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Formulation of design eccentricity to reduce ductility demand in asymmetric buildings

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Abstract

A critical analysis of the large number of papers about the seismic behaviour of asymmetric buildings shows some concordant results: the modal analysis correctly predicts their elastic dynamic response to seismic records, while it overestimates deck rotation in the inelastic range. On this basis, the authors propose to design asymmetric structures by twice repeating the modal analysis: the first one with the actual mass distribution, so as to cover the elastic behaviour; the second one by considering the centre of mass displaced towards the centre of rigidity by a design eccentricity, so as to fit the inelastic response. In order to assess a formulation for the design eccentricity that reduces the maximum ductility demand, the paper statistically analyses the inelastic response of an idealised one storey building, symmetric about one direction, to different sets of accelerograms (both natural and artificial) and compares it to that of the corresponding balanced building; the analysis is repeated many times, so as to evaluate the influence of the different geometrical and mechanical parameters governing the inelastic response. The proposed approach and formulations prove to be effective in evaluating the effects of asymmetry, thus providing a design criterion which limits the ductility demand of asymmetric schemes without relevant increments of structural costs. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Asymmetric buildings; Inelastic response; Design criteria

Notation

B	dimension of the deck along the y direction
C_M	mass centre
C_R	centre of rigidity
C_{Rb}	centre of rigidity of the *transformed basic system*
d_b	distance between G and G_b
e_p	distance between plastic centre and mass centre
e_s	stiffness eccentricity, i.e. distance between C_R and C_M
G	geometrical centre of the deck
G_b	centre of the *basic system*
K_b	total lateral stiffness of the elements of the *basic system* $K_b = \sum_{i=1}^{n_b} k_{ib} = \frac{1}{2} K_y$
k_{ib}	stiffness of the ith element of the *basic system*
k'_{ib}	stiffness of the ith element of the *transformed basic system*
k_{iy}	stiffness of the ith element parallel to y-axis
k_{jx}	stiffness of the jth element parallel to x-axis
K_x, K_y	total lateral stiffness of the elements parallel to the x and y-axis $K_x = \sum_{j=1}^{n_x} k_{jx} \qquad K_y = \sum_{i=1}^{n_y} k_{iy}$
K_θ	total torsional stiffness about C_R $K_\theta = K_{\theta x} + K_{\theta y}$
$K_{\theta b}$	total torsional stiffness of the elements of the *basic system* about G_b $K_{\theta b} = \sum_{i=1}^{n_b} k_{ib}\xi_{ib}^2$
$K'_{\theta b}$	total torsional stiffness of the elements of the *transformed basic system* about their stiffness centre

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$K_{\theta G_y}$ torsional stiffness of the elements parallel to the y-axis about G $K_{\theta G_y} = \sum_{i=1}^{n_y} k_{iy} x_i^2$

$K_{\theta x}$, $K_{\theta y}$ torsional stiffness of the elements parallel to the x and y-axis about C_R

$$K_{\theta x} = \sum_{j=1}^{n_x} k_{jx}(y_j - y_{CR}^2)$$

$$K_{\theta y} = \sum_{i=1}^{n_y} k_{iy}(x_i - x_{CR})^2$$

L dimension of the deck along the x direction

m mass of the deck

n_b number of elements of the *basic system*

n_x, n_y number of resisting elements parallel to the x and y-axis

O_s overstrength ratio, i.e. ratio of total strength of resistant elements along y-direction of an asymmetric system over total strength of the correspondent system designed by multi-modal analysis without design eccentricity

r_k stiffness radius of gyration about C_R

$$r_k = \sqrt{\frac{K_\theta}{K_y}}$$

r_m mass radius of gyration about the mass centre

T_x, T_y uncoupled translational period along the x and y directions

$$T_x = 2\pi\sqrt{\frac{m}{K_x}} \qquad T_y = 2\pi\sqrt{\frac{m}{K_y}}$$

T_θ uncoupled torsional period $T_\theta = 2\pi\sqrt{\frac{mr_m^2}{K_\theta}}$

u_y normalised displacement, i.e. ratio of displacement of asymmetric systems over displacement of the corresponding torsionally balanced systems

x_{CR}, y_{CR} coordinates of C_R

x_i, y_j distance of the resisting elements parallel to the y and x-axis from the y and x-axis respectively

γ_x share of torsional stiffness due to the elements parallel to x-axis $\gamma_x = \frac{K_{\theta x}}{K_\theta}$

ξ'_{CRb} abscissa of the rigidity centre of the *transformed basic system* in the local reference system

ξ_{ib} abscissa of the element of the *basic system* in the local reference system

ω_x, ω_y uncoupled translational frequency along the x and y directions

$$\omega_x = \frac{2\pi}{T_x} = \sqrt{\frac{K_x}{m}}$$

$$\omega_y = \frac{2\pi}{T_y} = \sqrt{\frac{K_y}{m}}$$

ω_θ uncoupled torsional frequency

$$\omega_\theta = \frac{2\pi}{T_\theta} = \sqrt{\frac{K_\theta}{mr_m^2}}$$

Ω_θ uncoupled lateral–torsional frequency ratio

$$\Omega_\theta = \frac{\omega_\theta}{\omega_y} = \frac{r_k}{r_m}$$

1. Inelastic response of asymmetric buildings

Whoever analyses the large number of papers on this subject will probably be struck by the complexity of the problem and the discrepancies among the conclusions of the researchers. In effect, while the elastic seismic behaviour is ruled by few global parameters (eccentricity between mass and stiffness centres, uncoupled lateral–torsional frequency ratio and, in a lesser way, period of vibration, shape of the response spectrum and position of mass centre with respect to the edges of the floor deck), at first sight the inelastic response seems to be influenced by location and strength of each resisting element. A considerable effort is therefore presently devoted to the standardisation of definitions and assumptions and to the identification and evaluation of the effect of every single parameter. One of the goals of this paper is to give proper relevance to the main aspects, putting more emphasis on some concordant results of the research; a few general considerations, which can be found in most papers on this subject, may in fact constitute the basis for a retrospective analysis of past work and for the proposition of a design approach able to limit the negative effects of asymmetry.

At first it must be noted that the conclusions of the researchers seem contradictory mainly when attention is focused on ductility demand, which in different papers is considered to reach the maximum at the stiff or at the flexible side and to be smaller, comparable or much greater than that of the corresponding balanced system. This is obviously related to the different design approaches and to the strength the structural elements are consequently provided with. On the contrary, many authors acknowledge that the inelastic displacements of the elements which constitute a spatial frame are scarcely dependent on their strength, i.e. that different structures, with elements having the same stiffness but designed so as to offer different strength, present approximately the same peak displacements. Goel and Chopra [1] clearly state that “the element deformations of systems designed according to most building codes