Building damage in Mexico City earthquake

from Adrian M. Chandler

One lesson to be learned from the recent Mexico City earthquake is that the Mexican earthquake-code torsional design recommendations for asymmetric buildings do not include a sufficient safety margin.

To engineers, the most disturbing aspect of the recent earthquake disaster in Mexico was the type and extent of the buildings which failed. Many were modern, engineered structures designed and built to withstand just such an occurrence. In the central area of Mexico City, 177 buildings collapsed completely and 85 suffered partial collapse as a result of the magnitude (M) 8.1 earthquake of 19 September 1985 and its aftershocks[1], while virtually every building in the city suffered some form of foundation failure. The nature and severity of this devastating earthquake has already forced a major reappraisal of engineering and architectural practices in earthquake-prone areas of the world.

Mexico itself has one of the most advanced building codes for earthquake-resistant design[2], but the extent of its enforcement and possible corruption in construction practices has come under sharp attack in the wake of the disaster[3]. The unprecedented severity of the earthquake, however, was chiefly responsible for the extent of the damage caused.

A joint venture by the US National Science Foundation and the Instituto de Ingenieria of the Universidad Nacional Autonoma de Mexico funded the installation only weeks before the earthquake of an array of 20 state-of-the-art accelerographs spread along the west coast of Mexico north of Acapulco. The accelerograph project was set up to record the strong-motion earthquakes predicted for the Guerrero seismic gap in the Mid-American trench. Major ground movements were expected in the area because there had been a 75-year lull following a decade (1900-1911) in which 24 large earthquakes had occurred. In addition, a network of accelerographs had been set up over the past 30 years in and around the capital city. Thus the documentation collected from the Mexico City earthquake and aftershocks constitutes the most detailed and extensive ever recorded, and full analysis of the mass of information generated will take several months or even years. Work so far has concentrated on the initial earthquake. Careful analysis is being made of the source of the shocks beneath the Pacific near Playa Azul. The first evidence from the coastal arrays is that the earthquake contained a significant proportion of its energy at frequencies of ~0.5 Hz. Examination of data from the arrays established farther inland will show how the initial spectrum of vibrations was attenuated or amplified as it spread out across the country. Of interest to engineers is the local amplification of ground motion imparted by Mexico City's soft lake-bed subsoil which resulted in a series of 0.5-Hz shockwaves at ~400 km from the earthquake epicentre.

Resonance of Mexico City's subsoil at a period of ~2 s was observed during the earthquake on 28 July 1957 (ref. 4), but its significance was not fully appreciated at that time. Far less damage occurred in the city than during the latest earthquake, but the event prompted the establishment of a building code for seismic design[5] (one of the first of its kind), together with the foundation of the engineering institute. Engineers in Japan and the United States in particular are awaiting the results of seismological surveys which will analyse to what extent the apparent local amplification of the 2-s ground waves is peculiar to the sedimentary basin of Lake Texcoco on which Mexico City is founded (Fig 1*a*); there may well be important implications for places such as Oakland in California and the many Japanese cities that are built on soft alluvial coastal plains[6]. Both the Californian Earthquake Engineering Research Institute (EERI) and Britain's Earthquake Engineering Field Investigation Team (EEFIT) have sent groups of engineers to study the damaged areas and to report on why some buildings survived while others were completely destroyed. Visits of this nature are now commonplace following major earthquakes. EEFIT, for example, is a UK-based group of engineers and scientists with considerable experience in post-earthquake reconnaissance in Italy, Turkey, Chile, North Yemen, Belgium and Pakistan. A preliminary report on the Chilean earthquake ($M = 7.4$) of 3 March 1985[7] cited topographical effects similar to those in the region of Mexico City as a likely cause of the concentration of earthquake energy into the particular part of the alluvial plain on which the damaged towns are situated.

Comparison with Europe

Long-period amplification of ground motions has also been observed and extensively reported in eastern European earthquakes[8-11]. The Vrancea region of

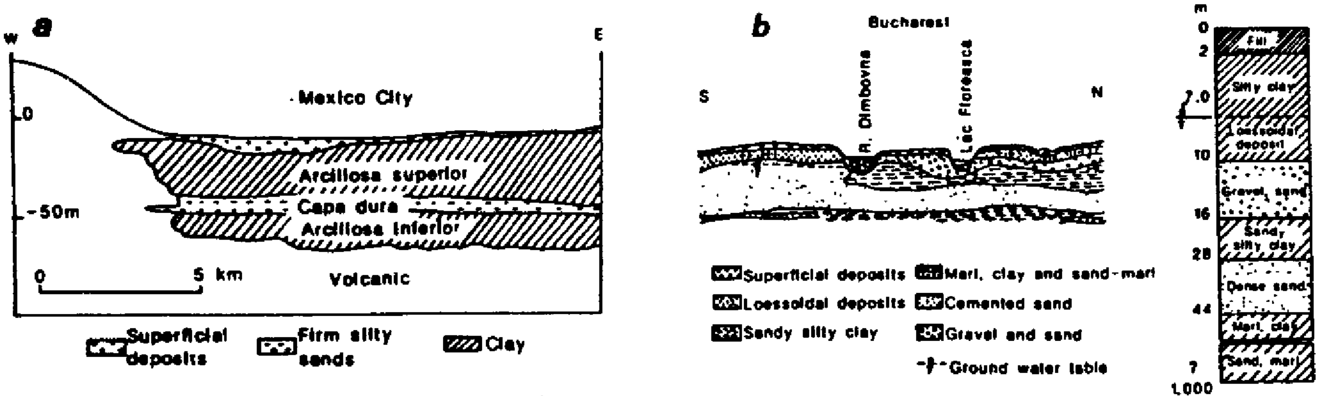


Fig. 1 An east-west section through Mexico City subsoil[1] (*a*), and a typical cross-section and soil profile in Bucharest[8] (*b*).

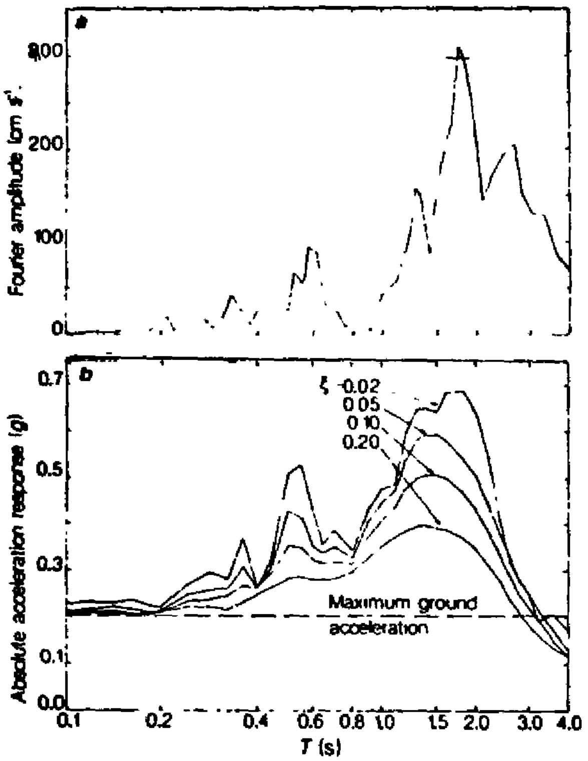


Fig. 2 *a*, Fourier amplitude spectrum and *b*, NS response spectra of the Romanian earthquake on 4 March 1977.

central Romania, for example, is a confined territory of ~2,000 km^2 in which about 50 seismic events with magnitudes greater than 5 have occurred since the beginning of the last century Four of these events, in 1802, 1929, 1940 and 1977, were especially destructive. For the 1977 event a substantial body of data is available[8,9], with both seismological and engineering significance. As in the recent Mexico City and Chilean earthquakes, the long-period components of the ground motion were amplified at long distances, especially through the alluvial deposits in southern Romania and Bulgaria. The Fourier amplitude spectrum of the north-south (NS) component, recorded at the Romanian Building Research Institute (INCERC) in Bucharest, is shown in Fig. 2*a*, and the corresponding soil profile in Fig. 1*b*. The peak recorded ground acceleration was 0.20*g*. Acceleration response spectra for the same earthquake are plotted in Fig. 2*b* for critical damping ratios $\xi = 0.02$, 0.05, 0.10 and 0.20, the response spectrum is an engineering representation of earthquake ground motion in terms of the variation of the peak response of a simple single-degree-of-freedom oscillator with natural period T (s), and damping ξ expressed as a proportion of critical damping The greatest accelerations occur for periods >0.8 s, and peak at ~1.5-2.0 s. The spectral acceleration is repesentative of the force experienced by a structure during the earthquake, and such long-period amplification is unusual when compared with standard spectra assumed for purposes of design in many countries[12,13].

The main geotechnical problem in Bucharest arises from the presence of loessial (soft, wind-deposited) soils. In some areas, in the presence of water, these soils settle as much as 2 m under their own weight, thus any kind of foundation construction on such soils poses a difficult problem for geotechnical engineers. A soil amplification study[8] based on analysis of nonlinear wave propagation through the soil profile in Fig. 1*b* demonstrated that the base-rock acceleration, with an amplitude estimated at 0.03*g*, is magnified about seven times, yielding a maximum surface acceleration of ~0.20*g* as recorded in the NS component. The predominant period of vibration of the soil was computed at ~1.2 s.

By far the greatest structural damage in Bucharest was suffered by relatively light, reinforced concrete buildings 8-14 storeys high with natural periods between 0.9 and 1.6 s. This observation confirms the indications given by the Fourier and response spectra of the earthquake record (Fig. 2*a* and *b* respectively). The relatively high stiffness of the massive reinforced-concrete structures, generally 6-8 storeys high, which are typical of post-war construction in the region, resulted in relatively short fundamental periods of vibration and consequently these buildings survived with little or no damage[9]. Similar damage reports have been published for the 1985 Mexico City earthquake[1], in which 106 reinforced-concrete-frame buildings collapsed and a further 36 were severely damaged Only one of these buildings exceeded 15 stories in height, and 69% were constructed after 1957, when earthquake-resistant design regulations were first introduced.

Dynamic torsional coupling

The principles of building construction to withstand earthquakes are well established[14,15]. First, the conceptual design must ensure a ductile structure which can absorb energy: for example, foundations must be designed to avoid any differential movement Differential stiffness between piles and columns which could cause torsion or rocking should be avoided; stiff upper stories resting on a relatively 'soft', open ground-floor can lead to excessive stress in the base columns. There must also be adequate provision for energy absorbtion, for example by the inclusion of structurally redundant partition walls designed to fail during earthquakes and be replaced afterwards. Here I concentrate on research into the problems of building configuration, in particular where the design is asymmetrical, as when stiff elements such as the shear walls surrounding lift shafts are located eccentrically on plan. A typical arrangement is shown in Fig. 3*a* In the present study I evaluate the margin of safety in the earthquake-resistant design of such buildings, termed 'torsionally coupled' as defined below, when building code provisions are adopted. In particular, the torsional design recommendations of the Mexican earthquake code[2] are evaluated for the response of a particular class of buildings to ground motion exhibiting long-period amplification, as for example in the record of the Romanian 1977 earthquake (Fig. 2*a*)

For the purposes of this article a torsion-

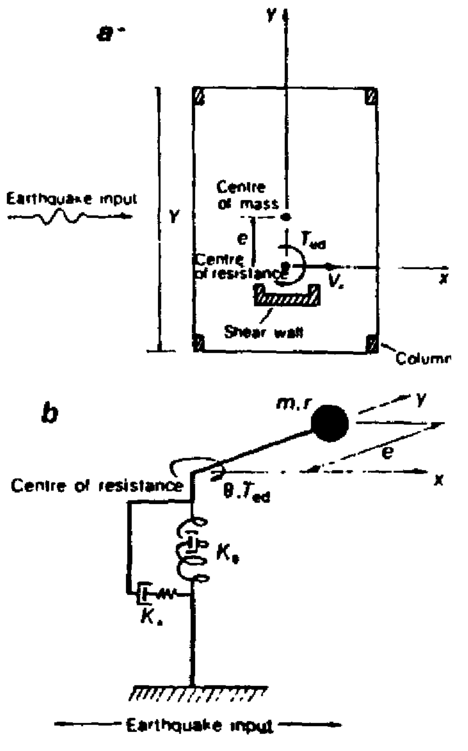
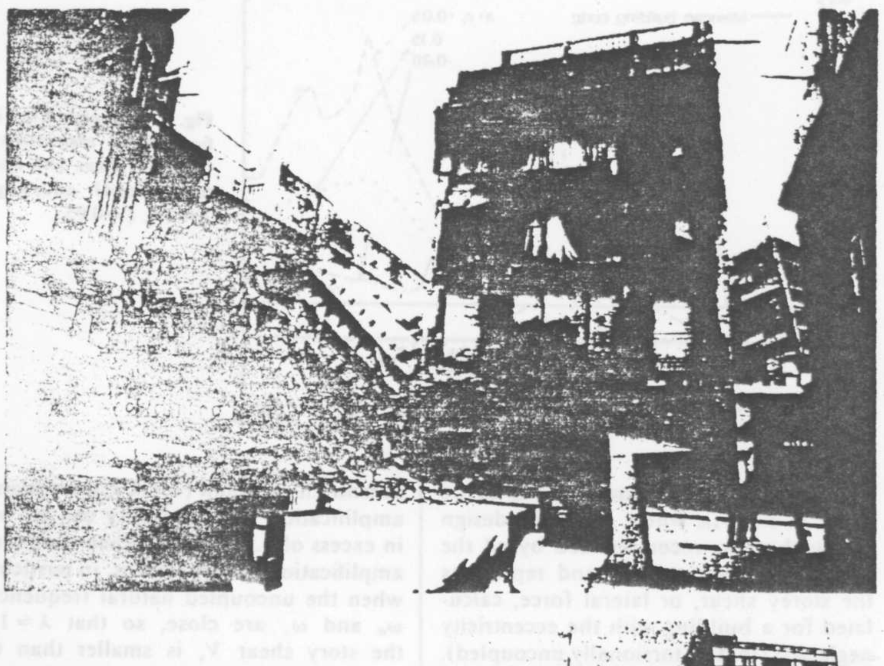


Fig. 3 *a*, Typical plan view of a torsionally coupled building with one eccentricity component; *b*, the corresponding model. K_y, Translational stiffness; K_θ, torsional stiffness.

ally coupled building is defined as one in which the centres of mass and resistance in at least one storey are not coincident. This means that the inertia forces (acting at the centre of mass) and the elastic forces (acting at the centre of resistance) form a dynamic couple which interconnects the translational and torsional response. In a torsionally uncoupled building, the centres of mass and resistance of all the stories lie on the same vertical axis and therefore translational and torsional responses are independent. The occurrence of torsional coupling is particularly evident in buildings in which the floor slabs act as diaphragms infinitely rigid in their own plane: for example, cast-in-place monolithic reinforced-concrete slabs supported on slender moment resisting frames.

The distance between the centres of mass and resistance is referred to as the static eccentricity, or simply the eccentricity. This quantity may be determined by applying the principles of static engineering mechanics to a specified mass and stiffness distribution. Irregularities of this kind may arise, for example, from the functional architectural requirements of the building, an irregular plan configuration or an unbalanced distribution of the vertical structural elements. It has been recognized, however, in research work[17-20] and in building codes[21] that there is an uncertainty about the magnitude of the eccentricity during an earthquake. Accidental eccentricities may result from a number of causes which cannot be quantitatively determined[22]: variations between the actual and assumed mass and stiffness distributions; the presence and participation in the building response of stairs, partitions or masonry in-fill walls, nonlinearities, failures and consequent shifting in the structural response characteristics; displacement constraints from adjacent structures; the rotational component of ground motion about a vertical axis, and multi-support excitation.

Computer programs[23,24] using complex multi-degree-of-freedom structural models have been developed to analyse the earthquake response of torsionally coupled buildings. Although the problem of torsional coupling in simple models was recognized and experimentally investigated in 1943 (ref. 25), it was not until 1958 that the first conclusion of practical significance was made[26], namely that the dynamic torque T_{ed} may be considerably larger than the product of the uncoupled shear force V_{x0} and eccentricity e. This conclusion has since been verified[5,22,27-30] using more general models of torsionally coupled buildings. The present study is concerned with single-storey torsionally coupled buildings with centres of mass and resistance lying on the same principal axis of resistance (Fig. 3*a*, modelled mathematically as in Fig. 3*b*). Detailed parametric analyses of such buildings have already been made[22,27-30], so emphasis is placed here on a comparison with the torsional recommendations of building codes[21], and the Mexican code[2] in particular.



An indication of the damage caused by the Mexico City earthquake. Above, precast concrete floor plates from a multi-storey car park have pushed sideways the adjacent old building. On the right, progressive collapse of the steel-framed Hotel de Carlo was contained after several stories were lost.

The building is considered to consist of a rigid floor-diaphragm supported on structural framing and shear walls. The floor slab behaves as a rigid body in a general plane motion with two degrees of freedom: horizontal translation, and rotation about a vertical axis through the centre of resistance. Such buildings are commonly called 'shear' buildings because of the shape of their primary deformation mode. It is assumed that the mass of the building is lumped at the centre of mass, which coincides with the centroid of the floor slab. The structural elements supporting the slab and providing the lateral resistance are massless, elastic and viscously damped springs (see Fig. 3*b*). The investigation of single-storey buildings is justified because the response of multi-storey torsionally coupled buildings can, in many cases, be predicted[31,32] from the response of associated single-storey buildings.

The earthquake ground motion is assumed to act in the x-direction only, and consists of the digitized NS Romanian 1977 ground acceleration record. The coupled translational and torsional response components of the structure have been computed in the frequency domain using numerical integration methods[22,33], and are expressed parametrically in terms of the damping ratio ξ, the static eccentricity ratio $e_r = e/r$, where r is the radius of gyration of the floor mass m about the centre of mass, and the uncoupled frequency ratio $\lambda = \omega_\theta/\omega_x$ where ω_θ and ω_x are, respectively, the torsional and translational natural frequencies of the torsionally uncoupled building ($e = 0$). Note that the translational natural period $T = 2\pi/\omega_x$ (Fig. 2*b*).

Comparison with Mexican code

In 1979, Rosenblueth[34] discussed a number of improvements which had been implemented in the Mexican code[2] as a result of research and of an interchange of ideas and experiences with the Applied Technology Council of the United States. Among the improvements was a more detailed treatment of design storey torques, intended to account for the dynamic amplification of eccentricity which results from torsional coupling, and based on earlier results by Rosenblueth and Elorduy[28]. To this end, an amplification of 1.5 in the static eccentricity e was recommended to define the dynamic eccentricity e_d; that is,

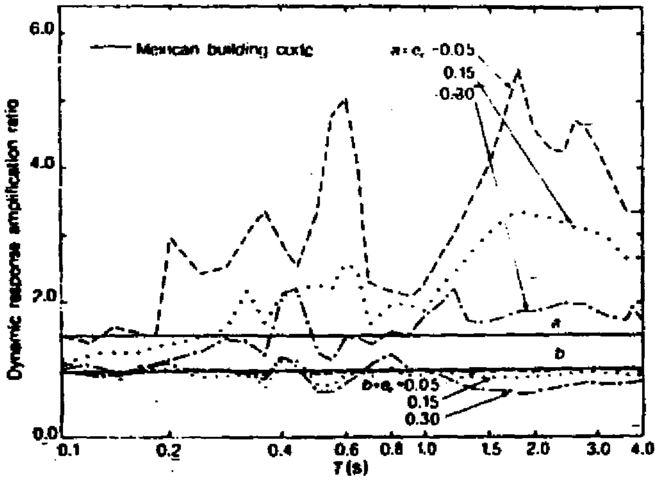


Fig. 4 Dynamic amplification of eccentricity (*a*) and shear (*b*) due to torsional coupling. $\lambda = 1.0$, $\xi = 0.05$.

the design storey torque T_{eh} was to be taken as $1.5eV_{x0}$, where V_{x0} is the design storey shear as recommended by all the various building codes[21] and represents the storey shear, or lateral force, calculated for a building with the eccentricity neglected (that is, torsionally uncoupled). In addition, the design eccentricity was to be increased by $0.1\,Y$, where Y is the plan story dimension measured perpendicular to the direction of the applied earthquake forces (Fig. 3*a*). This additional term accounts for the probable accidental eccentricity e_a arising from the various sources listed earlier. Although this latter term was recognized to be a crude way of dealing with several variables, it was felt that such an approach was justified because, first, a more ambitious and therefore time-consuming and costly provision would meet with objections and probable rejection by practising engineers, and second, the current state of knowledge would not realistically justify a more refined treatment. In summary, the recommendations of the Mexican 1977 code[2] for the design torque T_h are

$$\begin{aligned} T_h &= T_{eh} + T_a \\ &= (e_d + e_a)V_{x0} \\ &= (1.5\,e + 0.1\,Y)V_{x0} \end{aligned}$$

The development of equivalent static methods for incorporating torsional effects in building design stems from the work of Bustamante and Rosenblueth[5], who first introduced the concepts of dynamic eccentricity and the dynamic amplification of static eccentricity as described above. These concepts were later implemented in the majority of building codes. Although compilers of building codes were quick to adopt the dynamic amplification concept, it has become apparent from the work of various investigators[22,27,28,30] that this method does not provide a complete (or conservative) description of the effects of torsional coupling over the full ranges of the controlling parameters which define the dynamic torsional characteristics of typical buildings. The studies have shown that when the eccentricity is small ($e \ll Y$), the dynamic amplification of eccentricity can be well in excess of 1.5, but that when such large amplification occurs (that is, in particular when the uncoupled natural frequencies ω_θ and ω_x are close, so that $\lambda \simeq 1.0$) the story shear V_x is smaller than the design value V_{x0}, hence the dynamic amplification of shear is <1.0.

The torsional provisions of the Mexican code, in common with most codes, take no account of the effects of the frequency ratio λ or of the level of damping ξ present in the structure. The results presented in Fig. 4 relate to the worst-case situation for design (that is, $\lambda = 1.0$) and further assume $\xi = 0.05$, a value which is conservative for the majority of buildings. A study by Hart *et al.*[16] has shown that of 19 buildings investigated, 9 had fundamental torsional frequencies within 25% of the corresponding lateral frequencies; hence, torsional coupling probably has a significant effect on the earthquake response of many buildings, particularly since greatest amplification of eccentricity occurs when the static eccentricity ratio e_r is small.

Figure 4 illustrates the effects of torsional coupling on the dynamic amplification of shear and eccentricity for $e_r = 0.05$, 0.15 and 0.30 in the response to the NS Romanian 1977 earthquake, clearly demonstrating the implications of long-period amplification of ground motion on the magnitude of coupling effects. In particular, for fundamental (uncoupled) building periods $T > 1.0$ s and for $e_r = 0.05$, the dynamic eccentricity is amplified compared with the static value by a factor of up to 5.5, in comparison with the building code estimate of 1.5 as shown. Furthermore, the dynamic shear is approximately equal to the uncoupled (design) value V_{x0} in this range. Hence the dynamic forces on the building will in combination exceed design values to an extent which may result in the widespread damage or failure of buildings with fundamental periods in this range; that is, buildings that are 10-15 storeys high[18]. This observation coincides with the reported damage to buildings in both the Chilean[7] and Mexican earthquakes[35] (1985), in which torsional effects were cited as a major cause of failure, as in the Romanian earthquake itself[8,9].

The deficiency of the torsional recommendation of the Mexican code is less evident for larger eccentricities, when the dynamic amplification of eccentricity assumes smaller values (Fig. 4). Nevertheless, the provision underestimates to some extent the dynamic torque even for large static eccentricity ($e_r = 0.30$), especially when $T > 0.9$ s. However, in the same range the dynamic shear is reduced to ~60-70% of the design value V_{x0} and will thus offset to some extent the underestimation of dynamic torque.

Conclusions

Early reconnaissance reports following the 19 September 1985 earthquake in Mexico City gave strong indications that even those buildings that had been designed and built strictly in accordance with the local earthquake codes and modern engineering practice, collapsed as a result of the earthquake. This may be explained, in part at least, by the unusual amplifying effects of the geological formations beneath the city. In addition, however, the present study shows that the earthquake design procedures accounting for torsional coupling in the Mexican code underestimate the effect within particular ranges of the controlling parameters defining the dynamic characteristics of buildings. In particular, torsional coupling is more significant in the response of asymmetric buildings to an earthquake whose spectrum exhibits a concentration of energy in the range of natural periods typical of many modern multi-storey buildings of medium height and of conventional construction. Because of the uncertainties surrounding the precise distribution of mass and/or stiffness, even buildings which are nominally symmetric can respond with strongly coupled lateral and torsional modes of vibration[19], resulting in an amplification of torsional response which significantly exceeds the design value in the Mexican building code.

The lessons learnt in the wake of the Mexico City disaster[36] must be followed by a detailed re-examination of earthquake-resistant design principles as indicated by the present research, followed by worldwide enforcement through more stringent design and supervision building codes in seismic zones. ☐

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