2. Fundamental equations of structural dynamics

Consider the equations of motion of a n-degrees-of-freedom system:

$$\sum_{1}^{n}{}_j\, m_{ij}\, \ddot{q}_j(t) + \sum_{1}^{n}{}_j\, c_{ij}\, \dot{q}_j(t) + \sum_{1}^{n}{}_j\, k_{ij}\, q_j(t) = f_i(t) \quad (i=1,\cdots,n), \tag{1}$$

where m_{ij}, c_{ij} and k_{ij} are respectively the terms of mass, viscous damping and stiffness matrices; q_j is the j-th Lagrangian coordinate; f_i is the external force applied to the i-th degree of freedom; t is time. Solving the eigenvalues problem:

$$([K] - \omega_k^2\,[M])\,\{\Psi^k\} = \{0\}, \tag{2}$$

where ω_k is the k-th angular frequency and $\{\Psi^k\}$ is the corresponding eigenvector, and applying the law of principle transformation, the Lagrangian coordinates of the motion are given by calculating:

$$q_j(t)=\sum_{1}^{n}{}_k \psi_j^k p_k(t) \quad (j=1,\cdots,n), \tag{3}$$

in which: ψ_j^k is the j-th component of the k-th eigenvector, assumed to be normalized to a unit mass matrix, and p_k is the k-th principle coordinate which, if the structure possesses classic modes of vibration, is offered by the solution of the differential equation:

$$\ddot{p}_k(t)+2\xi_k\,\omega_k\,\dot{p}_k(t)+\omega_k^2\,p_k(t)=g_k(t), \tag{4}$$

where g_k is the k-th modal force and ξ_k is the damping coefficient of the k-th mode, given by:

$$\xi_k=\frac{1}{2\omega_k}\sum_{1}^{n}{}_i\sum_{1}^{n}{}_j\, c_{ij}\,\psi_i^k\,\psi_j^k. \tag{5}$$

The dynamic response of a building can be evaluated (a) by direct integration of the system of eqs. (1), (b) by the modal analysis, generally using the technique of modal truncation, solving the first m ($m \leqslant n$) equations in principal coordinates (4), and (c) using response spectrum techniques, actually also applicable to the wind engineering [3].

In the two following chapters the physical meaning of introduced dynamic parameters and the existing analytical and experimental methodologies for their evaluation will be discussed.

3. Bending and torsion periods of vibration

The vibration periods ($T_k=2\pi/\omega_k$) are analytically obtained from the solution of the eigenvalues problem (2), once known the mass and the stiffness matrices; nevertheless, uncertainties remain in the roles played by the non-structural elements (partition walls) and by the foundations, factors which are rarely taken into consideration.

Operating with modal analysis or with response spectrum techniques, it is often useful to resort to simple formulae of empirical origin which supply the periods in accordance with global parameters of the building, such as the height and the dimensions of the plan.

In the chapter of the Eurocode 1 [2] dedicated to the "Wind Actions" it is proposed for the fundamental period the formula:

$$T_1=H/46, \tag{6}$$

where the height H is expressed in m. This formula has been obtained by Ellis [4] on the basis of many experimental tests; he also proposed analogous formulae for the period of vibration in the orthogonal direction ($T_1=H/58$) and for the torsion period ($T_t = H/72$). It is worth to note in Ellis' model that the height of the building is the only parameter which is considered. Other formulae define the fundamental period according to the number of floors, a criteria which is qualitatively analogous to that of Ellis, or take into account the dimensions of the building's plan, or consider explicitly the effect of partition walls [5]; however, the increased complexity of these criteria does not appear to be justified by the results they provide.

All these formulae have been derived from statistic analyses carried out on experimental measurements; it is possible to get theoretical information about the qualitative dependency from the geometric parameters by referring to an extremely simple model. Idealizing the building as a cantilever beam of length H and dimensions of the section L and T, without formulating hypotheses on the vertical distribution of mass and stiffness, the following law, expressing the fundamental period, can be obtained:

$$T_1 = \alpha_1 H \sqrt{1 + \beta_1 \frac{H^2}{LT}}, \tag{7}$$

where α_1 and β_1 are constants linked to the structural material and the distribution of mass and stiffness. The two addenda are respectively representative of the shear and bending behavior; the formulae proposed by Ellis correspond to the hypothesis of a global shear deformation of the building.

Considering the torsion period, by operating analogously, it is possible to obtain the expression:

$$T_t = \alpha_t H, \tag{8}$$

where α_t is a function of the plan's form, of the structural material and of the mass and stiffness distribution. The theoretical model confirms, also in this case, the validity of Ellis' model.

The formulae (7) and (8) constitute the basis for the definition of the forecast models which will be developed afterwards estimating, on the basis of collected experimental data, the coefficients α_1, β_1 and α_t by means of least-squares regressions.

4. Dissipation in buildings

Damping measures the building's capacity to dissipate energy during vibration and is usually taken into account by means of the viscous model, defining an appropriate damping matrix $[C]$ or the modal damping coefficients ξ_k.

However, it is not possible to evaluate the coefficients of the damping matrix in a direct manner since this model, although convenient from a resolutive point of view, does not always represent the true physical nature of the phenomenon. In the special case of Rayleigh damping ($[C] = \alpha[M] + \beta[K]$) the condition is sufficient to decouple the equations of motion (1), allowing the use of modal analysis: the k-th damping coefficient is:

$$\xi_k = \frac{1}{2}\left(\frac{\alpha}{\omega_k} + \beta\omega_k\right) = \alpha\frac{T_k}{4\pi} + \frac{\beta\pi}{T_k}, \tag{9}$$

but the problem of attributing adequate values to α and β remains unresolved.

The physical meaning of the coefficient ξ_k is clear if we consider a linear elastic one-degree-of-freedom system excited by the corresponding angular frequency ω_k; the response (Fig. 1a) assumes an elliptical form and it results that ξ_k is proportional to the ratio between the dissipated energy ΔE_k in a cycle and the potential energy E_k related to the maximum displacement attained:

$$\xi_k = \frac{\Delta E_k}{4\pi E_k}. \tag{10}$$

The nature of the dissipative phenomenon is, anyhow, complex and non-viscous sources of damping are often predominant; among these, nonlinear behavior of the structural material and the frictional forces, activated by the slipping action during oscillation, are of particular importance in buildings. In these cases (10) supplies a criterion for the definition of an equivalent viscous damping in the k-th mode (Fig. 1b).

The mechanisms which produce dissipation during oscillation in a building are varied in nature: (a) damping intrinsic to the structural material, (b) damping due to friction in the structural joints and between structural and non-structural elements, (c) energy dissipated in the foundation soil, (d) aerodynamic damping, and (e) passive and active dissipative systems.

The first two factors constitute the structural damping of the building; in this paper both the phenomenological aspects and the mechanical models

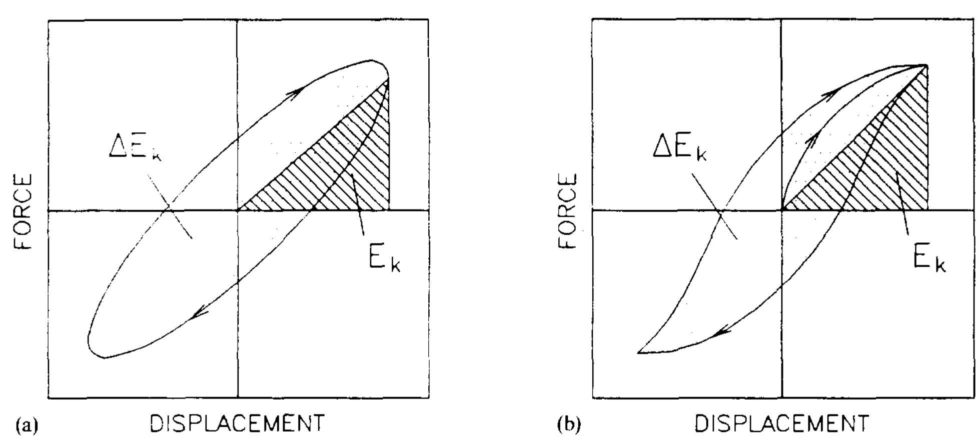

Fig. 1. Comparison between viscous (a) and hysteretic (b) damping.

capable of interpreting it will be discussed in detail. Other sources of dissipation, on the contrary, will not be taken into consideration since they are significant only for particular structures.

Damping in the material manifests itself with different characteristics, either in ductile materials (metals) or in brittle ones (concrete, brick, mortar, rock, etc.).

For ductile materials, damping seems to be principally due to viscous phenomena; highly accurate measurements for low stress levels have been conducted by Capecchi [6], who links damping to the phase velocity, that is the speed of propagation of the deformation in the structural element. Lazan [7] proposes a phenomenological model, extended also to high stress levels, according to which dissipated energy in an elastic cycle is linked to the amplitude of the cycle itself; Fig. 2a shows damping as a function of the amplitude of oscillation: initially it is constant, then it weakly rises till the yielding stress is reached (at which point a fatigue phenomenon and plastic deformation which lead to a significant increase of damping develop). The results obtained by both researchers confirm that the contribution to structural damping due to damping in ductile materials is negligible, resulting two orders of magnitude less than that which is found in a building as a whole.

Dissipations of a different nature can be found in brittle materials, which present a microstructure with vacuities and cracks of variable shape and dimension; the application of stresses produces both the deformation of the matrix and slidings between the crack faces, limited by friction actions. Since these actions are nonconservative, dissipation in a cycle is produced even in the absence of damage or plastic phenomena. A constitutive model able to embrace such aspects is that proposed by Gambarotta and Lagomarsino [8]; with this description it results that damping tends to vanish to zero of the cycle's amplitude and subsequently grows until it reaches a threshold, relating

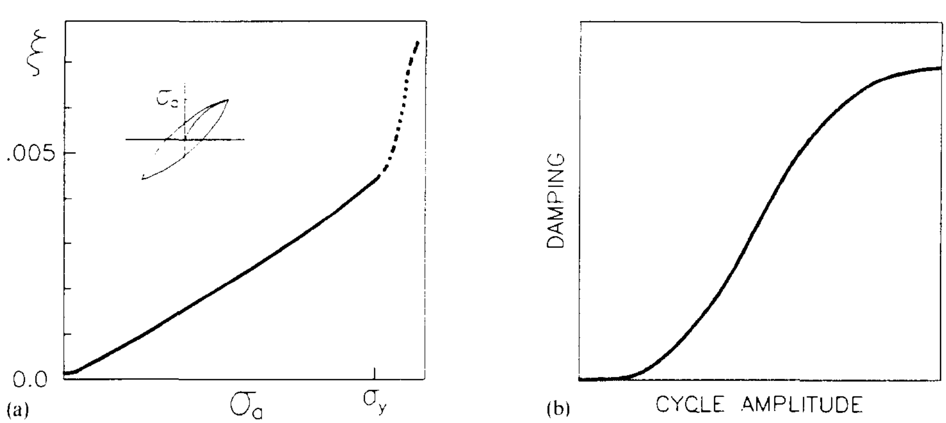

Fig. 2. Damping in ductile (a) and brittle (b) materials.

to the activation of slidings on all the cracks (Fig. 2b). This model has been implemented in finite element programs in order to evaluate damping in structural elements: in Ref. [9] the damping in walls is obtained by applying cyclic horizontal forces and using Eq. (10); in Ref. [10] the damping in a RC tower is obtained by the decay of the free vibrations on different natural modes. In both cases, the influence of the vibration amplitude on damping is analogous to that found for uniform states of stress. The values of damping depend on the free parameters of the model: friction coefficient, dimension and quantity of the cracks; damping is anyhow greater than that which ductile materials manifest and represents a significant contribution to the total structural damping.

Damping due to friction between contacting elements in the structure is typical of steel structures with bolted joints; significant dissipation due to slippings between structural and non-structural elements (partition walls, installations, etc.) is, however, produced in any building. The behavior of a joint can be interpreted using a simple slip model consisting of two springs and a linear friction element (Fig. 3); the equivalent viscous damping is deduced from the force–displacement cycle and results as a function of the cycle amplitude x_m. Varying the parameters we obtain results which are qualitatively similar; as soon as slipping takes place damping increases rapidly, remains almost stable for a while and then decreases asymptotically towards zero. As a matter of fact, there are many joints in a structure which become active at different levels of vibration; this situation can be qualitatively interpreted by considering a certain number of slip models in parallel. In Fig. 4 we note that the subsequent activation of friction elements produces an

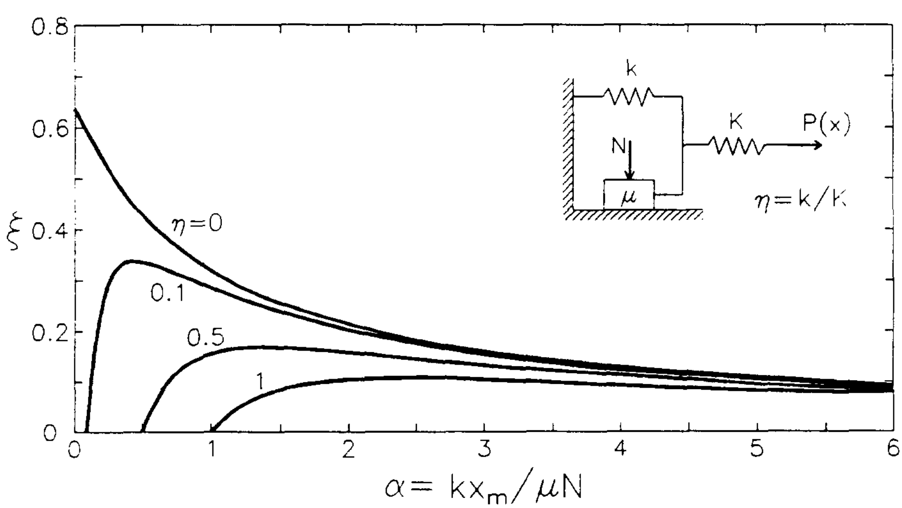

Fig. 3. Elementary slip model.

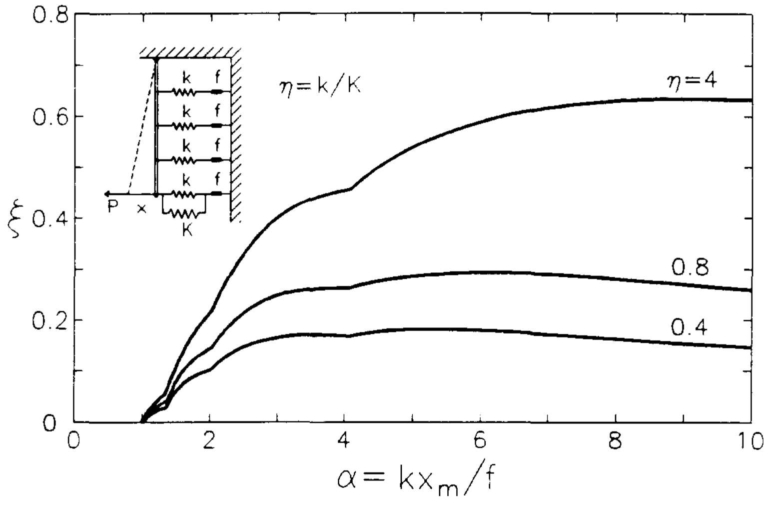

Fig. 4. Slip elements in parallel.

initial phase of growth followed by a steady phase wider than that of the single friction element.

These considerations lead to the definition of different qualitative forecast models for the damping in the cases of steel or of reinforced concrete buildings:

(a) structural damping in steel buildings can be attributed to the friction actions in the joints, considering the material's contribution as negligible, and shows, increasing the vibration amplitude, an initial growth followed by a long steady phase;

(b) in reinforced concrete buildings structural damping is due both to the slippings between structural and non-structural elements (which take place for small vibrations), and to the dissipation in the material (significant only for high stresses); therefore, the structural damping is a function of the vibration amplitude which presents two thresholds. The first (initial damping) represents the dissipation in the joints, while the second corresponds to the activation of microslidings in the material.

We can justify the presence of two thresholds by considering the model of Fig. 5, constituted by two slip models in series, provided with parameters which activate the slipping for different values of the force; the first to slip is considered significant of macroslippings in the joints, whereas the second describes the microslidings in the structural material.

The models just presented are not directly applicable; in the engineering practice other kinds of forecast criteria are used. The simplest ones can be found in the codes and define a value according to the characteristics of the building; more reliable models, deduced from experimental data, define damping, according to some building's parameters, as a function of the vibration amplitude. The models of Jeary [11], Davenport and Hill Caroll [12] and

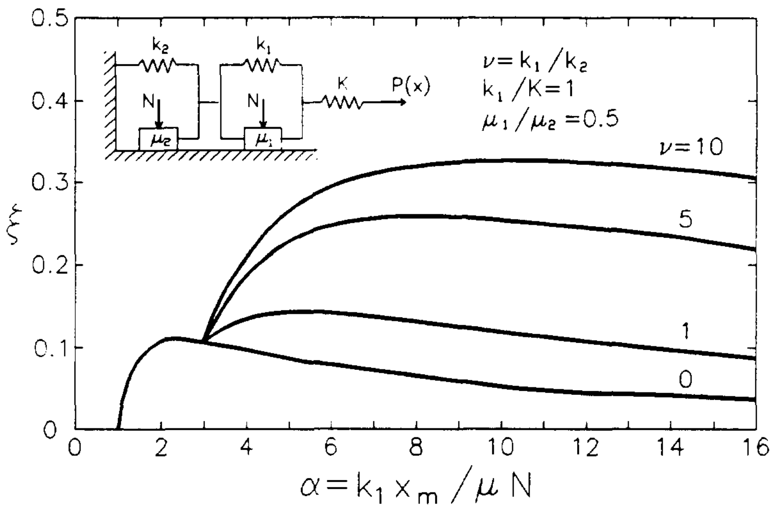

Fig. 5. Slip elements in series.

Lagomarsino et al. [1] belong to this category; the forecast formula are, respectively:

$$\xi = 0.01\ n_1 + 10^{\sqrt{D}/2}\ x/H \quad (\xi \leqslant 0.6/H + 0.013); \tag{11}$$

$$\xi = A\ (\sigma_x/H)^{\zeta}; \tag{12}$$

$$\xi = \beta_1/n_1 + \beta_2 n_1 + (\beta_3/\lambda)\,x/H \quad (\xi \leqslant \xi_p); \tag{13}$$

where: D and H are the plan dimension and the height of the building (expressed in m); x is the maximum displacement at the top of the building (in m); σ_x is the standard deviation of the displacement at the top of the building (in mm); $\lambda = H/D$ is the slenderness; A, ζ, β_1, β_2 and β_3 are parameters related to the building characteristics. Models (11) and (13) qualitatively agree with the theoretical model identified in this paper, whereas model [12] is inconsistent both for low and for high vibration amplitudes; in Ref. [1] these models are critically compared.

5. The experimental data base

Once the physical theoretical aspects linked to the definition of dynamic parameters has been clarified, in order to define reliable forecast models we need to organize a broad experimental data base, which has to be both representative and homogeneous. In Ref. [13] the data base used is widely described; it collects the results of full-scale tests performed on buildings to determine the vibration periods and the modal dampings. The data have been catalogued and organized into three separate data base files: (a) a general data file, (b) a geometric and structural characteristics data file, (c) an experimental observations file (containing the measured values of periods and dampings). Each structure is catalogued by inserting a record in the first two files and, in the third, by inserting as many records as there are available measurements. The input of data is simplified by a specific program; amongst the catalogued information there are the building's dimensions, the structural elements, the bracings, the foundation and the type of soil, the density of partition walls, the method of excitation used in the test and the method used to evaluate damping.

Table 1

Number of measurements for the different modes

	Bending modes			Torsion modes		
	1st	2nd	3rd	1st	2nd	3rd
period	673	263	99	135	47	18
damping	546	148	62	97	25	11

Table 2

The structural elements of 185 buildings

Structural elements	Number
Steel building	69
RC building	52
Mixed building	40
Pre-cast building	18
Masonry building	4
Unknown	2

Table 3

The bracings of 185 buildings

Bracing	Longitudinal	Transversal
Steel frames	34	29
RC frames	17	16
RC walls	48	51
Core + steel frames	4	4
Steel tube	3	3
RC tube	1	1
RC core	14	12
Truss bracing	2	7
Unknown	62	62

In total, data were collected for 185 different buildings, almost all characterized by information related to two perpendicular directions of vibration; periods and modal dampings were often measured for different values of the vibration amplitude (Table 1). Tables 2 and 3 show how these 185 buildings are subdivided relative to the structural elements and the bracings.

6. Forecast model for the vibration periods

The statistic analysis was initially carried out on the fundamental period; in light of the theoretical considerations developed, the period has been represented as a function of the height of the building. In Fig. 6 the fundamental period is shown with exception of some buildings (20 structures) which are highly irregular in shape and for which simple forecast models are not applicable. As we can see, the data are linearly correlated to the height, which is characteristic of prevalent shear deformations; estimating the parameter of Eq. (7) with the minimum least-squares technique (with $\beta=0$), we arrive at:

$$T_1 = H/50. \tag{14}$$

This formula supplies intermediate values to those Ellis' models offer for the fundamental period and for the first natural period in the orthogonal direction; however, as it may be observed in Fig. 6, from the available data it results not justifiable to adopt two distinct models. Fig. 6 shows Eq. (14) and the confidence intervals at 50% and at 80%, together with Eq. (6), proposed by

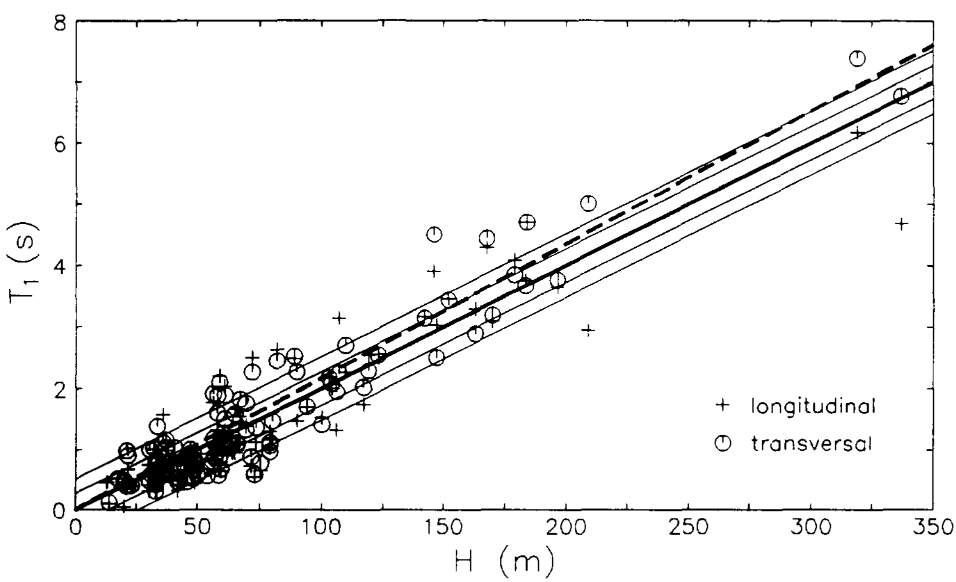

Fig. 6. Fundamental period of vibration.

Eurocode 1; possible safety estimates of the fundamental period respect to wind or seismic action are obtained by choosing, for example, the lower and the upper confidence interval at 80%:

$$T_1 = H/50 + 0.05 \qquad \text{wind action}; \tag{15}$$

$$T_1 = H/50 - 0.05 \geqslant 0 \qquad \text{seismic action}. \tag{16}$$

Analyses of the data chosen for structural elements lead to much restricted confidence intervals; steel buildings show slightly higher period values with respect to those of reinforced concrete or mixed structure buildings of the same height. The formulae obtained are:

$$T_1 = H/45 \quad \text{steel buildings}; \tag{17}$$

$$T_1 = H/55 \quad \text{RC buildings}; \tag{18}$$

$$T_1 = H/57 \quad \text{mixed buildings}. \tag{19}$$

In Figs. 7a–7c experimental data and the relative forecast formulae are shown; once more it may be observed that there is not any correlation between the fundamental period and the vibration direction.

Moreover, an analysis has been conducted dividing buildings by bracings into two classes: (a) frame bracings (the first three classes in Table 3), (b) bracings with prevalent bending behavior (all the others); predictably, the first class has slightly higher period values and is linearly correlated with the height, in accordance with the shear behavior, whereas the second is well-represented by taking into account in Eq. (7) the coefficient β, because of the bending behavior. Finally, it is also verified that no other parameter exist (such as dimensions of the plan, foundation, soil, partition wall density, slenderness) which can be inserted into the forecast model in order to obtain results which are more reliable.

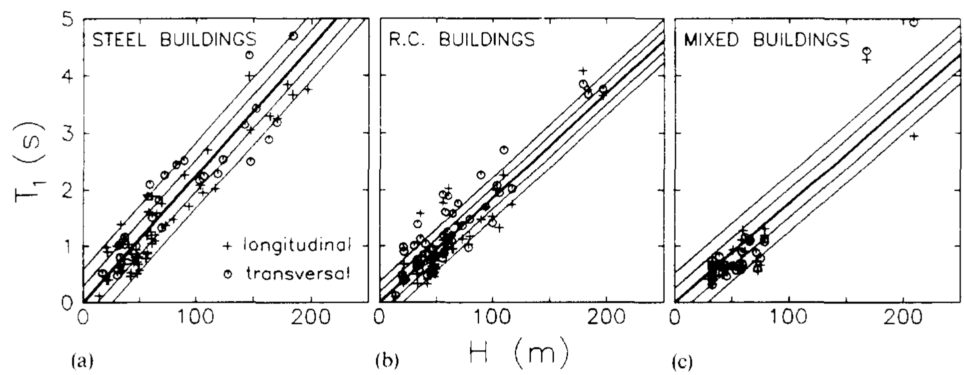

Fig. 7. Fundamental period of vibration: (a) steel buildings; (b) RC buildings; (c) mixed buildings.

The natural periods on higher modes correlate to the corresponding fundamental period T_1 by a linear law; Figs. 8 and 9 show respectively the second and third natural periods. The laws obtained are:

$$T_2 = 0.313\ T_1; \quad T_3 = 0.179\ T_1. \tag{20}$$

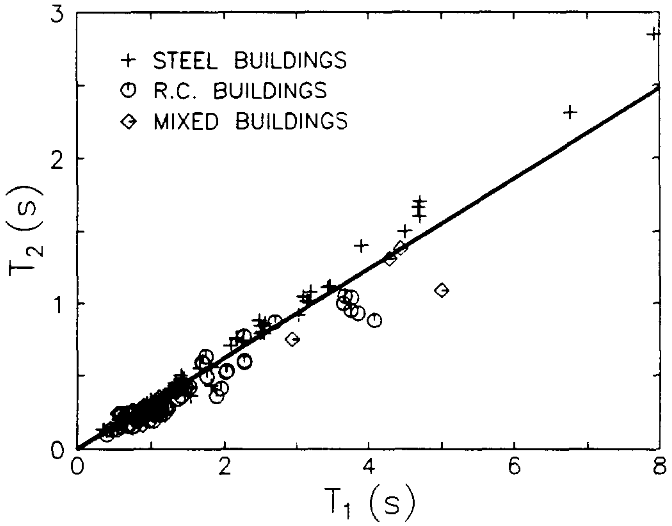

Fig. 8. Second natural period.

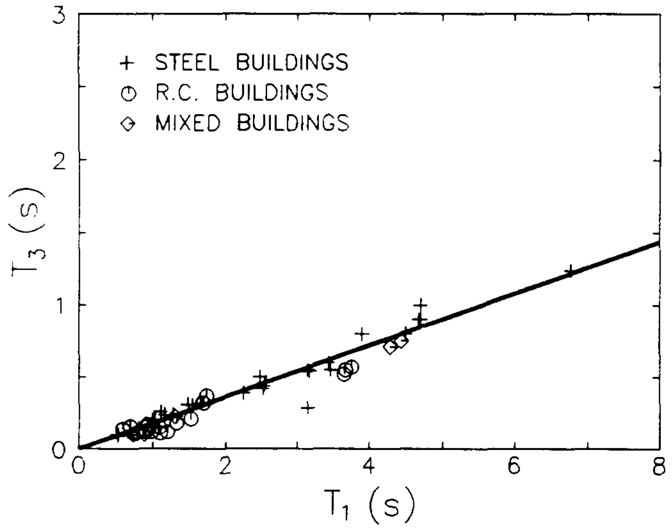

Fig. 9. Third natural period.

The scattering of data diminishes still if they are subdivided according to structural elements (identified by different symbols in Figs. 8 and 9); in this case the forecast formulae are:

$$T_2 = 0.338\,T_1; \quad T_3 = 0.185\,T_1 \quad \text{steel buildings;} \tag{21}$$

$$T_2 = 0.266\,T_1; \quad T_3 = 0.154\,T_1 \quad \text{RC buildings;} \tag{22}$$

$$T_2 = 0.274\,T_1; \quad T_3 = 0.168\,T_1 \quad \text{mixed structures.} \tag{23}$$

We can see that the coefficients obtained are similar to those theoretical for a prismatic shear cantilever beams ($T_2 = T_1/3$, $T_3 = T_1/5$).

Finally, the correlation between the torsion period of vibration and the height of the building is analyzed (Fig. 10); even in this case the linear law appears to be acceptable and the estimate supplies the law:

$$T_t = H/78 \tag{24}$$

which is very similar to Ellis' formula. Scattering is nonetheless greater than in the previous cases and does not diminish by choosing buildings according to structural elements. However, a good result can be obtained by distinguishing between buildings with frame or wall bracings ($T_t = H/60$; the first four classes of Table 3) and the other bracings ($T_t = H/108$) which are, evidently, more effective with respect to torsion; Figs. 11a and 11b show the forecast models for the two classes of buildings.

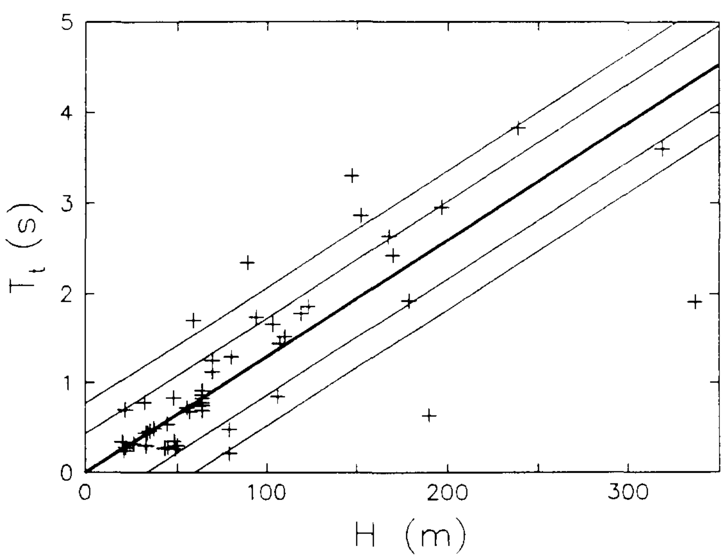

Fig. 10. Torsion period of vibration.

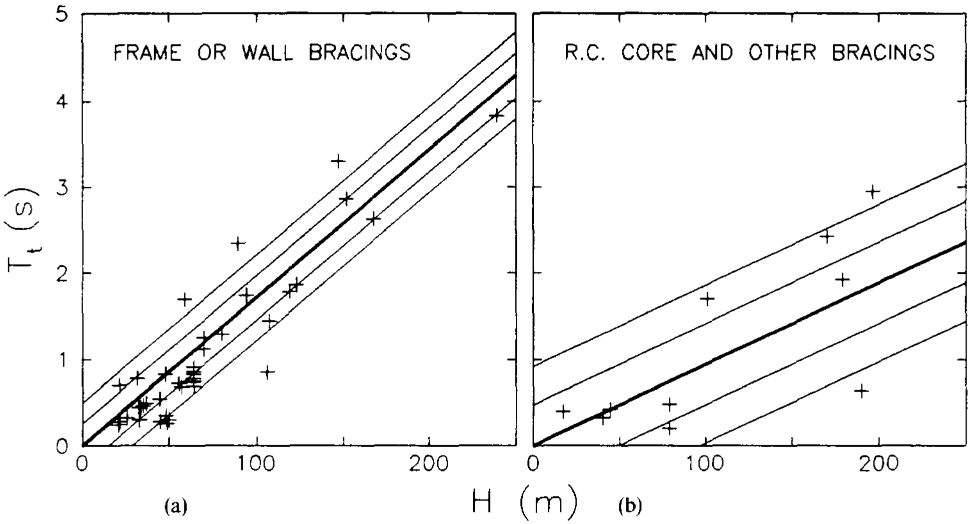

Fig. 11. Torsion period of vibration: (a) buildings with frame or wall bracings; (b) other buildings.

7. Forecast model for structural damping

Initially, the analysis concerns the data relative to the first modal damping and, in particular, its increment with the vibration amplitude. A reliable law of growth cannot be identified by considering, in the cases which provide measurements for, at least, three different vibration amplitudes, damping as a function of the ratio σ_x/H, even by taking into account the parameters considered in forecast models (11), (12) and (13) (structural elements, slenderness and plan dimensions of the building); this is partly due to the limited number of buildings considered, but it is also caused by an approach to the problem which is not coherent with the theoretical model. In fact, damping, in reinforced concrete buildings, is related to the stress level in structural elements and the parameter σ_x/H cannot be considered representative; therefore, the new variable $x_{\lim}$, named limit displacement, is introduced, that is the displacement for which the building exits from the elastic field. The damping values represented as a function of $\sigma_x/x_{\lim}$ may be interpreted in the light of the theoretical model specified in Section 4:

(a) steel buildings show an initial growth followed by a constant value of damping (Fig. 12a shows a case wherein the vibrations reached the limit displacement);
(b) reinforced concrete buildings also show an initial growth but, after a brief constant value, damping resumes growth (Fig. 12b).

The first threshold ξ_0 is reached by values $\sigma_x/x_{\lim} \approx 0.1$ and it is useless to determine a law which describes this growth; on the contrary, it is necessary to define the value of the initial damping ξ_0, according to the building characteristics. For reinforced concrete buildings it would be furthermore important to describe the growth which manifests after this threshold but, unfortunately, the data do not go beyond $\sigma_x/x_{\mathrm{lim}}=0.3$ and this does not allow to deduce the information for higher values of displacement; an increment to the initial damping of 0.005 is therefore acknowledged, considered a justified amount from the experimental data gathered.

The objective of the statistic analysis is hence to define a forecast model for the initial damping ξ_0; the data base used for the analysis is obtained from the initial one defining a significant value of initial damping for each building, handling the original data according to homogeneous criteria; some data, considered unreliable, were discarded. The correlation between the initial first modal damping and the building parameters has been analyzed. Particularly interesting is the result obtained considering the density of partition walls; in fact, for some buildings we have measurements carried out during the construction phases which prove that the initial damping is strictly related to the

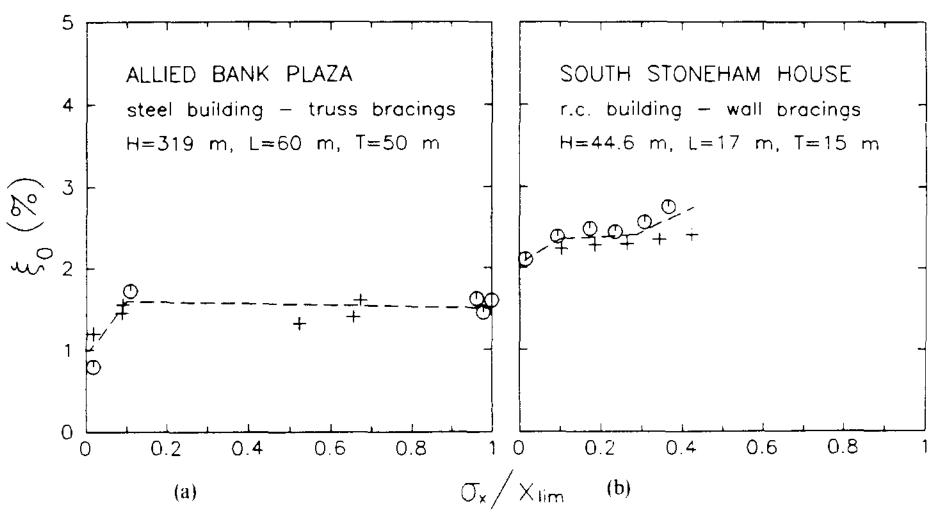

Fig. 12. Damping versus vibration amplitude: (a) steel building; (b) RC building.

Table 4

Parameters of the forecast model for damping

	Edifici in acciaio	Edifici in c.a.	Edifici misti
α'	0.3192	0.7238	0.2884
β'	0.7813	0.7026	1.2856

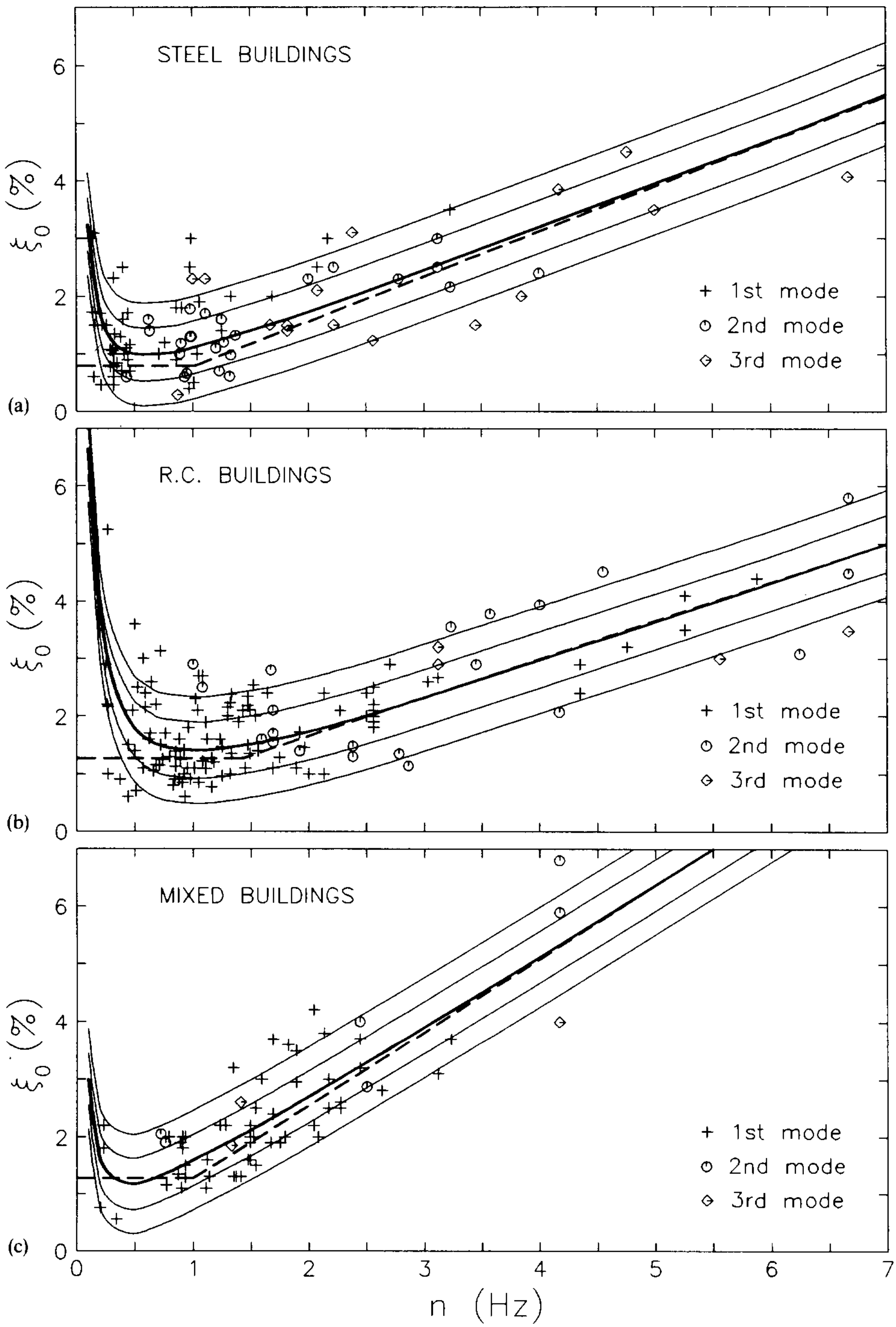

Fig. 13. Forecast models for initial damping ξ_0.

slippings in the joints. Unfortunately the informations about the partition wall density are collectively poor and do not allow to establish a reliable model.

Statistic analysis has shown that the only parameter from which the initial first modal damping evidently depends is the fundamental period T_1; the proposed forecast formula is: $\xi_{01}=\alpha' T_1+\beta'/T_1$, formally analogous to Rayleigh's damping law (9). Since this law is valid for all modes, the damping values ξ_{0k} ($k=2, 3$), relative to the higher modes, have also been recovered and a common law found; even damping values in torsion modes, although not used in the statistical analysis because they possess less reliability, follow the same trend. Therefore, the following forecast law for initial damping is defined:

$$\xi_0=\alpha' T+\beta'/T \tag{25}$$

that can be used for all vibration modes. The estimated coefficients α' and β' are given in Table 4, according to different structural elements; an interesting aspect of this model is that the coefficients can also be used to define the equivalent viscous damping matrix:

$$[C]=4\pi\alpha' \; [M]+\beta'/\pi \; [K]. \tag{26}$$

Even if Eq. (25) is valuable, it does not prove that damping in buildings is effectively of a viscous nature.

Figure 13 shows the available data as a function of the frequency $n=1/T$ and the forecast models with confidence intervals at 50 and 80%. These figures also show, by a dashed line, the model proposed by the Eurocode 1, directly derived from the results of this research by operating a simplification for the sake of safety. We should highlight that analogous forecast models, used by Eurocode 1 for tower and chimney structures, have been drawn from Ref. [1].

8. Conclusion

In the present paper forecast models are proposed for the bending and torsion periods of vibration and for the modal damping coefficients in buildings. These models result from statistic analyses performed with a broad experimental data base and supported by suitable theoretical models.

Further developments of this research will be addressed to increase the data base and to up-dating the model parameters and the corresponding confidence intervals; in particular it would be important to improve the quality of building informations and to single out other meaningful parameters to reduce scattering. Moreover, this methodology will be applied also to full-scale measurements of periods and dampings in chimneys and tower structures.

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